Accelerating the Successful Integration of Metal Additive Manufacturing with Conventional Technologies and Value Chains

TECHNOLOGY ROADMAP

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CAM-IT
Consortium for Advanced Hybrid Manufacturing Integrating Technologies
Table of Contents

List of Figures .......................................................................................................................... ii
List of Tables ........................................................................................................................... ii
Executive Summary ................................................................................................................ 1
Overview .................................................................................................................................. 3-7
Swim Lane 1: Materials Properties Enhancement ................................................................. 9-12
  Background ............................................................................................................................. 9
  Results ................................................................................................................................... 10
  Summary .................................................................................................................................. 10-12
Swim Lane 2: System Integration ............................................................................................. 13-16
  Background ............................................................................................................................. 13
  Integration Methodology ........................................................................................................ 14-16
  Integration Development ......................................................................................................... 16
Swim Lane 3: Achieving GD&T through Machining ................................................................. 17-24
  Background ............................................................................................................................. 17
  AM Process Planning ................................................................................................................ 18-19
  Summary .................................................................................................................................. 20
  Results ................................................................................................................................... 21-24
Swim Lane 4: Surface Finish Considerations .......................................................................... 25-35
  Background ............................................................................................................................. 25-28
  Current State Assessment ........................................................................................................ 28-29
  Summary .................................................................................................................................. 30
  Future State and Gap Analysis ................................................................................................. 30-32
  Results ................................................................................................................................... 32-35
Swim Lane 5: Inspection (Qualification / Certification / Standards) ........................................ 37-44
  Background ............................................................................................................................. 37-39
  In-situ and Ex-situ Inspection .................................................................................................. 39-42
  Summary .................................................................................................................................. 43-44
Swim Lane 6: In-Envelope Hybrid .......................................................................................... 45-51
  Background ............................................................................................................................. 45
  Ex-Envelope Hybrid Manufacturing ....................................................................................... 45
  In-Envelope Hybrid Manufacturing ....................................................................................... 46-47
  Summary .................................................................................................................................. 48-51
Workforce and Education ......................................................................................................... 53-56
  Current Challenges .................................................................................................................. 53-54
  Future Vision ........................................................................................................................... 55
  Workforce and Education Gaps ............................................................................................... 56
Summary .................................................................................................................................... 57-60
APPENDICES .......................................................................................................................... 61-65
APPENDIX I: CAM-IT Leadership Team ............................................................................. 61
APPENDIX II: CAM-IT Executive Committee ...................................................................... 62
APPENDIX III: CAM-IT Roadmap Contributors ................................................................. 63-64
APPENDIX IV: Glossary .......................................................................................................... 65
Figures

Figure 1  CAM-IT Value Chain ........................................................................................................................................ 4
Figure 2  Jet Engine Loading Bracket - AM Part Design (Courtesy of GE Aviation) ................................................................. 14
Figure 3  Schematic of a Hybrid Manufacturing System Using AM ...................................................................................... 21
Figure 4  A Typical Hip Replacement and Knee Replacement Assembly .................................................................................. 26
Figure 5  Ex-envelope Hybrid Example DMLS Part Build and HAAS 3-axis CNC Milling Machine ........................................... 46
Figure 6  Commercial In-envelope HM Systems DMG Mori Seiki and Matsuura Lumex ............................................................... 46
Figure 7  Retrofit HM Technologies Hybrid Manufacturing Technologies AMBIT System and Optomec ........................................ 47
Figure 8  Ex-envelope Hybrid Manufacturing Process Flow .................................................................................................. 47
Figure 9  In-Envelope Hybrid Manufacturing Process Flow .................................................................................................. 48

Tables

Table 1  Workshop Schedule, Topics, and Leaders ............................................................................................................. 7
Table 2  Initial Summary Materials for Materials Properties Enhancement Workshop ............................................................... 12
Table 3  Systems Integration Issues Discussed ...................................................................................................................... 15
Table 4  Integration Components that Need Research and Development .................................................................................. 16
Table 5  List of Tasks Associated with Current AM Process Planning ...................................................................................... 18
Table 6  List of Current Challenges Associated with AM Process Planning .............................................................................. 18
Table 7  List of Current State Assessment for SM Process Planning Associated with Hybrid Manufacturing ............................ 18
Table 8  List of Current State Challenges for SM Process Planning Associated with Hybrid Manufacturing ......................... 19
Table 9  List of Current Tasks Associated with Fixture/Setup Planning ...................................................................................... 19
Table 10  List of Current Challenges Associated with Fixture/Setup Planning ............................................................................... 19
Table 11  Future Vision and Technical Gaps / AM Process Planning ...................................................................................... 20
Table 12  Future Vision and Technical Gaps / SM Process Planning ...................................................................................... 20
Table 13  Future Vision and Technical Gaps / Fixture/Setup Planning .................................................................................. 20
Table 14  Achieving GD&T AM Process Planning Road Blocks ................................................................................................ 22
Table 15  Achieving GD&T SM Process Planning Road Blocks ................................................................................................ 23
Table 16  Achieving GD&T Fixture Planning Road Blocks ......................................................................................................... 24
Table 17  Hybrid Operations that Influence Surface Finish .................................................................................................. 27
Table 18  Summary of Road Blocks for Surface Finish Workshop Related to AM ................................................................. 34
Table 19  Summary of Road Blocks for Surface Finish Workshop Related to Finishing ............................................................. 35
Table 20  Summary of Results Inspection, Qualification, and Certification .................................................................................... 40
Table 21  Summary of Results Inspection, Qualification, and Certification (continued) ............................................................. 41
Table 22  Summary of Results Inspection, Qualification, and Certification (continued) ............................................................. 42
Table 23  Issues Associated with Inspection, Certification and Qualification Systems ................................................................. 43
Table 24  Issues Associated with Inspection, Certification and Qualification Systems (continued) ........................................... 44
Table 25  Summary of Results In-envelope vs. Distributed Hybrid .................................................................................................. 49
Table 26  Issues Associated with Material Properties to be Addressed in In-envelope vs. Distributed Systems ......................... 50
Table 27  Additional Issues that Need to be Addressed in In-envelope vs. Distributed Systems .................................................. 51
Advanced high performance and highly customized mechanical components are critical for the continued development of sophisticated products, such as metal prosthetics, aerospace structures, and other low production-run parts.

Additive manufacturing (AM) has been viewed as the solution to making these high-performance products affordable. Additive manufacturing (AM) is a rapidly growing field within the United States especially for the manufacturing of metal parts. AM describes processes where a product is fabricated by fusing or depositing material often layer-by-layer. The evolution and broad commercial utilization and growth of AM have been limited by a number of factors. These factors include dimensional accuracy, surface qualities, material properties and variation, costs (i.e. speed, yield), and broad supply chain capability – all of which are needed for high-performance metal components but cannot be achieved exclusively using AM.

Improving our ability to use AM is critical to the continued development of sophisticated products as well as a healthy manufacturing environment. A roadmap and coordinated approach to developing and implementing next-generation strategies for using AM is essential to realize and fully commercialize this technology and to securing the United States lead in this emerging field.

This report provides a vision and roadmap to address the challenges of combining AM with traditional and not-so-traditional subtractive manufacturing (SM). Hybrid manufacturing (HM) is defined as an integrated set of dissimilar manufacturing processes such as an AM process linked to one or more manufacturing processes including but not limited to, machining, material property enhancement, finishing, and other processes required to satisfy the final product engineering specifications. This report highlights the recommended technical activities and focus areas (i.e. roadmap) required to evolve both in-envelope and serial hybrid AM and associated advanced manufacturing technologies.
Overview

The Problem: Although there is optimism that additive manufacturing (AM) will reduce the time required to achieve a fully functional first item product to a few days, current practice still typically yields times of more than three weeks for typical mechanical parts. Metal-based AM cannot yet achieve the same finish and tolerances as conventional metal manufacturing methods such as machining and grinding. As a result, uptake of this potentially transformative technology requires not only a substantial capital investment, but also the production sophistication to augment AM techniques with at least one or more series of finishing, post-processing, and inspection steps. The complications of manually routing printed parts through a series of additional production steps is daunting and discourages many would-be adopters. A simplified approach is needed to achieve widespread acceptance of metal-based AM.

Hybrid Manufacturing (HM): HM is defined as an integrated set of dissimilar manufacturing processes such as an AM process (e.g. powder-bed fusion, binder jetting, directed energy deposition, sheet lamination) linked to one or more manufacturing processes including but not limited to, machining (subtractive manufacturing), material property enhancement (such as stress relieving, HIP, annealing), finishing (such as grinding, polishing), and other non-AM manufacturing processes required to satisfy the final product engineering specifications. The attributes of each process (e.g. part accuracy or internal grain structure) are planned together (preferably concurrently) so that the required product engineering specifications can be met. This is different than sequential production in that the decisions are coordinated so that intermediate part specifications are determined in the hybrid process.

Given the growing attention around AM, manufacturing companies have been trying to identify the value and viability of using AM in their existing processing and product portfolios. Arguably, the most prominent was President Obama’s reference in the 2013 State of the Union address. However, very few manufacturing companies have placed metal AM parts into production products. For instance, the CEO of GE, Jeff Immelt, considers AM to be a game changer and envisions that by 2020, GE Aviation will be producing over 100,000 metal additive parts for its LEAP and GE9X engines with the company planning to invest $3.5B in AM. Unfortunately, most articles in the open literature do not discuss the critical post-processing required to actually integrate AM-made parts into an assembly for final applications. The accuracy/tolerances and surface roughness of current metal AM capabilities is not comparable to traditional processes and most often AM requires secondary and tertiary processing. While Small and Medium Enterprises (SME) and Original Equipment Manufacturers (OEM) companies are aware of the endless opportunities that AM provides and are seeking a viable approach to enter the AM market, there are no well-defined strategies that would enable them to seamlessly integrate AM within their existing capabilities. In particular, integrating different manufacturing technologies requires careful planning and execution at different stages: material selection, design considerations, process selection, software integration, post-process parameters, etc. It has become increasingly clear that the potential post-processing or secondary processing of AM parts are not insignificant regarding cost and scheduling of AM production builds.

Most metal parts must go through mechanical conditioning, geometric enhancement (feature size and tolerance) and surface treatment. Developing a technology roadmap that would detail the requirements/framework to address these challenges is the focus of CAM-IT. CAM-IT is a consortium focused on the development of hybrid metals manufacturing systems with an initial goal of identifying the roadblocks and developmental strategies to integrate design, additive manufacturing, subtractive manufacturing, and other production finishing processes to benefit the commercial evolution of AM methods.

The vision of CAM-IT is to identify major barriers for existing manufacturing industries (in particular SMEs) from being part of this growing AM and post-processing supply chain and benefit from expanding their offerings beyond traditional product and services through the efforts of this consortium. The scope of CAM-IT is limited to metal AM mechanical products with a focus that is “post design but design-driven” and targets that include: production processes, planning for manufacturing, tooling, software, automation and production systems design. This report outlines the development of an Advanced Hybrid Metal Additive Manufacturing technology roadmap that aims to:
1) create a US-based consortium of entities including industries, academia, government agencies, professional organizations, and research entities who can both add to and benefit from advanced and hybrid manufacturing.
2) identify and prioritize current shortcomings under industry leadership and the technical challenges in achieving efficient hybrid processing.
3) develop a roadmap and technology infrastructure
that is a ready-to-implement post-processing system designed for finish machining of metallic AM parts, without significant modifications to existing machine set-up; this will provide a viable low-cost path to entry for SMEs and OEMs who currently (and in the near future) do not have the capital, technical know-how and experience in metal AM, 4) identify and detail technological infrastructures required to address those challenges, and 5) outline workforce development and education outreach programs for the implementation of the hybrid approach which will greatly enhance the technical expertise of our manufacturing companies.

CAM-IT was funded as part of NIST’s AMTech program; and in order to identify key foundational elements for this roadmap, CAM-IT began with a kick-off workshop on November 16th, 2015 at Youngstown State University (YSU) in Youngstown, Ohio. This report outlines the steps and procedures used to develop a Roadmap for Commercialization of Hybrid AM/SM production activities. The roadmap workshop employed a systems engineering based approach (pull demand based on applications for hybrid metal AM Critical Technological Elements) and identified six (6) swim lanes to use in the development of the Roadmap. These swim lanes were the focus of three additional focused workshops where the details of each topic were discussed. In the following sections, these swim lanes are first described, and then detailed into specific technological roadblocks that have inhibited the commercial adoption of metal AM technologies.

We envision a hybrid process used to produce AM mechanical parts as shown below in Figure 1. As can be seen in the figure, the process is design-driven, and the design can require that a part will go through several different production processes before the desired part requirements will be achieved. The goal of this engineering process is to produce highly customized products efficiently and inexpensively.
CAM-IT has focused on:

1) developing a U.S.-based consortium of entities including industries, academic, professional organizations and research entities who both add to and benefit from advanced hybrid manufacturing.

2) identifying and prioritizing current shortcomings under industry leadership and the technical challenges in achieving efficient hybrid processing.

3) developing a roadmap and technology infrastructure for a ready-to-implement post-processing system designed for finish machining of metallic AM parts – without significant modifications to existing machine set-up; that provides a viable low-cost path to entry for SMEs and OEMs who currently (and in the near future) do not have the capital, technical know-how and experience in metal AM,

4) identifying and detailing technological infrastructures required to address those challenges, and

5) defining the workforce development and education outreach programs for the implementation of the hybrid approach which will greatly enhance the technical expertise of our manufacturing companies.

Swim lanes were the focus of three additional workshops where the details of each swim lane and the roadblocks were discussed. In the following sections, these swim lanes are first described, and then detailed into specific technological roadblocks that have inhibited the commercial adoption of metal AM technologies.

At the first workshop, each member of the audience contributed one “Hybrid Metal Additive Manufacturing Application”, followed by providing some commentary towards answering “Why Tech Insertion is Not Considered Today”. This method captured a number of applications for hybrid metal AM, across a variety of markets. With these gaps identified, the group identified a set of seven “Technology Needs”. A final down-selection by the workshop leaders/organizers was performed to capture the most frequently identified needs that were critical to enhancing the properties through hybrid metal AM. The topics that fell from this workshop are described briefly below:

**SL1 Materials Properties Enhancement**

Materials and properties are foundational engineering components for the development of any product. The processes used to develop the AM product will affect the material properties through changes to material structure at all levels (nano to macro). These include but are not limited to: thermal processes affecting grain size morphology or compositional segregation, heat treatments for precipitation strengthening, pressing (i.e. hot isostatic press), residual stress relief, cold work, and chemical species diffusion such as carburization or nitriding. These processes can be in-situ or ex-situ to the additive build envelope.

**SL2 Systems Integration**

Integration methods related to hybrid metal AM include but are not limited to: process planning, prior to AM to account for post-processing (build direction, sacrificial supports needed for the AM build, machining allowance) and in-process monitoring and control; design and location of sacrificial supports to AM part design for location and fixturing AM parts for post-processing (location of the supports, size of the supports, mechanical properties of the support so that deflection can be predicted, etc.), data representation format that can be used for all operations so that build geometries can be tracked and used for different activities, and tooling requirements and NC code generation for subtractive processing, and localization of the AM part in the NC machine that will be used for subtractive-processing.

**SL3 Achieving GD&T through Machining**

The “as-processed” AM parts currently produce metal parts with less than desired feature tolerances (e.g. warping, scale, shrinkage). Dimensional control and tolerance include but are not limited to: specification of dimensions and tolerances during design stage for hybrid processing, measurement and analysis of “as-processed” AM part, process planning/monitoring of hybrid processing for specified GD&T, quality control of final parts and measurement techniques adopted for metal Hybrid AM. These processes can be in-situ or ex-situ to the additive build envelope.
Overview — continued

Surface Finish Considerations

The surface finish and the integrity of AM surfaces are of critical importance for fully functional parts as well as for prolonged use of a component. All metal AM processes produce parts with less than optimal surface conditions so in many instances secondary processes will be necessary. These secondary processes can include but are not limited to traditional machining, grinding and polishing, electro polishing, electrochemical machining, electrical discharge machining, and well as chemical surface enhancing processes.

