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ARMD Workshop on Materials and Methods for Rapid Manufacturing for Commercial and Urban Aviation

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November 2019

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Space Administration

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Executive Summary

This report is based on the outcomes of a NASA Aeronautics Research Mission Directorate (ARMD)-sponsored workshop held in Tysons Corner, VA, on November 14-15, 2018. The workshop, Materials and Methods for Rapid Manufacturing for Commercial and Urban Aviation Workshop, was focused on identifying and assessing the state of technology areas relevant to rapid/advanced manufacturing, understanding critical technology gaps and identifying high-priority investment areas for NASA. One hundred twenty-two participants attended, including materials and manufacturing professionals, original equipment manufacturers, material suppliers, researchers, government agencies and academia.

The workshop was inspired by several related factors, including the growing worldwide demand for personal and business travel. To meet this growing demand, commercial aircraft manufacturers need to double production rates within the next 20 years while the emerging urban air mobility (UAM) manufacturers are developing vehicles for passenger and package delivery, requiring high efficiencies while still meeting strict regulatory structures and materials performance requirements similar to those of commercial aviation. If the aviation industry is to meet production needs at per unit costs and factory floor space that are equivalent or less than today's costs and floor space requirements, the advanced manufacturing technologies being developed will require corresponding advances in materials, processing and certification technologies.

The purpose of the workshop was to obtain information from subject matter experts on the technical challenges and the high-payoff technical focus areas that can accelerate the implementation of rapid manufacturing methods by the aviation industry. The workshop focused on understanding emerging and envisioned developments in advanced manufacturing; design and development of materials that are optimized for specific manufacturing approaches; the unique design possibilities associated with advanced manufacturing; computational materials simulation of material processing and performance; and development of the future qualification, certification and sustainment technologies that are needed to ensure safety throughout the vehicle's lifecycle.

The workshop began with a series of plenary presentations by leaders in the field of structures and materials, followed by concurrent symposia focused on forecasting the future of various technologies related to rapid manufacturing of metallic materials and polymeric matrix composites, referred to herein as composites. The metals symposium was organized into four inter-related sessions that included approximately 50 representatives from government, academia, and industry consisting of material producers, manufacturers and original equipment manufacturers (OEMs) focused on future manufacturing approaches, design and development of materials for those manufacturing methods, design approaches that exploit emerging rapid manufacturing, and related capabilities for qualification and certification. Similarly, the composites symposium was organized into five inter-related sessions that included approximately 70 representatives from government, academia, and industry consisting of material producers, manufacturers

and OEMs focused on rapid manufacturing of thermoset resin-based composites, rapid manufacturing of thermoplastic resin-based composites, in-process monitoring/nondestructive evaluation (NDE) technologies, process modeling and simulation of advanced manufacturing, composite materials testing requirements followed by a wrap-up discussion.

Shortly after the workshop, questionnaires were sent to representative workshop participants from the aerospace industry with requests to rank the importance of a series of potential investment areas that were identified during the workshop. Areas surveyed for metals included manufacturing, certification, material and structural design, non-destructive evaluation, in-situ monitoring and development of a digital thread for metals. Areas surveyed for composites included unitized structures, thermoset and thermoplastic material development, non-destructive evaluation and in-situ monitoring, process modeling, testing and cross-cutting technologies, such as adhesive bonding. Responses were received and subsequently collated by the workshop organizers. Outcomes from the workshop and subsequent questionnaires are being used as guidance for NASA investments in this important technology area.

The following technologies were identified as the most promising and high impact approaches to meet the needs of future aircraft production rate and were included in the OEM survey of potential investment areas. This information will be used to advise senior NASA management about potential areas for future investment.

Potential Investment Areas for Metals

- Objectively **evaluate emerging metals manufacturing methods** for their efficacy and potential impact as a means of rapid manufacturing of flight certified aerospace structures.
- Develop computational materials-based capabilities to support **qualification and certification** of the most viable rapid manufacturing methodologies to enable their use in production environments.
- Develop capabilities for **design and optimization of materials and structures** for rapid manufacturing including materials that are designed to be compatible with rapid manufacturing processes, optimized structures that exploit new and emerging manufacturing capabilities and structural systems that integrate both technologies.
- Develop improved capabilities for **NDE and in-situ monitoring** that are compatible with computational materials-based certification.
- Develop a comprehensive physics-based/ machine learning-informed computational framework (**digital thread**) for processing, materials, performance and life.

Potential Investment Areas for Composites

- Design and analyze **unitized and bonded structural concepts** (low part count/reduced assembly/minimal mechanical fastening) optimized for rapid manufacturing methods.

- Develop fast curing **thermoset** (TS) resins tailored for out-of-autoclave (OOA) processes including automated fiber placement (AFP) w/vacuum bag only (VBO) curing and resin infusion with VBO curing.
- Develop in-situ consolidation of continuous carbon fiber **thermoplastic** (TP) matrix resins by defining relationship of TP tape quality requirements and process parameter optimization for quality part production. Evaluate thermoforming of flat, continuous fiber panels to wing skin curvatures.
- Develop advanced **in-process monitoring and real-time nondestructive inspection** (fiber placement/FOD/autonomous defect recognition) and cure monitoring of material state (chemistry required for mechanical properties) methodologies.
- Develop robust **process modeling and simulation** technologies that can be used to predict defects and material properties for varying process parameters.
- Develop advanced **test methodologies** for lower cost/rapid certification of new materials/processing methods and model development validation.
- Develop high throughput **cross-cutting technologies**, including a rapid surface treatment process with integrated surface analysis to measure residual contamination for adhesive bonding which will minimize drilling and mechanical fastening.

Abstract

This report documents the goals, organization and outcomes of the NASA Aeronautics Research Mission Directorate's (ARMD) Materials and Methods for Rapid Manufacturing for Commercial and Urban