Inspection (Qualification / Certification / Standards)

Current (and under-development) qualification and certification standards are primarily related to traditional processes (relatively well-established) and AM (e.g. ASTM F42, B46). This is a major requirement of metal hybrid AM pertaining to Inspection (qualification and certification standard), and is not limited to: development of inspection methods for metal hybrid material properties, surface morphology, GD&T, data representation terminologies and process integration. These processes can be in-situ or ex-situ to the additive build envelope.

In-Envelope Hybrid

The category of In-Envelope Hybrid machines where both additive and subtractive processing occurs within the same production resource presents different technological challenges (e.g. warping, dwell time after deposition prior to machining, and feedstock disposal). This category of hybrid metal AM includes but is not limited to sequential cycles of deposition and material removal, incorporation of multi-material deposition and electronic components as well as process monitoring to enhance surface properties, material properties and part feature GD&T.

The Workshops

Area experts from industry, academia and government were assembled so that groups of experts could collectively participate in brainstorming sessions, with each workshop participant contributing an industry-driven application. The participants identified technical barriers or gaps that must be addressed in order to more effectively use the application. The workshop leaders then categorized the maturation ideas into four groups requiring further investigation.

Group leaders/facilitators were selected for each of the swim lanes, and at each workshop, these leaders provided an overview of capabilities and limitations associated with each swim lane topic. The participants then assembled into groups based on a self-assessment of each participant’s expertise and familiarity with the technical maturation area. Specific road blocks were discussed with a focus on impact, difficulty and expected time duration before solutions could be developed.

Reports for each workshops were prepared and served as the basis for this Technology Roadmap.

The first focused swim lane workshop was held on April 19, 2016 at North Carolina State University in conjunction with the CAMAL Semi-Annual Members Event. The Group Leaders for the Materials Properties Enhancement focus were Drs. Shawn Kelly (EWI) and Richard Martukanitz (Penn State University) with representatives from academia, industry, and government attending their session. The Leaders for the Systems Integration session were Drs. Sanjay Joshi (Penn State University) and Richard Wysk (NC State University). The second focused workshop was held in Chicago, Illinois in conjunction with the International Machine Tool Show on September 15, 2016. Drs. Matthew Frank (Iowa State University) and Ronald Aman (EWI) served as Leaders/facilitators for the Achieving GD&T Using Machining session, Drs. John Taylor (Lawrence Livermore National Laboratory (LLNL)) and Satish Bakkapatnam (Texas A&M University) lead the Surface Finish Considerations discussions. The final focused workshop was held in El Paso, Texas in conjunction with the America Makes Technical Review Meeting on March 10, 2017. The group leaders for the Inspection (qualification, certification and standards) focus were Drs. John Ziegert (UNC-C) and Frank Liou (UMST). Drs. Jason Jones (Hybrid Systems Inc.) and Harshad Srinivasan (Xeometry) served as leaders for the In-envelope versus Distributed Hybrid Systems focus. Finally, meetings with the Industry Executive Committee were held both in person and via the internet to reach consensus concerning the issues presented herein.

A summary of the workshops is shown in Table 1.
## Table 1
Workshop Schedule, Topics, and Leaders

<table>
<thead>
<tr>
<th>Category</th>
<th>Integration Technology Roadmap Component</th>
<th>Leaders</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Taxonomy</strong></td>
<td>Is there a classification of AM hybrid that lends itself for systems analysis?</td>
<td>Guha Manogharan, Rick Wysk</td>
<td>Nov 16, 2015</td>
</tr>
<tr>
<td><strong>Materials Properties</strong></td>
<td>Metals AM requires a range of in-situ and ex-situ processes needed to obtain desired part performance.</td>
<td>Shawn Kelly, Rich Martukanitz</td>
<td>Apr 19, 2016</td>
</tr>
<tr>
<td>Enhancement</td>
<td><em>Integrated processes leading to structure, properties, and performance.</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Finishing for GD&amp;T</strong></td>
<td>Virtually every AM metal component needs secondary and/or tertiary processing. Cost of secondary processing are typically far greater than AM. <em>Automatic finishing of AM metal parts using CNC machining.</em></td>
<td>Matt Frank, Ron Aman</td>
<td>Sep 15, 2016</td>
</tr>
<tr>
<td><strong>Systems Integration</strong></td>
<td>Traditional processing of metal mechanical parts has evolved into a series of operations integrated through years of experience. <em>Integration engineering for hybrid metal parts.</em></td>
<td>Sanjay Joshi, Rick Wysk</td>
<td>Apr 19, 2016</td>
</tr>
<tr>
<td><strong>In-Envelope vs Sequential</strong></td>
<td>A small number of hybrid single envelope AM/SM machines have been developed. Is there technical drivers determining what should be used? <em>In-envelope versus sequential processing systems.</em></td>
<td>Jason Jones, Harshad Srinivasan</td>
<td>Mar 10, 2017</td>
</tr>
<tr>
<td><strong>Surface control</strong></td>
<td>Complex geometries of AM create a new problem of creating functional surface conditions. <em>Surface control and conditioning.</em></td>
<td>Satish Bakkapatnam, John Taylor</td>
<td>Sep 15, 2016</td>
</tr>
<tr>
<td><strong>Certification, Qualification and Inspection</strong></td>
<td>Complex geometries and multi-functionality create additional engineering problems for qualified components. <em>Certification, Qualification, and inspection.</em></td>
<td>John Ziegert, Frank Liou</td>
<td>Mar 10, 2017</td>
</tr>
</tbody>
</table>

The initial workshop to define critical technology elements for the enhancement and use of hybrid methods successfully identified areas specific to metal hybrid AM that if further matured would lead to broader adoption of this AM process subset. The detailed areas/swim lanes that have direct application to hybrid metal AM are discussed in the following sections. Detailed reports containing attendees for these meetings, methods used during the meetings and voting taken during the meetings are available at the CAM-IT website.
Materials Properties Enhancement

Background

Define Tech Needs for Hybrid Metal AM Material Property Enhancement

The first swim lane workshop conducted for using metal AM focused on Materials Properties Enhancement. In an ideal world of manufacturing, a single AM machine would be used where the part would be produced to final dimension and materials specifications using a single process. The chemical segregation that may occur in AM processing during melting and solidification can result in the formation of scale and surface anomalies. Because of this, pre- and post-processing issues may be required in order to produce acceptable parts. Secondary and tertiary operations must be integrated into the planning of a product so that geometric requirements for assembly and function, as well as adequate mechanical properties (tensile strength, fatigue specifics, etc.) can be met.

The world of AM processing opens many doors for creative designs like: low-density components with improved strength to weight ratios, internal channels that have no geometric limitations, and the potential for gradient-based properties where each layer can have different malleability, strength and conductivity. Unfortunately, many physical properties are predicated on: surface texture, microstructure, and microscopic flaws in the component, which can be unpredictable and/or uncontrollable with current equipment and controllers.

The result is that current AM components frequently require post AM heat treatment, mechanical conditioning, e.g., HIPping, dimensional improvement, and surface finish improvement. Determining how much material to add to the AM processed component (overbuild) is still being empirically determined. Similarly, understanding the interactions between non-homogeneous layers of materials or how a material might be alloyed by using different metal powders are current materials science research topics. Given the current set of AM machine process specifications (controllable physics and chemistry for powder-based and binder-based systems), this swim lane activity looked at the technical issues that need to be addressed to produce high-performance functional parts quickly and economically.
Materials Properties Enhancement Results

The following critical technology topics were the focus of the Materials Properties Enhancement. Each critical technology element is defined in terms of the current technical barriers and needs, what qualification needs and barriers exist, what is the anticipated level of risk and reward, and finally what market segments and applications are driving these critical technology elements.

Many of the swim lanes that the participants identified centered on the following key themes:

- **Post Process Surface Treatment**

  Post process surface treatment was discussed in terms of the ability to modify the surface following primary additive process. In many engineering applications, the surface of a manufactured component is required to have a different set of properties and characteristics, for example increased corrosion resistance, increased hardness, increased thermal corrosion resistance, biocompatibility, or high cycle fatigue resistance. The presence of surface flaws, varying surface roughness and varying microstructure at the surface of the as-built material were identified as a current technical gap associated with hybrid metal additive manufacturing. In combination with these gaps, the ability to harden surfaces for certain wear applications via surface modifications, such as through deposition, carburizing, and nitrizing, or the functionalization of a surface through the application of bio-compatible or hydrophobic coatings were also identified as current technical gaps or barriers related to applications. For example, carburization of AM produced surfaces (microstructures and surface roughness) have not been largely studied. Understanding these impacts will broaden the range of applications that hybrid additive manufacture can be applied to, specifically, enable life-cycle enhancement through improved corrosion, wear resistance, and improved biocompatibility.

  Specific industries identified included the Defense (fatigue, corrosion resistance), Aerospace rotary parts (effect of surface finish on flow characteristics). Aerospace structural parts (stress and thermal induced cyclic loading) and Medical (biocompatibility). It should be noted that the above discussion on post process surface treatment is an industrial need for the metal additive manufacturing industry as a whole.

- **In-Process Surface Treatment**

  As described above, treatment of the surface of an engineered component is a conventional means to improve the performance of the component relative to the environment the component sees at the surface. In-process surface treatment or modification seeks to improve the surface performance, and is but one part of the hybrid AM process. The technical gaps presented above for post-process surface treatment apply to in-process surface treatment as well. However, the addition and recommended focus of the in-process surface treatment critical technical element (CTE) would be to focus on the process-specific technical barriers required to enable in process surface treatment.

  Currently, commercial powder bed fusion systems possess limited capability to modify the surface of the part beyond dealing with different oriented surfaces. However, commercial available directed energy deposition systems do possess the ability to modify surface chemistry through addition of different chemistry powders at the surface. The requirement of this CTE would be to understand and develop processes to directly modify the surface characteristics as part of a hybrid process scheme. Specifically, develop the processes necessary to modify surfaces in-process, develop the ability to measure surface characteristics in process, and develop models necessary to perform in-process surface modification. The ability to induce compressive residual stress, a conventional means of increasing fatigue performance, is an in-process step that largely unexplored, especially in terms of the use of using other tools to impart this residual stress. Means to quantify surfaces in-process via sensors, specifically measurement of residual stress was also defined as a technical barrier.

  The benefits of in-process surface treatment echo those presented above for post process surface treatment. Additionally, in-process surface treatment would have the added benefit to potentially eliminate post-processing steps. Also of significance would be the ability to modify internal surfaces that could not be accessed during a post process surface treatment. The costs associated with in-process surface treatment would be higher due to the process/equipment requirements, as well as the identified need to measure certain surface properties in situ. The implication is further broadening the application space to include components with internal geometries that might still require internal surfaces to be hardened or functionalized. The market pull for this CTE was identified and was similar to those applications for post process surface treatment, but emphasized those applications where internal features would not be accessible after the part was produced.
Materials Properties Enhancement — continued

- Heat Treatment Related to Distortion

Most components produced by hybrid additive manufacturing in the near term will still require the use of a post process thermal treatment to develop acceptable bulk material properties. In hybrid applications, where material addition and subtraction are combined into a single process to produce a net-shape part meeting tolerance, many components require subsequent heat treatment of the part, which may impact the ability of the part to meet tolerance due to stress relief and thermal distortion. Understanding and predicting distortion was identified as a critical need for hybrid metal AM. Secondly, applying this understanding for different process variability (powder, machines, build orientations, and geometries) needs to be mapped in order for hybrid metal AM to be successful.

The maturation requirements include developing guidance for engineers and heat treatment facilities for controlling and understanding limits of heat treatment induced distortion, understanding the impact of various AM (and hybrid AM) variables on distortion, developing the ability to modify processes (AM and heat treatment) to mitigate distortion, and finally incorporating modeling into AM and heat treatment process plans to control distortion.

The most impactful (lower difficulty, higher impact) current need was identified as understanding and developing process modifications to minimize heat treatment distortion. This will ultimately lead to the development of distortion guidelines for hybrid AM part producers and heat treatment facilities. Understanding the impact of AM process materials and modeling could have a high impact as well but due to the large number of yet to be understood variables with these processes the difficulty was ranked as high.

The Qualification and certification needs for heat treatment of AM parts are not necessarily unique to hybrid AM, but needed by the metal AM community as a whole. For example, general GD&T guidance for these hybrid AM produced components is needed. Minimizing material variability through standards for AM-specific material heat treatment and processing was also identified as a qualification and certification requirement.

The market pull for this particular CTE was generalized as all markets requiring hybrid AM parts and materials requiring heat treatment to develop the required mechanical properties. This would apply to most engineering applications across all market segments.

- Properties

The properties category was a catch-all category for a variety of hybrid AM process attributes that would be required for metal additive manufacturing with or without the hybrid context. Powder quality (size, shape, trapped porosity, and source), powder packing variation with the powder bed, and identifying correlations between powder quality, process consistency, and properties, and development of various sensing modalities, and modeling techniques, were identified as needs. The requirements of the properties identified process monitoring, closed loop controls, powder quality, creating homogenous microstructures, achieving theoretical densities, and uniform properties, were identified as maturation requirements necessary to achieve the desired properties of hybrid (or non-hybrid) AM. Maturation requirements identified that could be more closely tied to hybrid metal AM were understanding and quantifying surface characteristics such as roughness and residual stress both in and post process. It was noted that some recent work at NC State using the ARCAM A2 EBM used 50 µm particle titanium powder for some sample builds and reduced the build time significantly while only marginally worsening the part surface texture.

Understanding powder quality and developing modeling tools (in general) were sign as high cost, high impact activities to pursue, whereas understanding powder variation was seen as moderately difficult and an impactful activity. The integration of sensors, for surface finish and residual stress measurement were both indicated to have a high impact, with moderate to high difficulty (respectively).

Industrial pull identified for this CTE would again be applicable to a wide range of applications requiring a desired set of properties. Specifically identified were surgical and medical, tooling, components needing repair, and structural and rotating components. Further emphasis was placed on mesh (lattice-type) structures.

Materials Properties Enhancement Summary

The discussions concerning materials spanned a broad set of topics including: materials (metals and their alloys), processing of these materials, qualifying these materials and processes, and the effect of geometry on process and product performance. Tables 2A, 2B and 2C provide a summary of the topics and issues discussed. From the figures, one can note that this is an area that is still evolving and will require a significant amount of research and development.
### Table 2
Initial Summary Materials for Materials Properties Enhancement Workshop

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<tbody>
<tr>
<td>Process control</td>
<td>Develop better analytical models (with instrumentation specifications) and process controls for AM</td>
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</tr>
<tr>
<td>Testing methods</td>
<td>Develop better methods to predict part porosity, flaws, and mechanical properties</td>
<td></td>
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</tr>
<tr>
<td>Certification</td>
<td>Develop new metallic materials and procedures to certify them quickly. Define secondary processes required to obtain required strength, and other properties.</td>
<td></td>
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</tr>
<tr>
<td>Process control</td>
<td>Develop better methods for alloy development that will use base powder alloys with EBM or laser creating the alloy</td>
<td></td>
<td></td>
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<tr>
<td>Process control</td>
<td>Develop better process / thermal models (geometry-based) for new products to reduce distortion</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Process control</td>
<td>Develop models of material flaws and treatment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process control</td>
<td>Develop models of process flaws and treatment so that secondary processes can be determined to mitigate AM maladies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process control</td>
<td>Develop better methods for predicting processing affects on part porosity and flaws due to AM build process</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process control</td>
<td>Develop better control and understanding of particle size, shape and distribution</td>
<td></td>
<td></td>
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<tr>
<td>Process control and design</td>
<td>Develop better models for in situ build support, i.e., better design of sacrificial supports for product restraint and removal</td>
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</tbody>
</table>
As mentioned earlier, Systems Integration is the broadest of all of the swim lanes in that it serves as the glue that will hold all of the pieces of the AM hybrid puzzle together. For more than a century, we have engineered products that have traveled through a variety of different manufacturing processes that served to provide:

1) initial near net shaped parts, e.g., casting or forging,
2) sequential processes that have enhanced the mechanical properties of the materials, e.g., heat treating, peening, etc.,
3) processes that have improved the surface accuracy and quality for better function, e.g., machining or grinding, and
4) processes that have improved the corrosion resistance of products, e.g., anodizing, cladding, etc.

The engineering of these products has evolved over the past century so that functional supply chains for defining source, make and deliver components activities exist to make complex products like automobiles and computers. Here suppliers provide castings to engine producers, and the engine manufacturers convert the cast into a properly functioning engine block and do similarly with other engine components, and then assemble the engine into a working subcomponent. With the advent of Additive Manufacturing (AM) methods, we are at a place where we can now expand the geometries that are used for many parts, and can potentially utilize multi-materials to take advantage to different material properties at different junctions of the product. Since we do not have a hundred years to evolve the integration of this system, we need to utilize the principles that have gone into the evolution of other similar systems to integrate AM with other manufacturing processes. This will involve the integration of all of the methods and supply chain components that are in place for traditional manufacturing systems. Engineering designs that will facilitate the linking of machines into coordinated systems that will facilitate the economic and timely production of products into these systems is a must.

The envisaged product of this integration is the evolution of a system that is capable of (semi-) automatically producing mechanical products to
final geometric specification directly from a CAD file using one or more production resources, or Direct Digital Manufacturing Using AM Systems (DDMUAMS). In this section, we describe the integration requirements for a hybrid manufacturing system that uses additive and then other production processing methods like subtractive processing or heat treating so that many of the geometric complexities provided by AM processing can be directly linked to the precision of CNC machining and other secondary processing required by today’s complex mechanical components. The integration components developed and described herein are used so that mechanical parts can be “digitally manufactured” to meet the necessary final geometric accuracy and other engineering requirements specified.

Integration Methodology

The Integration of all products engineered to be produced using AM methods will go through the following engineering steps:

1) Fundamental product design where a component will be detailed for function,

2) Design for additive manufacturing using AMF or a similar model file format to include metal geometric part representations that might need to be overgrowth during AM processing so that subsequent SM processing can be properly conducted (See Figure 2).

3) Process engineering and equipment for direct subtractive manufacturing,

4) Design enhancement/modification so that placement of sacrificial supports for secondary processing can be efficiently performed,

5) Localization of parts into the secondary processing work envelope,

6) Process planning and code generation, and

7) Qualification of the component for proper use.

The Value Chain for the engineering can be accomplished using two current approaches to accomplish DDUAMS. These approaches are:

1) In-Envelope Hybrid manufacturing methods, and

2) Out of envelope hybrid manufacturing methods.

These concepts will be more fully expanded in another swim lane.

The advantages of In-Envelope Hybrid systems are: a component can be completed in a single machine visit, complete component and repair processing defects can be accomplished in one setup, complex parts can be rapidly produced, no relocating is needed, and a single user interface is used for all processing. The disadvantages for an In-Envelope system are: geometrical interferences for access and processing is difficult, parts can still require heat treating, high machining tool wear can hamper productivity, combining operations constrains geometries that can be produced, and programming the equipment is hard. Integrating all of these issues into the engineering process is a difficult concept to even discuss completely.

The new engineering process for hybrid AM includes:

1) developing a procedure that can be used to modify a mechanical part design so that the part can be produced using an additive manufacturing process, with appropriate sacrificial supports needed for the additive process and then adding additional sacrificial fixtures that can be used to secure and locate the part for subtractive processing.

2) developing a methodology that will allow for the use of current ASME Y14.5 tolerance standard to ASTM 52915:2013(E) for use in Additive Manufacturing File (AMF) Format and creating a method to store “features” in an AMF file.
## Table 3
### Systems Integration Issues Discussed.

<table>
<thead>
<tr>
<th>Perceived deficiency</th>
<th>Problem</th>
<th>Actions</th>
<th>Difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Currently, there is no design platform that allows for the easy use of new capabilities of AM geometries directly onto a mechanical component</td>
<td>Meshes, free-form geometric shapes and varied geometries are very difficult to generate, and few assists exist to help a designer select these features.</td>
<td>Develop a new set of design for manufacturing standards for AM and hybrid processing</td>
<td>Non-uniform materials models and geometric models for complex patterns (meshes) are not part of any of the CAD systems</td>
</tr>
<tr>
<td>Currently, there is no way to move to/from a feature-based environment and featureless model environment</td>
<td>Current CAD systems use a single model perspective to represent part geometry</td>
<td>Develop a new CAD model platform that can easily move from features to featureless models and vice versa</td>
<td>AMF, 3MF and Voxel-based models have been tried, but no accepted format is widely used.</td>
</tr>
<tr>
<td>Currently, there are no plug and play models or environs for hybrid manufacturing physical components</td>
<td>Two very different approaches are being developed (in-envelope and out-of-envelope) by hardware providers</td>
<td>Develop a set of physical processing tasks and the related hardware requirements</td>
<td>In-envelope systems reduce the time requirements to secure and locate a part between processes, but also impose significant constraints for processes (both AM and SM)</td>
</tr>
<tr>
<td>Currently, there are no methods to analyze the properties (mechanical, electrical, etc.) of new complex design geometries that could possibly be used for multi-functional design</td>
<td>Predicting the performance of new novel designs using traditional methods, e.g., FEA, are difficult or impossible</td>
<td>For unique one-of-a-kind products, such as prosthetics, uniquely customized tooling, etc., there are few if any methods that can determine use life and limits for new unique products</td>
<td>Complex free-form and non-uniform geometries and materials are difficult to analyze</td>
</tr>
<tr>
<td>Currently, in process qualification of engineering specifications is not possible during processing of the components</td>
<td>Processing environs are difficult to observe and few models exist that allow for the prediction of form as a function of processing variables</td>
<td>Develop in-situ probing and measurement systems that allow closed loop adaptive modification of geometry.</td>
<td>Integration of measurement and adaptive control into machine controllers. Protocols for integration.</td>
</tr>
<tr>
<td>Currently, there are no control models (process or flow) that allow for the piecewise assembly of hybrid systems</td>
<td>Integrating diverse equipment into a manufacturing system is difficult and time consuming</td>
<td>Develop a control architecture and software system to integrate different processing systems</td>
<td>Multi-purpose and multi-functional manufacturing resources are routine developed, and based on their capabilities do not integrate easily.</td>
</tr>
</tbody>
</table>
3) developing “best fit methods” for fitting AM-built parts to a point cloud scan of the part and use this information to “localize the part within a CNC workspace”.

4) utilizing “Case studies” to help new users understand these requirements before they become problems.

5) predicting or better understanding the characteristics of parts that will lead them to being produced on these types of systems.

Table 3 presents a summary of many of the topics discussed during the breakout session.

**Integration Development**

General topics for integration were developed and are presented in Table 4. This table represents some of the roadblocks and issues limiting the rapid evolution to hybrid AM systems. As one might expect, integration issues fall into categories associated with:

1) design (specifically design for hybrid manufacturing),

2) certification and qualification of unique “one-of-a-kind” products,

3) planning for manufacturing low volume, high-complexity products,

4) developing a “plug and play” systems architecture so that equipment can be added as needed for new geometries and materials,

5) developing an integrated control environment for these complex processing systems, and

6) determining what product attributes make hybrid manufacturing the most suitable method for manufacturing.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Cross cutting</td>
<td>Develop a new set of design for manufacturing standards for AM and hybrid processing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross cutting</td>
<td>Develop better process models and testing standards for different materials and applications in order to enable in process qualification</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross cutting</td>
<td>Develop a catalogue/taxonomy of physical processing tasks and the related hardware requirements</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Cross cutting</td>
<td>Develop a certification system to qualify the use-life for unique one-of-a-kind critical use products, e.g., prosthetics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross cutting</td>
<td>Develop a control architecture and software system to integrate different processing systems</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross cutting</td>
<td>Develop a new CAD model platform/format that can easily move from features to featureless models and vice versa</td>
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<td></td>
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<tr>
<td>Cross cutting</td>
<td>Develop the knowledge base for hybrid processing containing the impact and influence of processing conditions on process metrics and both geometric and mechanical property requirements for components</td>
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</tbody>
</table>
Background

Hybrid Manufacturing Challenges

Whether one uses Ex- or In-Envelope Hybrid Manufacturing, many challenges persist that are unique to this production method. AM technologies are affording the user extraordinary capability to produce complex geometries, and to execute the process at nearly the push-of-a-button. However, expensive and long build processes from precious AM powder cannot be wasted by a miss-written piece of NC code, or in general, lose that advantage of short lead time when the queue to get parts finish machined is measured in weeks.

The identification and elimination of roadblocks for HM faced by users is paramount to expanding adoption of the technology. The “Achieving GD&T through Machining” workshop focused on identifying 3 or 4 key technological barriers to implementation of HM (either in-envelope or ex-envelope) which will be presented in a Technology Roadmap to government funding agencies. The goal of this roadmap will be to help these agencies identify areas for focused research and development to eliminate these barriers with respect to GD&T.

Three technical elements (TE) for Hybrid Manufacturing were defined as critical needs:

- **AM Process Planning (TE1)**: includes things such as determination of build orientation, integration of fixturing, material selection related to machinability, and other tunable parameters affecting the final part quality after building and finishing.
- **SM Process Planning (TE2)**: includes processes such as automatic code generation, standard code adaptation (as opposed to new creation), feature-based tool paths, machining sequence, automation, etc.
- **Fixture/Setup Planning (TE3)**: includes processes such as proper fixturing considering machining forces, fixturing strategies, positioning in finishing operations, number and orientation of discrete set-ups, tool access and selection, etc.

These three areas were used as a way of focusing our workshop into brief sessions.
**Achieving GD&T through Machining — continued**

**AM Process Planning**

**Current State Assessment — Achieving GD&T through Machining**

A current state assessment was performed focusing on three main technical element areas, AM process planning, SM process planning and fixture/setup planning.

Two questions were addressed.

1) What do you currently have to do to make Hybrid Manufacturing work? and

2) What makes these tasks hard/ expensive?

Table 5 shows the resulting current tasks and challenges associated with AM process planning.

Also identified were questions related to determining functionally graded materials, process maps, and process planning to optimize superposition of layers, and feedback control of powder flow. Table 6 contains a list of challenges associated with AM process planning.

These challenges will be summarized at the end of this section of the report.

A similar set of current tasks and challenges associated with SM Process Planning was next posed to the experts. Table 7 contains the most common responses to these questions for subtractive processing.

---

**Table 5**

<table>
<thead>
<tr>
<th>Current State Tasks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM feasibility</td>
</tr>
<tr>
<td>Added material agreement</td>
</tr>
<tr>
<td>File conversion (STL/AMF/3MF) – duplication – feature vs. featureless</td>
</tr>
<tr>
<td>Process selection</td>
</tr>
<tr>
<td>Integration with other processes – fixturing, measurement, machining</td>
</tr>
<tr>
<td>Build orientation – Interaction between design, supports and removal, and material properties</td>
</tr>
<tr>
<td>Supports</td>
</tr>
<tr>
<td>Scan strategies</td>
</tr>
<tr>
<td>Process parameter decision</td>
</tr>
<tr>
<td>Decision on datum</td>
</tr>
<tr>
<td>Material recycling</td>
</tr>
</tbody>
</table>

**Table 6**

<table>
<thead>
<tr>
<th>Current Challenges:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer specifications between processes</td>
</tr>
<tr>
<td>Workforce</td>
</tr>
<tr>
<td>Build failures</td>
</tr>
<tr>
<td>Process monitoring</td>
</tr>
<tr>
<td>CAD/CAM/CAE integration and interoperability between, among, and across all systems</td>
</tr>
<tr>
<td>Expertise in both AM and SM techniques</td>
</tr>
<tr>
<td>Machining strategy</td>
</tr>
<tr>
<td>Variability (mechanical properties, defects)</td>
</tr>
<tr>
<td>SPC-Like thought process</td>
</tr>
<tr>
<td>Cost model</td>
</tr>
<tr>
<td>Materials of different properties</td>
</tr>
</tbody>
</table>

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**Table 7**

<table>
<thead>
<tr>
<th>Current State Tasks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleaning powder</td>
</tr>
<tr>
<td>Swarf management with powder</td>
</tr>
<tr>
<td>Parameter selection</td>
</tr>
<tr>
<td>Incorporate heat treat and/or stress relief</td>
</tr>
<tr>
<td>Bulk machining followed by features added with AM</td>
</tr>
<tr>
<td>Define the output</td>
</tr>
<tr>
<td>Adding machining allowance</td>
</tr>
<tr>
<td>NC code generation</td>
</tr>
<tr>
<td>Cutting tool access</td>
</tr>
<tr>
<td>Determining what will be machined</td>
</tr>
<tr>
<td>Tooling selection</td>
</tr>
<tr>
<td>Machine selection</td>
</tr>
<tr>
<td>In-process measurement</td>
</tr>
<tr>
<td>Operation sequence</td>
</tr>
<tr>
<td>Scanning/Probing/Locating the stock for NC code</td>
</tr>
<tr>
<td>After orientation datums must be checked</td>
</tr>
</tbody>
</table>
Achieving GD&T through Machining — continued

Again, a similar set of current challenges associated with SM Process Planning was next posed to the experts, with Table 8 containing the most common responses to these questions for subtractive processing.

Finally, the experts chose the fixture/setup planning. Tasks and challenges. These tasks are summarized in Table 9 and the challenges noted in Table 10.

The groups chose the three Fixture/Setup Planning challenges outlined in Tables 9 and 10 as having the largest potential to impact the adoption of hybrid manufacturing.

Table 8

<table>
<thead>
<tr>
<th>Current Challenges:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not damaging fine AM features</td>
</tr>
<tr>
<td>How to determine what should be built from AM</td>
</tr>
<tr>
<td>Internal features</td>
</tr>
<tr>
<td>Material handling</td>
</tr>
<tr>
<td>Remaining supports (either AM or other)</td>
</tr>
<tr>
<td>Graded materials machining</td>
</tr>
<tr>
<td>Where is the part located?</td>
</tr>
<tr>
<td>DFM for Hybrid</td>
</tr>
<tr>
<td>Integration with heat treat and stress relief</td>
</tr>
<tr>
<td>Process optimization for measure</td>
</tr>
<tr>
<td>Bringing measurement to the system</td>
</tr>
<tr>
<td>Software not there for automation</td>
</tr>
<tr>
<td>SPC</td>
</tr>
<tr>
<td>Variability in material properties, etc.</td>
</tr>
<tr>
<td>Dealing with AM fill strategies</td>
</tr>
<tr>
<td>Thermal management</td>
</tr>
</tbody>
</table>

Table 9

<table>
<thead>
<tr>
<th>Current State Tasks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sufficient Clamping force with residual stress</td>
</tr>
<tr>
<td>DFM activities influencing final product design for process consideration</td>
</tr>
<tr>
<td>Limitations of distortion related with fixturing</td>
</tr>
<tr>
<td>Planning for process deficiencies (where will not achieve what we want, surface finish, tolerance, etc.)</td>
</tr>
<tr>
<td>Orientation planning for the AM/SM tooling</td>
</tr>
<tr>
<td>Design fixturing surfaces</td>
</tr>
<tr>
<td>Fixture/Setup planning part height and allowable tooling for internal machining</td>
</tr>
<tr>
<td>Explore jigging into AM/SM process</td>
</tr>
<tr>
<td>Design for achieving tight tolerance, i.e. true position</td>
</tr>
<tr>
<td>Starting stock – how much to make with SM or AM</td>
</tr>
<tr>
<td>Locating – identify estimate of where in envelope</td>
</tr>
</tbody>
</table>

Table 10

<table>
<thead>
<tr>
<th>Current Challenges:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software solutions at the moment inadequate</td>
</tr>
<tr>
<td>Part distortion and change in material properties, microstructure after stress relief</td>
</tr>
<tr>
<td>Powder/excessive powder removal</td>
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<tr>
<td>Gross to close</td>
</tr>
<tr>
<td>Intrinsic vs sacrificial datums and/or fixture features</td>
</tr>
<tr>
<td>Standard cutting tool designs may not accommodate AM part design</td>
</tr>
<tr>
<td>Enhancing (updating) geometric standards</td>
</tr>
<tr>
<td>Dual fixturing requirements (how to minimize speed a cost to add and remove)</td>
</tr>
<tr>
<td>Part variability</td>
</tr>
<tr>
<td>How do you deal with compound errors associated with multiple process steps?</td>
</tr>
<tr>
<td>Decision machine datum, account for variability – Tradeoffs</td>
</tr>
</tbody>
</table>
Achieving GD&T through Machining — continued

Summary

The attendees of the Achieving GD&T workshop were motivated to look at specific challenges, a future vision and technical gaps associated with the three technical elements of GD&T. These specifics are shown in Tables 11, 12 and 13.

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Future Vision</th>
<th>Technical Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Variability</td>
<td>Being able to detect and quantify variability, use Adaptive control</td>
<td>Lack of in-situ process monitoring</td>
</tr>
<tr>
<td>Cost Model</td>
<td>Comprehensive model, integrated with CAD/CAM</td>
<td></td>
</tr>
<tr>
<td>CAD/CAM/CAE/TO</td>
<td>Thermal analysis, Comprehensive software</td>
<td>Functionally graded materials</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Challenge</th>
<th>Future Vision</th>
<th>Technical Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automation/Software</td>
<td>A CAM system that considers AM also, Software that goes from design to finishing, works across platforms, considers optimization</td>
<td>Lack of market to drive it, we have no current software, feature based machining is not sufficient, lack the ability to design for both.</td>
</tr>
<tr>
<td>Variability</td>
<td>We can predict it, measure it, and compensate for it</td>
<td>We make small parts, in small lots, can we deal with this in situ?, lack the technical expertise.</td>
</tr>
<tr>
<td>DFM</td>
<td>Educated designers</td>
<td>We don’t even know what to teach them, CAD and CAM is not integrated for this.</td>
</tr>
<tr>
<td>FGM</td>
<td>Ability to handle it in CAM</td>
<td>Lack the NDE to test, how do we validate a grading?, lack of tooling</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Challenge</th>
<th>Future Vision</th>
<th>Technical Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision Making – Machine datum vs. variability tradeoffs (AM process dependent)</td>
<td>Complex multi-datum parts will be (semi-) automatically planned, and to include the proper production sequence of features that become DATUM</td>
<td>Defining tolerance stacks and feature location directly from a CAD model has not been achieved.</td>
</tr>
<tr>
<td>Part variability</td>
<td>Complex products that utilize AM features will routinely be engineered reducing strength- to-weigh requirements to meet rigorous mechanical requirements.</td>
<td>AM production variability and surface textures make predicting fatigue very difficult.</td>
</tr>
<tr>
<td>Integrate vs. sacrificial</td>
<td>Minimizing sacrificial supports for AM and SM will be minimized by determining which part features can be used for fixturing</td>
<td>Automatically identifying which part features can be sued to secure and locate a part is still an unsolved geometric and mechanics problem.</td>
</tr>
</tbody>
</table>
Results

Many of the challenges and directions that came from the Achieving GD&T through Machining can be illustrated in Figure 3. This figure illustrates the steps required to take a customer model (as shown in the first box) and then embellish the model with tolerances, the addition of sacrificial supports for secondary machining, the overgrowing of the AM part so that sufficient material will be available for machining, the AM build with sacrificial supports for part stability during the AM process, the actual machining (with views noting that the part needs to be localized within the CNC machine).

Metal AM technologies are enabling significant design freedom nearly unlimited geometry. The cost of feedstock material demands accurate NC subtractive processing and the speed advantage of AM should not be lost waiting for finish machining. The identification and elimination of roadblocks for HM faced by users is paramount to expanding adoption of the technology. This session focused on three technical elements: Additive Manufacturing (AM) Process Planning, Subtractive Manufacturing (SM) Process Planning, and Fixture/Setup Planning. AM Process Planning can include things such as determination of build orientation, integration of fixturing, material selection related to machinability, and other tunable parameters affecting the final part quality after building and finishing. SM Process Planning can include processes such as automatic code generation, standard code adaptation (as opposed to new creation), feature-based tool paths, machining sequence, automation, etc. Finally, Fixture/Setup Planning can include processes such as proper fixturing considering machining forces, fixturing strategies, positioning in finishing operations, number and orientation of discrete set-ups, tool access and selection, etc.

Tables are again used to summarize the major road blocks. These tables are presented with regard to the specific GD&T Task Element (AM, SM and Fixturing) to show the principle needs associated with each of these areas. Table 12A contains the AM Process Planning issues. Table 12B contains the SM Process Planning issues, and Table 12C contains the Fixture Planning issues.
Achieving GD&T through Machining — continued

Table 14
Achieving GD&T AM Process Planning Road Blocks

<table>
<thead>
<tr>
<th>Category</th>
<th>Achieving GD&amp;T Machining Roadmap Component</th>
<th>2018-2020</th>
<th>2020-2025</th>
<th>2025-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM Process Planning</td>
<td>Create process planning models working in concert with in situ monitoring able to detect and quantify variability and use adaptive control.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM Process Planning</td>
<td>Develop comprehensive models that accurately predict the cost and time for AM build and these models are integrated with CAD/CAM packages.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>AM Process Planning</td>
<td>Develop tailored engineering process model platforms (including thermal analysis, etc.) to facilitate engineering requirements including functional graded materials.</td>
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</tr>
</tbody>
</table>
### Achieving GD&T through Machining — continued

This has become the bottleneck process for hybrid manufacturing. CNC planning is probably the largest chunk of engineering.

Creating process plans that do not require special tooling is a problem.

<table>
<thead>
<tr>
<th>Category</th>
<th>Achieving GD&amp;T Machining Roadmap Component</th>
<th>2018-2020</th>
<th>2020-2025</th>
<th>2025-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM Process Planning</td>
<td>Develop a CAM system that includes AM. This software includes the entire process from design to finishing, works across platforms, and conducts optimization.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM Process Planning</td>
<td>Develop analytical planning models (predict, measure, compensate) to eliminate variability in methods (and costs) for subtractive manufacturing a given part.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM Process Planning</td>
<td>Create guidelines to assist in the design and design linkages of AM/SM parts.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM Process Planning</td>
<td>Developing CAM tools to create CNC code using standard tooling is still big problem. Non-dense AM parts create addition problems for machining.</td>
<td></td>
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</tr>
<tr>
<td>SM Process Planning</td>
<td>Create a grinding planning model enabling grinding precision on complex contours.</td>
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<td></td>
</tr>
</tbody>
</table>
### Table 16

**Achieving GD&T Fixture Planning Road Blocks**

<table>
<thead>
<tr>
<th>Category</th>
<th>Achieving GD&amp;T Machining Roadmap Component</th>
<th>2018-2020</th>
<th>2020-2025</th>
<th>2025-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixture/Setup Planning</td>
<td>Create a process planning model that enables complex multi-datum parts to be (semi-) automatically planned, and to include the proper production sequence of features that become DATUM.</td>
<td></td>
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<tr>
<td></td>
<td>Complex products that utilize AM features (such as lattices) will routinely be engineered reducing strength-to-weight requirements to meet rigorous mechanical requirements including fatigue.</td>
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<td></td>
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</tr>
<tr>
<td>Fixture/Setup Planning</td>
<td>Develop an advanced engineering process model that enables minimizing sacrificial supports for AM and SM by automatically determining which part features can be used for fixturing.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

GD&T is the really BIG problem with hybrid. Creating unique fixturing methods normally takes more time than any other piece of the problem.

Some AM part shapes are so complex that they are impossible to secure and locate without a custom fixture. Creating these unique fixtures can be more difficult than making the part.
Surface Finish Considerations

Background

Hybrid Manufacturing Challenges – Surface Finish Considerations

Workshop 3 “Meeting the Surface Finish Requirements” session focused on identifying key technological barriers to implementation of HM either in-envelope or ex-envelope. The goal of this section is to describe the barriers discussed during this workshop.

This workshop again focused on three technical elements (TE) for Hybrid Manufacturing:

- **TE1** AM Finishing Needs
- **TE2** AM Finishing Measures
- **TE3** AM Finishing Processes

The AM Finishing Needs discussions included things such as determination of surface finish specifications, current challenges in realizing these, and elicitation of specific application scenarios. These scenarios will be translated into specific use cases for the community to pursue. The AM Finishing Measures discussions focused on determining the various alternative measures employed to specify the surface requirements as well as instruments to measure these, development of cost models to determine finish specifications for various applications, and challenges associated with current instruments to effectively measurement of these quantifiers. The AM Finishing Processes discussions focused on determining alternative process chains to meet various finish (texture) specifications, and can include aspects of automation (code generation, standard code adaptation), tool path generation, machining sequence, etc. These three areas will be used as a way of focusing our workshop into brief sessions that all participants will cycle through in the breakout sessions we will moderate.

The medical parts shown in Figure 4 used to facilitate this discussion. Figure 4 contains the assemblies for a hip and knee replacement. As can be seen in the figure, textures and roughnesses for the parts span a broad range. Each texture serves a specific purpose. For instance, the very rough surfaces serve to catalyze the osseointegration of bone with the prosthetic. Similarly, many of the smooth surfaces serve as bearing surfaces to promote minimum friction sliding.
Surface finish is not often a central point of discussion for AM, due to a variety of reasons that will be described in this section. Yet, achieving surface finish requirements for the functional use of a component is an essential hurdle to be crossed for commercializing AM and AM-hybrid processes. An initial barrier to adopting AM is the need to define and meet requirements for surface finish for product lines that are already deemed acceptable using current processes. Later, as product lines are developed with a mature view of Design for AM, finish requirements may be conceived from the start with the benchmarked expectations of an AM process. But at the current time, requirements for surface finish from functional or cosmetic perspectives are hard to quantify and may not be uniquely defined using statistical parameters defined in ISO and ASME standards; i.e. it may not be possible to distinguish good and bad surfaces using a simple greater-than or less-than statistical metric. In particular, the historical use of Ra may provide little insight on the functionality of the surface or the process that created it. It may be known that a current component meets functional requirements because "it works", but it may not be possible to describe the acceptable surface finish characteristics in a sufficiently quantitative manner so that the product could be duplicated by a different fabrication process. Hence, this will lead to inertia for a company considering deviating from process A to process B when there is risk that parts will fail for ill-defined reasons. A key sentiment discussed in the 2016 ASPE Topical Conference on Dimensional Accuracy and Surface Finish in Additive Manufacturing is that the lack of quantitative functional requirements for the surface finish of additively manufactured components presents a major hindrance in formulating drawing specifications, goals for process development, and metrology methods. Even if functional requirements existed, there remains the identification of hybrid fabrication methods (ex- or in-envelope) to meet them and the development of metrology tools and analysis algorithms needed for validation.

Additive manufacturing has the potential for being inserted in a sequence of fabrication operations at various stages. At one extreme, AM may be the main and final step, yielding a finished component. At the other extreme, it is a near-net-shape process, conceptually similar to casting or forging, and will followed by one or more secondary finishing operations or surface treatments. This latter situation defines the hybrid manufacturing arena. In the realm of metal AM of industrial components which will be assembled into fluid and mechanical systems, essentially all components are made using hybrid processes. Similarly, in bio-engineering applications, some level of surface treatment is always employed. Yet, in setting goals for future AM developments, it is also important to consider paths for achieving surface finish requirements directly with AM, and hence, offering quantitative specifications and metrology methods to those groups performing the development. This could potentially eliminate some costly secondary processing operations and costs.

The surface finish requirements for components that will be machined (or other hybrid process) poses a conundrum. In one sense, if the surface will be machined, then there is only the final surface requirement to consider; this leads some production
Surface Finish Considerations — continued

engineers to be disinterested in AM surface finish since they will remove this surface during their next operation. However, the requirement for controlling or quantifying surface finish at this intermediate stage has multiple indirect motivations. First, it must be demonstrated that the peak-to-valley roughness will not exceed the machining allowance such that when the component is machined, there are not residual valleys that have not been machined. Because the measuring of a rough AM surface is difficult, and highly variable even the definition of “where the surface is” may be ill-defined depending on weather one finds a peak or valley. It is likely that some level of extra machining allowance will be reserved to account for roughness, which increases cost. Furthermore, large values of AM-caused roughness will impact the fixturability of the component in secondary machining operations, issues such as component to component placement repeatability may be significantly degraded with rough surface components. Finally, depending on the method of secondary machining and/or surface treatment, characteristics of the initial AM roughness may be difficult to predict. Hence, a contract for a company to machine, etch, or coat an AM-made component may require an incoming specification for surface finish that limits the risk to the machining company.

Table 17 provides a summary of some of the secondary finishing operations related to surface finish improvement for AM metal components. Although the list is by no means complete, it provides an indication of the breadth of operations that can be performed post AM processing.

<table>
<thead>
<tr>
<th>Table 17</th>
<th>Hybrid Operations that Influence Surface Finish.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Native Additive Processes</strong></td>
<td></td>
</tr>
<tr>
<td>a. Surfaces remaining in original AM condition</td>
<td></td>
</tr>
<tr>
<td>b. AM surfaces with superficial cleaning</td>
<td></td>
</tr>
<tr>
<td>c. Print-through of native surface topography after secondary operations</td>
<td></td>
</tr>
<tr>
<td><strong>2. Treatments Focusing on Finish Modifications</strong></td>
<td></td>
</tr>
<tr>
<td>a. Electro-polishing</td>
<td></td>
</tr>
<tr>
<td>b. Coating and Plating</td>
<td></td>
</tr>
<tr>
<td>c. Etching</td>
<td></td>
</tr>
<tr>
<td>d. Lapping</td>
<td></td>
</tr>
<tr>
<td>e. Laser Texturing</td>
<td></td>
</tr>
<tr>
<td>f. Bead blasting</td>
<td></td>
</tr>
<tr>
<td>g. Slurry finishing (honing), abrasive flow finishing</td>
<td></td>
</tr>
<tr>
<td>h. Laser polishing</td>
<td></td>
</tr>
<tr>
<td>i. Sanding</td>
<td></td>
</tr>
<tr>
<td><strong>3. Material Removal &amp; Addition Focusing on Shape Modifications</strong></td>
<td></td>
</tr>
<tr>
<td>a. Milling</td>
<td></td>
</tr>
<tr>
<td>b. Turning</td>
<td></td>
</tr>
<tr>
<td>c. Grinding</td>
<td></td>
</tr>
<tr>
<td>d. Lapping</td>
<td></td>
</tr>
<tr>
<td>e. ECM</td>
<td></td>
</tr>
<tr>
<td>f. EDM</td>
<td></td>
</tr>
<tr>
<td>g. Sanding</td>
<td></td>
</tr>
<tr>
<td>h. Laser Cutting</td>
<td></td>
</tr>
<tr>
<td>i. Additional AM</td>
<td></td>
</tr>
<tr>
<td><strong>4. Other Modifications</strong></td>
<td></td>
</tr>
<tr>
<td>a. Cleaning operations</td>
<td></td>
</tr>
<tr>
<td>b. Annealing (e.g. influence of grain texture on roughness)</td>
<td></td>
</tr>
<tr>
<td>c. Laser and Shot Peening</td>
<td></td>
</tr>
<tr>
<td>d. Chemical Mods, such as for corrosion inhibition or bio-activation</td>
<td></td>
</tr>
<tr>
<td>e. Anodizing (possible to include under Chemical Mods)</td>
<td></td>
</tr>
<tr>
<td>f. Hot Isostatic Pressing (Hipping)</td>
<td></td>
</tr>
</tbody>
</table>
In the following sections, the ideas, comments, and priorities of the participants at the workshop are reported. The participants are an abbreviated snapshot of the AM community, but who contributed in a holistic community spirit to capture both personal and community-based concerns. The categories spanning the Current State and Current Challenges greatly overlap but also demonstrate the concerns of the participants. The broad categories of AM Finishing Needs, AM Finishing Measures, and AM Finishing Processes also overlap and inter-relate. The bullets listed below were taken from notes submitted by the participants and discussed as a group.

**AM Finishing Needs: Current State Assessment**

**Current State**

- AM users have minimal taxonomy for describing surfaces; this is typically a different taxonomy than the component customers and measurement communities; new quantifiers are required for AM; the historical use of $R_a$ is insufficient.

- Surfaces are created by both material addition and removal; models are not available outside of sophisticated research labs for predicting the creation of a surface using AM.

- Cleaning is major task; removing residual particulate from recesses and internal structures is difficult.

- There is a large effort by all users to understand how to finish AM surfaces.

- There is a lack of understanding on how processes affect surface finish.

**Current Challenges**

- There are different approaches for considering upward-facing, downward-facing, vertical, and contoured surfaces.

- There is a lack of data on how process parameters affect surface finish.

- We require a physics-based rationale for evaluating the condition of a surface; this includes the wide diversity of different surface textures and the chemical and metallurgical state of the surface.

- It is not well known how uniform the surface finish is on a surface; hence it is not known how many measurements are needed to characterize the surface.

- It is not known how to relate standardized descriptors for surface roughness to user requirements; the AM community is competing with historical terminology and training developed for the machining community.

- Models are required for predicting the cost of measurement and in achieving a given surface finish.

- Detecting defects on internal surfaces is difficult.

**AM Finishing Measures: Current State Assessment**

**Current State**

- There is a transition from 1D stylus measurements to 2D area measurements of surface topography; there is a significant increase in instrument sophistication in making this transition.

- Historically $R_a$ was measured with a 1D scan from a stylus instrument; most existing roughness data is in terms of $R_a$; $R_a$ is a very poor descriptor for complex 2D topography.

- CT scans are needed for internal surfaces; depending on the thickness and density of the component, CT may not present a detailed map of internal surfaces.

**Current Challenges**

- Some recessed and internal surfaces cannot be accessed by instruments; creating these surfaces is a key advantage for AM, hence characterizing them is an essential requirement for the use of AM.

- Different instruments give different results; the metrology community commonly addresses this topic, but it generally requires significant familiarity with the physics of the instrument.

---

21 There is some ambiguity on the use of terms 2D and 3D for area scans. Here we standardize on 2D referring to lateral dimensions on the surface, such as $x$, $y$. The height $z$ is a third dimension; hence this measurement refers to 3D dimensions. But the key concept here is that the single axis stylus profiler traverses in 1D; while an aerial image records a 2D area.

Surface Finish Considerations — continued

• The measurement of roughness should be coupled with measurement of material properties and surface quality including delamination

• Instruments for measuring the extremely rough surfaces from AM are still under development; “native additive” surfaces are outside the capabilities of many current instruments

• The metrics $R_a$ and $R_z$ measured using current instruments are not adequate to relate to functional need. There is not a clear method the using current instruments to distinguish between good and bad surfaces

• There is a commercialization gap between the AM and measurement communities. The markets for the instrument makers are well-established with existing customers, such as the machining industry or in semiconductor processing

• 2D instruments are expensive

AM Finishing Processes: Current State Assessment

Current State

• Currently, finishing processes are selected using requirements other than surface finish

• There are cost implications for improving or controlling surface finish, such as boring, honing, and lapping; it is important to understand cost-benefit with respect to improved finish

• It is often difficult to determine the type of finishing operation required to meet specification

• With the variety of surface shapes and orientations produced by AM, selecting the optimum finishing operations can be a complicated process

• Abrasive flow processes are limited in what surfaces they can address

• There are concerns about relating surface quality with performance (see other descriptions on needing quantitative specifications)

• Laser ablation should be considered for polishing

Current Challenges

• It is not clear how surface finish relates to fatigue life

• Upward versus downward facing surfaces made using AM can be very different

• Finishing internal channels is a challenge; machining is generally limited to line-of-sight operations

• There are material-specific process limitations

• There is a need to benchmark current AM processes in terms of the surface finish

• There are limited commercial solutions for producing acceptable AM components, hence limited solutions for meeting surface finish requirements along with other requirements

• There is a need to understand how machining parameters such as depth-of-cut and material removal rate affect surface finish of AM components

• We need to understand how to change the chemical properties of surfaces

• With the variety of surface shapes and orientations produced by AM, there is a complicated
Summary

Workshop participants examined the lists of Challenges that were identified and prepared the list below noting these to be most important. This is not intended to indicate that Challenges not voted for are not important, only as a first cut at assigning priority.

AM Finishing Needs

1) A physics-based rationale is required for evaluating the condition of a surface; this includes the wide diversity of different surface textures and the chemical and metallurgical state of the surface

2) It is not well known how uniform the surface finish is on a surface, hence it is not known how many measurements are needed to characterize the surface

3) It is not known how to relate standardized descriptors for surface roughness to user requirements; the AM community is competing with historical terminology and training developed for machining community

AM Finishing Measures

1) Some recessed and internal surfaces cannot be accessed by instruments; creating these surfaces is a key advantage for AM, hence characterizing them is an essential requirement for the use of AM

2) There is a commercialization gap between the AM and measurement communities; the markets for the instrument makers are well-established with existing customers, such as the machining industry or in semiconductor processing

3) The metrics measured using current instruments may not relate to functional need; Current metrics and instruments may not distinguish between good and bad surfaces (this relates well with the lack of quantitative functional specifications)

AM Finishing Processes

1) There is a need to benchmark current AM processes in terms of the surface finish

2) There are limited commercial solutions for producing acceptable AM components, hence limited solutions for meeting surface finish requirements along with other requirements

3) Finishing internal channels is a challenge; machining is generally limited to line-of-sight operations

AM Finishing Needs: Future State and Gap Analysis

Challenges

- Functional requirements for surface finish are required from customers, in order to distinguish good and bad surfaces is essential for validation
- Standards are required for describing surface finish requirements and for describing surfaces. There was discussion of existing ISO and ASME standards, lack of use of these within the AM community, and lack of applicability of the standards to describe the topography of AM-produced surfaces. There was also discussion of the difficulty of competing with an ingrained methodology and vernacular for describing traditional machined surfaces.
- It was proposed that an improved physics understanding of how roughness is generated, i.e. how the surface evolves, could lead to insight into how to describe the surface.

Future Vision

- A standardized means of capturing customer requirements for surface finish will be developed
- A reproducible numerical measure of surface finish that shows if the AM process is correct will exist
- A standardized set of terms to use in describing roughness with common links to training will be developed
- AM process models that can be used to identify process parameters for achieving required levels of roughness will be developed along with CAM software exists that addresses roughness
- Models showing how roughness is generated and depends on process variables and machine parameters, such as those that would be incorporated in CAM software will be used to control AM processes
Surface Finish Considerations — continued

Technical Gaps

- A clear and concise language that describes the topography of AM surfaces does not exist.
- CAM software (for AM) does not address roughness; CAM software that links hybrid operations does not exist.
- AM process knowledge that predicts roughness is lacking; improved modeling is required.
- Courses are required at universities regarding AM and surface finish; also professional training.
- Sharing of data is lacking or nonexistent in showing what surface finish topographies are achieved for a given set of process conditions; A database of use cases resulting in known levels of surface finish does not exist; limits on surface finish achievable with AM are not investigated.

Future Vision

- Physics-based models of the measurement process exist.
- Instruments are low cost and high speed.
- The measurement process can be cost effective.
- Measurements are collected into a database.
- A bridge exists between the measurement and AM communities.

Technical Gaps

- There is limited instrumentation among the AM companies (this may relate to company size).
- There are currently no approaches for measuring roughness while finishing; this may relate to both the AM and the secondary operations.
- The AM, subtractive, finishing, and instrument companies do not speak the same language.
- The AM market is not significant to the instrument companies.
- Certification of Process: The surface finish characteristics of AM need to be predictable from process parameters so that finish can be predicted for surfaces that cannot be measured.
- There is a lack of models that link finish measurements to fatigue.

AM Finishing Measures: Future State and Gap Analysis

Challenges

- Metrics are needed that can relate measurements with functional needs.
- Instruments or methodologies needed that can access all fabricated surfaces.
- Instruments need to be affordable (there was debate on how the size of company relates to this – large companies can afford current instruments, while SMEs will have trouble acquiring the same types of instruments).

Future Vision

- The specifics of the AM fabrication process and the measurement processes need to be recorded in order to assess reproducibility.
- An atlas of good & bad surfaces for specific applications is needed; A survey of finish characteristics required for different applications would facilitate development of specifications.
- Government-sponsored metrology programs are needed.

AM Finishing Processes: Future State and Gap Analysis

Challenges

- Benchmarking current AM processes in terms of surface finishes is needed.
- There is uncertainty on how to relate AM surface roughness to fatigue properties.
- There are difficulties in controlling and measuring surface finish on internal surfaces.
- A way of associating or cataloging which surface finishing processes can be used with AM processes is needed.
- Surface roughness information should be included in the AM machine specs.
- Chemical and laser ablation should be included in catalog of potential post-AM treatments.

1 Professor Richard Leach of the University of Nottingham reported on the benefits of an atlas of surface finish measurements for additive manufacturing at the 2016 ASPE Topical Meeting on Dimensional Accuracy and Surface Finish held in Raleigh. His group in Nottingham has a significant effort in developing surface finish technology for AM; also see similar efforts at the Center for Precision Metrology at the University of North Carolina at Charlotte.
Future Vision:

- Roughness (or finish) is a standard specification for creating AM or hybrid surfaces
- Measuring roughness of AM or hybrid surfaces is assumed to be standard practice or required
- Technology exists for accessing internal surface for characterizing roughness Technical Gaps
- There is a lack of standards (this may relate to both the ISO/ASME roughness standards and the F42 AM processing standards)
- Roughness coupons are needed that represent the orientations of the finished part that can be analyzed separately
- Powders are now selected for optimizing AM process speed; powders should be developed for optimizing finish
- For chemical surface treatments, chemicals need to be standardized
- Tables that map application needs with surface finish and process conditions are needed
- Data and the means of sharing data are lacking
- The ability to specify build-specific operations based on surface orientation is necessary
- Commercial partnerships between the AM industry and the finishing industry are needed to facilitate hybrid process development

Results – Surface Finish Considerations

The following critical technology elements (CTE) were identified during the Challenge analysis at the workshop. Many of the technology elements the participants identified centered on the following key themes:

AM Finishing Needs

- A clear quantitative statement of the functional specifications for surface finish needs to be developed by the customers of AM surfaces; this would be greatly augmented by the ability to share data that surface that are “good” versus those that are “bad”.
- A database is needed that shows the surface finishes that are achievable from AM and AM-hybrid processes; in turn, this would indicate the physical limits on achievable AM surface finish
- A deterministic methodology is needed to control surface finish using CAM or other machine control software; this will be possible only if AM process models (ranging from empirical to first principles) are available
- Workforce training in surface finish technology from the perspective of AM is needed to influence future generations of manufacturing engineers; this would include university courses in metrology, description of AM surface topography, and an understanding of how AM and other finishing technologies affect surface topography

AM Finishing Measures

- Availability of metrology instruments for areal characterization of AM surfaces is required for both large companies and SMEs; instrument affordability and worker training need to be addressed
- A quantitative standards-based language is required for describing the complex topography of AM surfaces
- A broad partnership among the AM community, ASTM F42 on Additive Manufacturing, ASME and ISO Committees on Surface Texture Metrology, and the instrument community would facilitate the industrialization of surface finish technology; this would be greatly enhanced by government-sponsored metrology projects
- An atlas of surface finish measurements needs to be created that discriminates between “good” and “bad” surfaces and also documents measurement parameters and the process parameters that created the surface
- A methodology for Certification of Process is needed that enables accurate prediction of surface finish when measurements are not possible or otherwise prohibitive
- In-process, in situ measurement technology would enable the measurement of surface finish during an AM build cycle
Surface Finish Considerations — continued

AM Finishing Processes

- Benchmarking AM and AM-hybrid processes would provide a basis for expected surface finish topographies; collating benchmark data in a table or graphical map as a function of process parameters would aid in establishing machine tool instructions.
- A database of surface finish improvements from hybrid process operations (e.g., polishing, bead blasting, etching, machining, etc.) would enable companies to design appropriate process chains to meet requirements; including information on cost would amplify the value of this database.
- Including build orientation in surface finish databases would enable finish prediction for all surfaces on a workpiece.
- A method for sharing surface finish and process data in a competitive environment using a common language is required.
- Greater involvement with the ASTM F42 additive manufacturing standards committee would facilitate inclusion of surface finish concerns into a government and industrial discussions; Similarly, involvement with the ASME B46 and ISO committees on surface finish metrology would facilitate this community's involvement in AM.

The workshop brought together a diverse range of participants from large companies, SMEs, AM equipment companies, research labs, and universities. There was general agreement that surface finish (roughness) was not receiving sufficient attention among the AM community and that it was significantly different from historical knowledge derived from subtractive fabrication methods. Brainstorming focused on understanding current challenges and also in identifying gaps between a desired future vision and the current situation. The complex and rich topography of AM-created surfaces demands a new standards-based language for describing its features. The customer’s functional requirements need to be quantitatively described and motivate specific developments in AM technology, secondary finishing operations (hybrid process), GD&T, and measurement instruments. There is currently a significant lacking of documented data of the topography of AM surfaces and a lack of correlation of AM process parameters with surface finish.

Tables 18 and 19 provide a list of roadblocks from the Surface Finish discussions. From these tables, one can see that this area requires significant research and development.

A recommendation to determine what current surface finish levels and topographies are possible and what user specifications (functional requirements) will be used was recommended. For this, a standards-based language is needed to describe the surface, as well as instruments to make the measurements, and a trained workforce. A physical understanding of how surface roughness is generated by the AM process is essential so that process parameters can be deterministically selected to meet specifications.

The conclusions derived from the workshop take the form of recommendations in the areas of AM Finishing Needs, AM Finishing Measures, and AM Finishing Processes. Many of the recommendations are directed at the AM community, but also map directly into AM-hybrid processes.
### Table 18
**Summary of roadblocks for Surface Finish workshop related to AM.**

It is inadequate to simply use qualifications like $R_a$ or $Z_{max}$. We need better ways to specify what we need as well as methods to inspect surface condition.

<table>
<thead>
<tr>
<th>Category</th>
<th>Achieving GD&amp;T Machining Roadmap Component</th>
<th>2018-2020</th>
<th>2020-2025</th>
<th>2025-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AM Finishing Needs</strong></td>
<td>Improve models for surface generation in AM and other processes</td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>Limits on surface finish achievable with AM</td>
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<td></td>
</tr>
<tr>
<td><strong>AM Finishing Measures</strong></td>
<td>Certification of processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lack of models connecting measurements and machine processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AM Finishing Processes</strong></td>
<td>Orientation-build specific surface finish operations</td>
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</tr>
<tr>
<td></td>
<td>Lack of standards or knowledge on current AM finish capabilities</td>
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</tbody>
</table>
### Summary of roadblocks for Surface Finish workshop related to finishing.

<table>
<thead>
<tr>
<th>Category</th>
<th>Achieving GD&amp;T Machining Roadmap Component</th>
<th>2018-2020</th>
<th>2020-2025</th>
<th>2025-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AM Finishing Needs</strong></td>
<td>A clear quantitative statement of the functional specifications for surface finish needs to be developed by the customers of AM surfaces</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>A database is needed that shows the surface finishes that are achievable from AM and AM-hybrid processes; this would indicate the physical limits on achievable AM surface finish</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>A deterministic methodology is needed to control surface finish using CAM or other machine control software. Enabled by AM process models (ranging from empirical to 1st principles) are available</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AM Finishing Measures</strong></td>
<td>Lack of models that link finish measurements to fatigue</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lack of models connecting measurements and machine processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Atlas of acceptable and non-acceptable surfaces for specific applications needed</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Need for low cost and high speed measurement instruments. Common understanding between AM, subtractive, and measurement companies</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Products like hip stems can have extreme differences in surface texture. Some of these requirements can be made using AM, but we need to be a lot better at this.
“Inspection, Qualification, and Certification” is a broad topic dealing with three critical concepts required for the commercialization of metal AM products. The majority of focus given here will be to inspection because it provides the basis for certification, and qualification will depend largely on the product use and function.

AM processes are often characterized by a high degree of variability in the resulting product. The extent of future adoption of AM into process chains is highly dependent on the ability to reduce that variability to acceptable levels for each application. For the purposes of this report, the term “qualification” is used to denote a combination of material system and manufacturing process that produces components with acceptable values of physical, mechanical, dimensional, and surface properties that are important for the successful functioning of that component. Additionally, the distribution of variation of these properties over a production run is well known.

There are three paths to qualification:

1) Statistical-based qualification, based on extensive empirical testing of physical samples to determine the distribution of important properties,

2) Equivalence-based qualification, based on moderate empirical testing of physical samples to demonstrate that a new process/material is equivalent to a previously qualified process/material system, and

3) Model-based qualification, where the performance of the process/material system is demonstrated with a computer model and verified with limited testing of physical samples.

Qualification is particularly important for some key industry sectors, such as aerospace and medical devices, that can potentially leverage the strengths of AM to their advantage. Aerospace companies would like to take advantage

1 https://www.nist.gov/programs-projects/measurement-science-additive-manufacturing-program
of the ability of AM to produce high levels of geometric complexity in components to reduce weight without sacrificing strength or stiffness. The relatively slow production rate of most AM processes is not a barrier for most aerospace companies due to the low production volume of aircraft. However, since component failure can lead to substantial loss of human life, qualification of material systems and manufacturing processes that produce these components is required, and is overseen by governmental agencies such as the FAA (and/or various defense agencies) or FDA.

Medical device manufacturers who make implantable devices must contend with the fact that no two patients are identical, and therefore the optimal implant is likely different for each individual patient. They would like to leverage the ability of AM to quickly and easily change the geometry of components without extensive human intervention and re-design, making devices that are customized to the specific requirements of each patient in an affordable manner. Again, device failure can have severe consequences, so material/process systems must be qualified before they can be used. Government agencies, e.g. FDA, oversee the approval process for medical devices, which includes qualification of the material/process system used to produce the devices. Many other potential application domains exist for metal-based AM where predictable material properties and range of geometric variation in components are strong requirements for a material/process system to be considered for adoption, even though there may be no formal legal requirements such as those governing aerospace and medical devices.

Components that result from qualified material/process systems can be “certified” for commercial use in an approved application. Certification is performed by authorized organizations, and is essentially a statement that the component in question was produced using a qualified material/process system, and meets all requirements and specifications. Certification can be performed by government agencies, trade organizations, or authorized vendors.

This section of the report will deal with two technical elements (TE) for Hybrid Manufacturing:

**TE1**  
**In-situ Inspection**

**TE2**  
**Ex-situ Inspection**

Inspection comprises the entire spectrum of measurements used to ensure that components are certified and material/process systems are qualified. These measurements may be performed pre-process, in-process, or post-process. For hybrid AM/SM processes, there may also be measurements performed between the AM and SM process steps.

Pre-process measurements may be performed to characterize the size distribution, morphology, chemistry, or void content of the powder feedstock, and the quality of the substrate being used. Other types of pre-process measurements may be aimed at characterizing the performance of the AM or SM manufacturing equipment to verify such things as static and dynamic positioning accuracy, laser spot size and power distribution, laser power, etc.

Post-process measurements may be performed to verify geometric and dimensional characteristics such as size, location, form accuracy, or surface topology/roughness. They may also comprise NDE evaluations to look for voids, cracks, or porosity; or other tests to evaluate mechanical and physical properties such as strength, stiffness, fatigue failure, fracture toughness, electrical properties, etc.

Intra-process measurements may take place when the AM and subsequent finishing or subtractive processes take place in separate machines. These measurements may include many, if not all, of the measurements listed under
post-process measurements. A notable addition is the use of intra-process measurements to locate the AM component relative to the SM machine’s native coordinate system after fixturing.

In-process measurements may include anything that can be sensed within the envelope of the AM, or potentially SM, processes. However, given the technological maturity of most SM processes, it is not envisaged that significant advances are required in the realm of in-process sensing to make them compatible with hybrid AM/SM activities. In-process sensing within the AM envelope offers many potential benefits, including

1) implementation of closed-loop control of the AM process to reduce variability,

2) early detection, and possible repair, of defects and voids in the AM build,

3) layer-by-layer inspection of the boundaries of the fused region to verify features that may not be accessible post-build, and

4) real-time monitoring of the fusion process to control material properties.

Roadblocks and Challenges

The following critical technology elements were identified. Each critical technology element associated with Inspection, Certification and Qualification was defined in terms of the current technical barriers and needs, what qualification needs and barriers exist, what is the anticipated level of risk and reward, and finally what market segments and applications are driving these critical technology elements.

**In-situ Inspection**

- Real-time in-situ control of the process is needed. The data capture rates and processing time of monitoring system should be sufficient for real time control. A comprehensive knowledge of correlation between recorded data, process control parameters, and resulting component properties is also needed.

- Data analytics algorithms and strategies are needed, such as efficient data interpretation, standard machine state output, and self-documenting data system.

- Sensing and related technologies need to be advanced, including sensors that have the ability to sense complex and thick parts, and enable layer-by-layer defect detection. The sensors must be robust and reliable in the process environment. Better sensors that allow in-situ dimension and tolerance inspection are needed.

- Process models validated by experiments and correlation to support design and in-situ inspection are needed.

**Ex-situ Inspection**

- Standards are needed that are acceptable to major industry groups that define what inspections must be completed to ensure acceptable products; including both pre-process characterization of feedstocks and post-process inspection of components.

- Better methods are needed for inspection of internal features, lattice structures, and other geometrically complex features. Methods must be cost-effective, time-efficient, and non-destructive.

- Better methods are needed for non-destructive characterization of hybrid AM material properties such as strength, fatigue, fracture toughness, residual stress, porosity, and microstructure. Model-based methods are highly desirable.

Tables 20, 21, and 22 provide a summary of the specific Problems, Challenges and Technical Gaps associated with Inspection, Certification and Qualification.
### Table 20

<table>
<thead>
<tr>
<th>Perceived deficiency</th>
<th>Challenge</th>
<th>Future Vision</th>
<th>Technical Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process understanding: AM process is still not well understood. We need to fully understand the relationship between the part being built and the sensor data.</td>
<td>Model based, fast, in-situ monitoring of the process is needed so that it can help us analyze the sensor data for in-line understanding and control of the process. This will greatly reduce process chaos and increase process robustness.</td>
<td>Modeling of AM processes that can effectively relate feedstock properties and process parameters to the resulting material properties. Detailed models should be available for component design, material design, AM process parameter selection, and interpretation of inspection/qualification data.</td>
<td>Detailed AM models are lacking. Analytical modeling is needed to predict material properties and defects in AM processing. Inspection data should be integrated with detailed AM process models to maximize throughput and quality.</td>
</tr>
<tr>
<td>Process monitoring: There is a lack of comprehensive sensors and tools available for process monitoring. A number of various technologies are being explored, although most of them are still in the experimental stage.</td>
<td>In-situ monitoring technologies for defect detection, residual stress, microstructure, or material discontinuity formation are needed. Reliable and precise sensors are needed that can function in the build chamber environment, and are not be influenced by geometry and clouding.</td>
<td>Better sensing tools such as smart, adaptive sensing, and robust/non-discriminatory sensing systems are available to signal when a critical event occurs, and to provide real time inter-layer defect detection.</td>
<td>Advanced sensing technologies, data analytics algorithms and strategies. Sensors able to operate robustly in the chamber environment. Cross-certification of multiple sensors are needed to ensure their sensing ranges overlap. Robustness and reliability of sensors. Ability to sense complex and thick-parts.</td>
</tr>
<tr>
<td>Process control: Due to sensor limitations, and lack of understanding of the process, the current process control is still very limited and operates in an open-loop fashion.</td>
<td>Real time feedback and data processing are required to enable closed loop process control. Limitations of in-situ monitoring systems, and lack of high-fidelity, model-based understanding of AM processes place severe limitations on the ability to implement closed-loop control.</td>
<td>An auto-healing process so that defects are detected in real time, and repair measures are automatically performed so that each layer is defect free. The eventual goal of in-situ process monitoring and control is to replace ex-situ inspection.</td>
<td>Robust and reliable sensors able to operate in the AM build environment. Process models for interpreting sensor data to provide feedback for process control. Improved sensor data processing speed and data reduction for layers is needed. On-board computing capability needs to be faster.</td>
</tr>
</tbody>
</table>
Perceived deficiency | Challenge | Future Vision | Technical Gaps
--- | --- | --- | ---
Qualification and certification: Potential high value applications of AM in the aerospace and medical device sectors are limited by the requirement for qualification and certification of materials and processes. | Standards are needed that define what steps are needed to produce commercially acceptable parts. This includes characterization of feedstock powders, monitoring of AM builds, and post-process inspection and NDE. | Detailed, high-fidelity models of AM processes are available to facilitate model-based qualification. Widely accepted standards enable users to select AM machines, powder feedstock, and AM process parameters with confidence that the resulting components will meet requirements and specifications. | High-fidelity AM process models. Standards for feedstock powder characterization, handling, and recycling. Standards and technologies for in-situ monitoring of AM builds.

NDE: Better methods and tools are needed for non-destructive characterization of AM components, including strength, fatigue and fracture, residual stress, porosity and internal defects, microstructure. | Conventional NDE tools are insufficient for inspection of components with high levels of internal geometric complexity, and which may not be homogeneous over the build volume. | Model-based methods are used to complement NDE results and to provide high confidence in as-built material properties. | High-fidelity AM process models. In-situ, in-process NDE tools for layer-wise inspection and characterization.

Post-process inspection: Many AM components have high geometric complexity, with the result that internal features critical for the functionality of the component are often not available for inspection after the build. | The vast majority of traditional inspection tools require tactile or optical access to the surfaces under inspection. For many AM components, this access is not possible. X-ray CT systems can help to inspect internal features, but have limited penetration depth in hard, dense metals; and are currently too expensive and slow. | Layer-wise inspection of internal features, supported by high-fidelity process models eliminates the need for post-process inspection. When inspection is needed, improved CT systems enable full penetration of large components and quick inspection times. | High-fidelity process models. Tools for layer-wise in-situ dimensional inspection of internal features. Fast, high-power CT systems capable of full penetration of thick sections.

**Table 21**
Summary of Results Inspection, Qualification, and Certification (continued)
### Table 22
Summary of Results Inspection, Qualification, and Certification (continued)

<table>
<thead>
<tr>
<th>Perceived deficiency</th>
<th>Challenge</th>
<th>Future Vision</th>
<th>Technical Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>GD&amp;T: Many AM components have high geometric complexity such as lattice-type structures. These structures can have thousands of individual struts that make up the lattice. It is impractical to treat each of these struts as a separate feature with tolerances on size, form, and position that must be individually evaluated.</td>
<td>New methods for specification and functional inspection of lattice-type structures, or other structures with high geometric complexity, must be developed and standardized.</td>
<td>Methods for managing the geometric complexity of AM components during inspection are developed and standardized. Software automatically distinguishes between functional features which require GD&amp;T specification and inspection, and other features which contribute to aggregate properties and do not need to be inspected individually. Algorithms and methods for automatic classification of features for inspection are developed and implemented. Methods for verification of the aggregate properties of complex structures are developed and standardized.</td>
<td></td>
</tr>
<tr>
<td>Surface characterization: AM processes create surface topologies substantially different and more complex from those created by other manufacturing processes. Traditional surface roughness parameters are not well suited to characterization or understanding of AM surfaces.</td>
<td>Surfaces produced by AM almost certainly contain much valuable information about the process parameters used to create them. New tools and metrics are needed to rapidly characterize AM surfaces and to correlate them to process parameters and quantities of interest such as microstructure.</td>
<td>New instruments and algorithms tailored to metal-based AM surfaces are developed and standardized. Instruments capable of collecting data on high surface slopes characteristic of AM. Algorithms for characterization of AM surfaces and correlation to process parameters and underlying microstructure.</td>
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</tbody>
</table>

The table illustrates the breadth of challenges associated with this area.
Summary

As with most product development, there appear to be no easy solutions for directions for Inspection, Certification and Qualification for hybrid AM/SM manufacturing systems. The product requirements, production volume and application domain of the product will all play a role in deciding the type of production system that best fits the manufacture of new products. There are many challenges and developments that need to occur before these systems will be “common practice”. Table 23 and 24 summarize some of the issues associated with Inspection, Certification and Qualification Systems.

Table 23
Issues associated with Inspection, Certification and Qualification Systems.

<table>
<thead>
<tr>
<th>Category</th>
<th>Inspection, Certification, and Qualification</th>
<th>2018-2020</th>
<th>2020-2025</th>
<th>2025-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standards</td>
<td>Standards for part acceptance are developed and adopted by major industry groups; including medical, aerospace, and transportation.</td>
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<tr>
<td>Process control</td>
<td>In-situ sensors developed and validated to enable closed-loop and/or adaptive control of metal AM processes.</td>
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</tr>
<tr>
<td>Material property verification</td>
<td>Establish correlations between sensor output and material properties of interest.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material property verification</td>
<td>Models are developed to predict strength, fatigue and fracture, porosity, microstructure and residual stress to enable model-based inspection.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor development</td>
<td>New sensors are developed for in-process monitoring of defects and other properties of interest.</td>
<td></td>
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</tr>
<tr>
<td>Quality data management</td>
<td>Data analysis and reduction methods are established to enable near-real-time processing of sensor data for closed-loop control.</td>
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</tbody>
</table>

“Although we may be able to produce a part more quickly using hybrid methods, it may take significant time to inspect, certify and qualify that part. This significantly reduces the benefit of hybrid.”
### Inspection (Qualification / Certification / Standards) — continued

**Table 24**

Issues Associated with Inspection, Certification and Qualification Systems (continued).

“We need to think about qualification and certification as part of the AM process where we can sense the process and determine the quality of certain part features before the part is even completed.”

<table>
<thead>
<tr>
<th>Category</th>
<th>Inspection, Certification, and Qualification</th>
<th>2018-2020</th>
<th>2020-2025</th>
<th>2025-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensional inspection</td>
<td>Improved methods are developed for inspection of internal features, lattice structures, and other non-line-of-sight or geometrically complex features.</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>NDE</td>
<td>Improved methods are developed for non-destructive evaluation of material properties, including defect detection in large or thick components.</td>
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</tr>
<tr>
<td>Surface Characterization</td>
<td>New approaches and metrics are developed for characterizing AM surfaces, and correlating them to underlying microstructure and mechanical properties.</td>
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<td></td>
</tr>
<tr>
<td>Sensor integration</td>
<td>New AM control architectures are developed to enable integration of in-process sensors and closed-loop or adaptive control based on their signals.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality data management</td>
<td>Data analytics algorithms and strategies are developed to enable efficient data interpretation, standard machine state monitoring, and self-documentation of layer-wise sensor output.</td>
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</tr>
</tbody>
</table>
In-Envelope Hybrid

Background

What is In-Envelope? How does it differ from serial hybrid?

Metal Additive Manufacturing (AM) has proven its value for low production volumes and highly complex geometries as demonstrated by annual growth rates of 30+%, and >50% OEM equipment sales. The demonstration of production parts via AM in the aerospace and biomedical domains has been well documented recently, but inevitably these parts require post processing to achieve accuracies and surface finishes suitable for most applications. In most cases, this is a sequential operation, where geometry is produced in AM with machining allowance followed by a second machine which removes the allowance and meets accuracy and finish requirements of the final part. The notion of this two-step process is where we define the term “Hybrid Manufacturing” (HM) as a process where two or more manufacturing processes are brought together. This combination can be done in sequential manner, or perhaps within the envelope of one machine.

Ex-Envelope Hybrid Manufacturing

The notion of “ex-envelope” HM is the sequential combination of AM and then subtractive manufacturing (SM) processing across two separate machines. As illustrated in Figure 5, this could include the combination of a traditional powder-bed printed metal part, and a 3+ axis CNC milling machine. This is practiced in the metal AM industry today, and has been commonplace for over a century in the metal casting industry. That is, the combined planning of a metal casting, with machining allowance for subsequent cutting operations IS a hybrid approach to manufacturing. However, metal casting is not nearly as suitable at low-volume production or capable in creating complex geometry. The advantage of an ex-envelope approach is the higher utilization of each individual technology; however, much consideration must be given in the process planning stages (both in AM as well as SM) to successfully realize a part meeting design requirements. Additionally, some internal geometry may not be accessible for finishing after the part is produced via AM making it infeasible to completely meet requirements.
In-Envelope Hybrid Manufacturing

“In-Envelope” HM has been demonstrated in multiple ways, the most obvious and straightforward of which is adding a directed energy deposition head inside a machining center or by adding a machining operation within a laser powder bed system. Commercial examples of these systems include DMG Mori Seiki LaserTec 65 and Matsuura Lumex, respectively (Figure 6).

As discussed in the Overview, Hybrid manufacturing systems can be classified as: 1) In-envelope and 2) Ex-envelope systems. In-Envelope Hybrid manufacturing systems integrate the Additive and Subtractive systems into the same envelope. This offers several advantages – a single system is required instead of two or more, material handling and transfer issues are reduced and the necessity of localizing the workpiece after transfer to a different processing station is eliminated. In addition, the subtractive and additive systems may operate concurrently (though usually not simultaneously) allowing capabilities such as tool access and corrective processing not easily achieved in sequential Ex-envelope hybrid systems. On the other hand, In-Envelope Hybrid manufacturing systems inherently face challenges resulting from the conflicting requirements imposed by the AM and SM subsystems, as well as the side effects on each process type from the other. Lastly, the capital expenditure required for distributed hybrid cell deters adoption until the volume of throughput to saturate such a cell is assured which may mean that in-envelope systems will be favored for early application prove-out.

Figure 8 shows a high-level overview of the processing sequence employed in Ex-envelope hybrid manufacturing systems, highlighting their sequential nature. While the AM and SM systems may individually possess sensing and
feedback for corrective operations, there is no easy avenue for a workpiece to return to the AM system once it has been transferred to subsequent processing stage. In contrast, Figure 9 shows the In-Envelope Hybrid manufacturing processing sequence. In an In-envelope process, depending on the specific system configuration as well as the choice of AM and SM subsystem type, the part may undergo multiple (sequential) AM and SM processing steps, until the controlling system determines the part has been successfully processed to meet the required specifications. This also allows pre-existing geometries to be processed, e.g. for repair of damaged parts.

The In-Envelope Hybrid manufacturing approaches have inherent advantages that render them attractive to a wide variety of applications and organizations. However, their development, use and deployment is restricted by several challenges.

Unfortunately, a lack of understanding and technological solutions that address the limitations of In-envelope hybrid manufacturing systems is a significant barrier to their deployment, and therefore to the value proposition that they may bring. A comparison of the limitations and advantages/disadvantages of these two hybrid manufacturing systems is the focus of this section of the report.

The need for both in-process real-time control and corresponding simulation tools are paramount in the minds of the stakeholders who participated in this event. Only both tools used in concert are perceived to be able to fully close the design and build loop and ensure defect-free parts with deliberate control of microstructure and other part properties.

Additionally, it is clear that there is a strong motivation to enable quick and efficient switchover between disparate processes (additive and subtractive) including the ability to adjust environmental conditions to achieve the highest quality parts. Of particular interest to enable in-situ hybrid are strategies to minimize defects and control residual stress so that ex-situ heat treatment and hot isostatic pressing can be avoided.

These themes together with the pre-requisite attention to safety for combined disparate processing form a very clear focus for continued technical development. Interestingly, the hardware for hybrid processing has
emerged in advance of the software tools and many of the needs and opportunities to address said needs like in the information technology and integrated computational materials engineering (ICME) domain.

This mismatch between the current (relatively advanced) state of hardware systems and associated software tools is a challenge due to the complexity of the In-Envelope Hybrid manufacturing process and the many interactions and requirements that must be balanced. Investment in systems to address this – from training and assistive documentation and strategies to automated measurement, control and finally totally integrated predictive planning tools is required. Table 25 contains a summary of the challenges associated with In-envelope and distributed hybrid systems. From the table, one can see that for every advantage gained by staying “in-envelope” a processing constraint is added. Similarly, for each constraint removed using distributed hybrid, there is an additional processing task added. Determining the production performance of these constraints will be highly-dependent of the part geometry and mechanical requirements.

**Summary**

As with most manufacturing systems and applications, there appear to be no easy solutions for the systems design for integrated hybrid AM/SM manufacturing systems. The product requirements, production volume and geometric complexity of the product will all play a role in deciding the type of production system that best fits the manufacture of new products. There are many challenges and developments that need to occur before these systems will be “common practice”. Tables 26 and 27 summarize the topics and issues discussed.
Table 25
Summary of Results In-envelope vs. Distributed Hybrid

<table>
<thead>
<tr>
<th>Perceived Problem</th>
<th>Challenge</th>
<th>Future Vision</th>
<th>Technical Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Managing residual stress in-situ is not yet developed</td>
<td>Conventional means for addressing residual stress such as heat treatment, anneal and HIP seem incompatible with all-in-one hybrid system built on conventional platforms</td>
<td>A predictive model/simulation that can quantify and be used to drive the process to mitigate/manage residual stress</td>
<td>Lack of predictive models/simulation capable of operating at the multiple scales and speed needed to be practical for routine part production</td>
</tr>
<tr>
<td>Consistent yield of ideal end-item properties from metal AM has not yet been established</td>
<td>Sensing in-process is not widely implemented or highly robust to rely on it for real-time feedback</td>
<td>A hybrid system that produces quality parts and compensates in-process to prevent defects</td>
<td>Lack of in-process sensing enabling real-time control</td>
</tr>
<tr>
<td>Desire and need to co-locate many (more) operations/processes (including grinding, EDM, HIP, DED, CNC, etc.)</td>
<td>Each process needs different environmental conditions which need to be adjusted quickly to allow viable co-location</td>
<td>“Factory in a box” swapping in and out functionality as needed</td>
<td>Need environment adjustment to allow co-location of more processes and operations in situ</td>
</tr>
<tr>
<td>Hybrid is perceived as not safe (particularly for non-reactive powders)</td>
<td>Multiple types of sensing and control are needed to ensure safe conditions</td>
<td>Standards and legal safety requirements are hard to find.</td>
<td>Sensing developments needed</td>
</tr>
<tr>
<td>Successfully running In-Envelope Hybrid systems as industrial equipment extremely difficult</td>
<td>Personnel capable of understanding design for In-Envelope Hybrid, thermal stresses, AM requirements and Machining parameters are hard to find.</td>
<td>University and Vocational training programs will produce a workforce who understand Hybrid processing and can run systems with less training</td>
<td>Lack of curricula and programs geared toward understanding complexities of AM, SM and Hybrid (especially metal) processing.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Design rules and guidelines will help operators make decisions rapidly and correctly.</td>
<td>Need understanding of design rules and impacts in In-Envelope Hybrid. Must generate and distribute high quality data to help drive rule generation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Software systems will automatically check process plans for common errors and feasibility.</td>
<td>Need to develop software systems that leverage design rules and process knowledge to aid operators.</td>
</tr>
</tbody>
</table>
### Table 26
**Issues associated with material properties that need to be addressed in In-envelope vs. Distributed Systems**

<table>
<thead>
<tr>
<th>Category</th>
<th>In-Envelope Roadmap Component</th>
<th>2018-2020</th>
<th>2020-2025</th>
<th>2025-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Managing residual stress in AM builds</td>
<td>Heat treatment, annealing and HIP incompatible with today’s conventional in-envelope platforms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low yield of ideal end-item properties</td>
<td>Sensing in-process is not widely implemented or sufficiently robust</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processing for different processes requires different conditions</td>
<td>Each process needs different environmental conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

“Determining the type of system a part is manufactured in can affect the cost significantly.”

“In envelope systems eliminate the need for relocating a part, but they also constrain the things that can be done in the envelope.”
### Table 27
Additional issues that need to be addressed in In-envelope vs. Distributed Systems.

<table>
<thead>
<tr>
<th>Category</th>
<th>In-Envelope Roadmap Component</th>
<th>2018-2020</th>
<th>2020-2025</th>
<th>2025-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>Multiple types of sensing and control are needed to ensure safe conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Single simple method for monitoring all safety conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Sensing developments needed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Standards and legal safety requirements are hard to find.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Simple tool to help find and comply with safety requirements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difficult to plan process and operate system</td>
<td>Personnel capable of understanding design for In-Envelope Hybrid, thermal stresses, AM requirements and Machining parameters are hard to find.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Educating operators and engineers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Design guidelines for hybrid</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*“An in envelope system can double the operational requirements for hybrid system while it reduces the material handling and positioning needs. We need to better understand why and how.”*
Workforce and Education

Current Challenges

Industry partners within the consortium reported a large gap in technical knowledge of advanced manufacturing for a full range of skills including welding/joining, machining, drawing, and AM. There is a need to educate and convert our existing workforce into new technologies while at the same time replace the retiring workforce. The need is most acute in the skilled trades. The pipeline for machinists, welders, inspectors, metrologists, additive and hybrid manufacturing technicians should be bolstered with increased targeting at high schools and vocational educational programs in addition to collegiate programs. Creative programs to form public-private partnerships, apprenticeships, and the associated research and development into these educational programs will be critical for advanced manufacturing at large including hybrid AM.

Leveraging the full value of hybrid manufacturing will require a workforce capable of understanding the full value chain and operating within this chain. This requires understanding beyond metal additive manufacturing alone. It requires skills and knowledge of the individual processes within the value chain and the effects of the integration of those processes. The emergence of In-Envelope Hybrid systems requires special attention as sequential processes become replaced by concurrent ones. New thinking and skills are needed.

Achieving GD&T – Dimensional Control

The consortium assessed the current challenges in three areas of Dimensional Control: AM Process Planning, Subtractive Manufacturing (SM) Process Planning, and Fixture/Setup Planning. For AM Process Planning, current challenges relevant to the workforce include CAD/CAM/CAE integration and interoperability (and topology optimization) and applying cost modeling. Workforce challenges for SM Process Planning include Design for Machining (DFM) and how to handle FGM (functionally graded materials). Fixture/Setup Planning challenges include: Decision Making to include Machine datum vs. variability tradeoffs (AM process dependent) and determining when to use integrated fixturing vs. sacrificial fixturing and how to design the fixtures. Each of areas also had workforce challenges involving understanding how to process plan for high variability (geometric, mechanical properties, defects, etc.).

Surface Finish

The three areas of surface finish explored during our roadmapping activities are Additive Manufacturing Finishing Needs, AM Finishing Measures, and AM Finishing Processes. With respect to AM Finishing Needs, AM users have minimal taxonomy for describing surfaces; this is typically a different taxonomy when compared to traditional classifications used by component customers and the measurement community; new quantifiers are required for AM. It is...
not known how to relate standardized descriptors for surface roughness to user requirements; the AM community is competing with historical terminology and training developed for the machining community. There is a large effort by all users to understand how to finish AM surfaces, but there is a lack of understanding on how processes affect surface finish.

In terms of surface finish and AM finishing measures, complex AM surfaces are driving a transition in surface measurement technologies from 1-D stylus measurements to 2-D areal measurements of surface topography. CT scans are needed for internal surfaces, but there are resolution limitations due to the thickness and density of the component. Taken together, these mean a significant increase in instrument sophistication, which leads to additional training requirements, and these new instruments are expensive and not widely available to education institutions and training centers. At the same time, there is a commercialization gap between the AM and surface measurement communities and this affects training the workforce. The markets and workforce training mechanisms for developers and suppliers of metrology equipment are well-established with existing customers, such as the machining industry or in semiconductor processing, but not with AM.

Lastly, for AM Finishing Processes there are a range of processes used to obtain desired surface finish. The effects of those processes on properties and the cost-benefits are either not known or are not available to educate the workforce. Courses are needed at universities regarding AM and surface finish, and so is professional training.

**In-Envelope Hybrid**

Successfully running In-Envelope Hybrid systems as industrial equipment is extremely difficult. Personnel capable of understanding design for In-Envelope Hybrid, thermal stresses, AM requirements and machining parameters are hard to find.

**Integration**

Integration will tie together all of the component sections associated with hybrid AM/SM. It stands to reason that the integration of Hybrid systems will require an understanding of all of the processes and the interfacing issues associated with combining the various components of hybrid AM/SM. The input and output for the various stages is a needed component. For instance, a reasonable understanding of the requirements for AM metals processing will be a fundamental requirement. The input for the process (STL or AMF file with part features and sacrificial supports, materials, processing instructions, etc.) will be required along with permission to begin processing (cycle start). An understanding of the secondary and/or tertiary processes such as heat treating and machining will also be necessary in order to link the processes together to get the desired product results. Input formats (product and process) and processing instructions will also be necessary along with any associated tooling or other resources such as measurement devices will all be necessary components for the systems integration.

The major driver for the use of hybrid manufacturing will be the economics of the process so an "activity-based costing" (ABC) of each of the components and independent design variables will also be key to integration. The method to create a series of processing steps will be driven by the product cost so the decisions associated with determining the Routing Summary will be critical to the success of hybrid AM/SM production.

**Inspection, Qualification, and Certification**

Inspection, qualification, and certification have several challenging issues in terms of workforce and education, such as analyzing and in-line understanding between sensed signals (big data), process parameters, and the resulting material property and geometry. The geometric complexity of many AM parts, coupled with the higher probability of porosity, internal defects, and uncertainty of material microstructure makes the selection of proper instruments and sensors for dimensional, surface, and NDE inspection very challenging for inspection personnel.
Future Vision

Achieving GD&T – Dimensional Control

The skilled workforce must conduct, AM Process Planning, SM Process Planning, and Fixture/Setup planning. This means a workforce able to mitigate variability from the AM process through planning for the build and planning for post-processing. This workforce will to be able to use the automated technologies but also have the understanding, expertise, and confidence to address these functions manually, if required.

The workforce will be trained in Design for Manufacturing across the full value chain. This includes being able to design integrated fixturing, determine the placement and extent of supports and how to remove them, design complex geometries with confidence in final dimensions, and design of functionally graded materials. Complex parts will be designed to be multi-datum parts and to include the proper production sequence of features that become datums. Designers will be cognizant of the cost impacts of each step needed for dimensional control.

Surface finish

For surface finish, the future involves a standardized means of capturing customer requirements for surface finish (the customer may be either the final user of the component or the group that will perform secondary operations). There is will be reproducible numerical measure of surface finish that will enable the determination of if the AM process is correct. The AM community has a standardized set of terms to use in describing roughness with common links to training. AM process models will exist that can be used to identify process parameters for achieving required levels of roughness; CAM software exists that addresses roughness. Modeling and simulation capabilities will exists that can show how roughness is generated, while defining the impact of process variables and machine parameters, such as those that would be incorporated in CAM software.

In-Envelope Hybrid

For In-Envelope Hybrid, the future University and Vocational training programs will produce a workforce who understand Hybrid processing and can run systems with less training. Design rules and guidelines will help operators make decisions rapidly and correctly. Operators will be aided by Software systems will automatically check process plans for common errors and feasibility.

Integration

Because integration will tie together all of the component sections associated with hybrid AM/SM, it is logical to assume that the integration specialists for Hybrid AM/SM manufacturing will need a broad and deep technical understanding of both AM and SM processes. The integration of these systems will also be completed via complex software systems that plugs into today’s ERP systems, like SAP, so an understanding of software development and integration will also be necessary. It stands to reason that the integration of Hybrid systems will require an understanding of all of the processes and the interfacing issues associated with combining the various components of hybrid AM/SM.

Inspection, Qualification, and Certification

The workforce will be trained with in-depth understanding of the AM processing and inspection, such as model-based design and inspection, so that we know what has happened in the process, and where, when, and how to inspect in order to maximize the benefits of inspection, maximize utilization of the acquired data, and minimize the number of defects. Other workforce training includes standardized testing requirements for AM, and AM CT analysts.
Workforce and Education Gaps

Achieving GD&T – Dimensional Control

There is a lack of understanding of what needs to be taught for Design for Manufacturing from a dimensional control standpoint. CAD and CAM tools are not even integrated for hybrid AM. Software tools and automation will become available, but it is not known what those tools will look like and the needs and requirements for the workforce in the near term. Sufficient and widely available cost data is lacking. There is a need to have the equipment in place at institutions to teach and practice the design and sequencing of multi-datum parts. The ability to teach voxelized control of functionally-graded materials is still in its infancy.

Surface finish

AM Finishing Needs: Workforce training in surface finish technology from the perspective of AM is needed to influence future generations of manufacturing engineers; this would include university courses in metrology, description of AM surface topography, and an understanding of how AM and other finishing technologies affect surface topography.

AM Finishing Measures: Availability of metrology instruments for areal characterization of AM surfaces is required for educational institutions. Instrument affordability and worker training need to be addressed. Two tools needed for industry adoption are also needed for workforce development and education. First, a quantitative standards-based language is required for describing the complex topography of AM surfaces. Second, an atlas of surface finish measurements needs to be created that discriminates between “good” and “bad” surfaces and also documents measurement parameters and the process parameters that created the surface.

In-Envelope Hybrid

For In-Envelope Hybrid, there is a lack of curricula and programs geared toward understanding complexities of AM, SM and Hybrid (especially metal) processing. There is a need for greater understanding of design rules and their impacts. In order to create these rules that would then be provided to students and workforce, high quality data must be generated and disseminated. There is a need to develop software systems that leverage design rules and process knowledge to aid operators. There is a lack of In Envelope Hybrid systems available for widespread education and training.

Integration

In order for integration to tie together all of the component sections associated with hybrid AM/SM, training in each of the previous areas will be required. The training will not need to be at the depth of operators for each of the components, but it will need to be deep enough to understand all of the file and data requirements for each process component in the system. Specialists in this area will likely require advanced engineering degrees with an understanding of manufacturing, materials science, geometric modeling and systems science.

Finally, there has been a general erosion of manufacturing education at four-year institutions throughout the United States that puts further pressure on the skills required to program hybrid processes utilizing CAD/CAM. Greater use of simulation technology integrated to CAD/CAM processes may be used to augment the training needed for hybrid processing.

Inspection, Qualification, and Certification

For inspection, training and education is needed to use models to support design and inspection, selection and use of suitable sensors to monitor the process conditions, design and integration of sensors within the machine, understand defect formation and detection, and comprehensive knowledge of correlation between recorded data, process control, and resulting material properties and product quality.
In summary, CAM-IT has identified six major technological thrust areas (Swim Lanes – SL) as the technological challenges in the roadmap that hinders the adoption of metal AM in the U.S. Following a systems engineering approach:

1) end-users of metal AM identified potential applications of metal AM that could not be currently achieved,
2) leading researchers presented current technological challenges in seamlessly integrating metal AM with conventional manufacturing processes, and
3) experts from national laboratories, government, industry leaders, and professional organizations evaluated the technological roadmap based on resource needed – impact – landscape of industry needs.

**SL1 Materials Properties Enhancement**

While material properties of metal AM parts have been improving since the early days of metal AM, there are four critical areas that were identified:

1) **Post-Process Surface Treatment:** Ability to modify surface morphology to attain desired functionality after AM processing
   - Demand Pull: Defense, Aerospace rotary and structural parts, and Medical industries
   - Examples: increased corrosion resistance, increased hardness, increased thermal corrosion resistance, biocompatibility, or high cycle fatigue resistance.
   - Time-line: Mid-Term (2018-2025)

2) **In-Process Surface Treatment:** Ability to modify surface morphology to attain desired functionality during AM processing
   - Demand Pull: Applications in Defense, Aerospace rotary and structural parts, and Medical industries with internal features that cannot otherwise be accessed post-AM
   - Examples: induce compressive residual stress and measure surface characteristics in process
   - Time-line: Long-Term (2018-2030)

3) **Heat Treatment Related to Distortion:** Understanding and predicting distortion in post-AM heat treatment for controlling heat treatment induced distortion
   - Demand Pull: all markets requiring hybrid AM parts and materials requiring heat treatment to develop the required mechanical properties
   - Examples: general GD&T guidance for these hybrid AM produced components
   - Time-line: Long-Term (2018-2030)

4) **Properties:** Integrated solution for process monitoring, closed loop controls, powder quality, creating homogenous microstructures, achieving theoretical densities, and uniform properties in as-AM
   - Demand Pull: Most metal-AM industries; specifically, were surgical and medical, tooling, components needing repair, and structural and rotating components
   - Examples: better correlation between AM process, powder characteristics, process planning and resulting material properties.
   - Time-line: Mid-Term (2018-2025)
Two critical areas were identified for the evolution of a system that is capable of (semi-)automatically producing mechanical products to final engineering specifications:

1) Integration Methodology: Developing an automated procedure to directly produce final mechanical part design using both AM-sacrificial supports and Hybrid-sacrificial support (i.e. in-built fixtures in AM parts) and incorporate current ASTM and ASME standards to explore part features in an otherwise feature-less STL format currently used in the AM industry.

   Demand Pull: all markets requiring hybrid AM parts with GD&T requirements
   Examples: reduced process planning in hybrid-AM and geometry-specific hybrid AM operations
   Time-line: Short-Term (2018-2020)

2) Integration Methodology: Ability to seamlessly integration design, certification and qualification of custom low volume parts and integration of hardware (across machine envelopes) and software (data integration).

   Demand Pull: all markets requiring hybrid AM parts with GD&T requirements
   Examples: new set of design for manufacturing standards for AM and hybrid processing
   Time-line: Mid-Term (2018-2025)

Three critical technological barriers to implementation of HM (either in-envelope or ex-envelope) were identified in order to achieve GD&T through material removal, i.e. machining:

1) AM Process Planning: Determination of build orientation, integration of fixturing, material selection related to machinability, and other tunable parameters affecting the final part quality after building and finishing.

   Demand Pull: all markets requiring hybrid AM parts with GD&T requirements
   Examples: Adapting machining strategies for AM material, geometry and build orientation
   Time-line: Long-Term (2018-2030)

2) SM Process Planning: Automatic NC code generation, standard code adaptation (as opposed to new creation), feature-based tool paths, machining sequence and automation.

   Demand Pull: all markets requiring hybrid AM parts with GD&T requirements
   Examples: Ability to machine fine AM features and Functionally Graded Material (FGM)
   Time-line: Mid-Term (2018-2025)

3) Fixture/Setup Planning: proper fixturing considering machining forces, fixturing strategies, positioning in finishing operations, number and orientation of discrete set-ups, tool access and selection.

   Demand Pull: all markets requiring hybrid AM parts with GD&T requirements
   Examples: Development of AM-specific cutting tools and elimination of compounding errors in multiple set-ups in hybrid AM
   Time-line: Mid-Term (2018-2025)
Surface Finish Considerations

Three critical technological barriers to implementation of HM (either in-envelope or ex-envelope) were identified in order to achieve desired surface morphology, i.e. roughness, texture, sub-surface integrity and surface chemistry:

1) AM Finishing Needs: Determination of surface finish specifications, current challenges in realizing these, and elicitation of specific application scenarios.

   Demand Pull: Biomedical components processed through metal AM

   Examples: Correlating AM build parameters and its effects on surface finish based on material and build orientation

   Time-line: Mid-Term (2018-2025)

2) AM Finishing Measures: Determining the various alternative measures employed to specify the surface requirements as well as instruments to measure these, development of cost models to determine finish specifications for various applications, and challenges associated with current instruments to effectively measurement of these quantifiers

   Demand Pull: all markets requiring hybrid AM parts with surface finishing considerations

   Examples: Instrumentation and sampling procedures that are catered towards as-AM surface morphology

   Time-line: Mid-Term (2018-2025)

3) AM Finishing Processes: Determining alternative process chains to meet various finish (texture) specifications, and can include aspects of automation (code generation, standard code adaptation), tool path generation and machining sequence

   Demand Pull: all markets requiring hybrid AM parts with surface finishing considerations

   Examples: Better methods for inspection of internal features, lattice structures, and other geometrically complex features

   Time-line: Mid-Term (2018-2025)

Inspection (Qualification / Certification / Standards)

The technological barriers in this swim-lane were classified based on the machine envelope during inspection:

1) In-situ Inspection: Determining technologies to sense, measure, qualify and certify process parameters within the envelope of AM and/or SM. It includes implementation of closed-loop control, defect detection, inspecting features that cannot be accessed post-AM and real-time monitoring in AM and SM processing.

   Demand Pull: all markets requiring hybrid AM parts including PBF and DED users

   Examples: including sensors that have the ability to sense complex and thick parts, and enable layer-by-layer defect detection

   Time-line: Short-Term (2018-2020)

2) Ex-situ Inspection: Determining measurements which include many, if not all of the measurements listed under post-process measurements with a notable addition of intra-process measurements to locate the AM component relative to the SM machine’s native coordinate system after fixturing.

   Demand Pull: all markets requiring hybrid AM parts with surface finishing considerations

   Examples: Better methods for inspection of internal features, lattice structures, and other geometrically complex features

   Time-line: Mid-Term (2018-2025)
In-Envelope Hybrid

The technological barriers in this swim-lane were classified based on the machine envelope during AM and/or Hybrid AM processing:

1) In-Envelope: Determination of methods to better understand physics of residual stress, improve material yield from AM processing and improving operation safety

   Demand Pull: Defense and Tooling sectors requiring repairing and add-on features to existing products

   Examples: Correlating process simulation and in-process real-time control

   Time-line: Mid-Term (2018-2025)

2) Distributed Hybrid: Determining post-AM processing needs for a range of material, geometry, final engineering requirements and AM processes

   Demand Pull: all markets requiring hybrid AM parts with emphasize on low-medium production volume

   Examples: Process mapping of all potential post-AM processes including heat treatment, HIP, EDM, CNC, grinding, etc.

   Time-line: Long-Term (2018-2030)

The CAM-IT Consortium

This NIST AMTech project has defined both technological challenges and resources to help push AM further into standard manufacturing practice. A group of dedicated academics, industry practitioners and government researchers have come together to create the materials outlined in this Technology Roadmap. An America Makes working group has been established to continue to support the efforts associated with finishing AM produced mechanical parts, and this Working Group will serve to host future activities associated with CAM-IT. This group also intends to pursue industry and government support to chip-away many of the challenges still in place to slow the adoption of additive manufacturing.
Appendix I: CAM-IT Leadership Team

Dr. Brett Conner  
Youngstown State University

Dr. Brett Conner is the Director of the Advanced Manufacturing Research Center and Associate Professor of the Manufacturing Center at Youngstown State University (YSU).

Dr. Conner is a co-founder of the Center for Innovation in Additive Manufacturing (CIAM) at YSU. Dr. Conner has research interests in the application of additive manufacturing for aerospace maintenance and sustainment, functional graded materials fabricated using additive manufacturing, high strain rate behavior of materials fabricated by additive manufacturing, and economics of additive manufacturing. Prior to joining the YSU faculty, Conner worked for 15 years in government and industry. Dr. Conner is also the co-founder and Chief Technology Officer for Freshmade 3D, a company that uses additive manufacturing for rare and custom automotive parts.

Dr. Ola Harrysson  
North Carolina State University

Dr. Ola Harrysson is Professor and Fitts Faculty Fellow in Biomedical Manufacturing and Co-Director of the Center for Additive Manufacturing and Logistics, for the Department of Industrial and Systems Engineering at North Carolina State University (NCSU).

Dr. Harrysson has been involved in Additive Manufacturing research since 1996 and acquired the world’s first Electron Beam Melting machine by Arcam in 2003. The Center for Additive Manufacturing and Logistics is heavily involved in direct metal powder bed AM development and finishing of metal AM components. The research team has over a decade of experience with new material development as well as custom design and fabrication of medical and industrial components. Dr. Harrysson is also the co-founder and president of Sindre Metals, a research company developing amorphous metals for AM.

Dr. Rick Wysk  
North Carolina State University

Richard Wysk, PhD, is a Dopaco Distinguished Professor with the Department of Industrial and Systems Engineering at North Carolina State University (NCSU).

Dr. Wysk has spent most of his professional career as an endowed professor at three different universities (Penn State University, Texas A&M University and NC State), where he has developed and evolved many successful programs and centers focused on modern manufacturing. He is the (co)author of nine books and more than 200 journal publications. He was the founding Co-Director of the NCSU/UNC Rehabilitation Engineering Center as well as the founding partner of a medical device company, AIONX Inc., housed in State College, PA. He has held industry positions at GE and Caterpillar Inc.

Dr. Guha Manogharan  
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Guha Manogharan, PhD, is an assistant professor of mechanical engineering at Pennsylvania State University (PSU) and an Entrepreneur in Residence for Additive Manufacturing at the Youngstown Business Incubator.

At PSU, he heads the SHAPE Lab (System for Hybrid-Additive Process Engineering) and his research interests in additive and hybrid manufacturing include: Design rules for CAD-CAM, 3D sand-printing, material development, process modeling, CNC machining and interdisciplinary biomedical, mechanical and aerospace applications. An active member of ASME, IISE and SME, he was named the 2016 Outstanding Young Investigator by the ISE-Manufacturing and Design Division. He was also awarded the 2017 Society of Manufacturing Engineers’ Yoram Koren Outstanding Young Manufacturing Engineer. He holds a Ph.D and an M.S. in Industrial and Systems Engineering from North Carolina State University and a B.S. in Mechanical Engineering from SASTRA University, India.
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Appendix IV: Glossary

The following is a list of abbreviations and their meaning used throughout this document.

**AM** – Additive Manufacturing

**ANSI** – American National Standards Institute

**ASTM** – American Section of the International Association for Testing Materials

**BAAM** – Big Area Additive Manufacturing

**CAD** – Computer Aided Design

**CAE** – Computer Aided Engineering

**CAM** – Computer Aided Machining

**CMM** – Coordinate Measurement Machine

**CNC** – Computer Numeric Control

**CT** – Computed Tomography

**DDUAMS** – Direct Digital Manufacturing Using Additive Manufacturing Systems

**DFM** – Design for Machining

**DMLS** – Direct Metal Laser Sintering

**EBM** – Electron Beam Melting

**EDM** – Electro Dishcarge Machining

**FDM** – Fused Deposition Modeling

**FGM** – Functionally Graded Material

**GD&T** – Geometric Dimension and Tolerance

**HIP** – Hot Isostatic Pressing

**HM** – Hybrid Manufacturing

**ICME** – Integrated Computational Materials Engineering

**NCSU** – North Carolina State University

**NDE** – Non-Destructive Evaluation

**NDI** – Non-Destructive Inspection

**NDT** – Non-Destructive Testing

**OEM** – Original Equipment Manufacturers

**PSU** – Pennsylvania State University (Penn State)

**SLM** – Selective Laser Melting

**SLS** – Selective Laser Sintering

**SM** – Subtractive Manufacturing

**SME** – multiple meanings:
- Subject Matter Expert
- Small and Medium Enterprise
- Society of Manufacturing Engineers (non-profit organizatio)

**SPC** – Statistical Process control

**UNC** – University of North Carolina

**WAAM** – Wide Area Additive Manufacturing

**YBI** – Youngstown Business Incubator

**YSU** – Youngstown State University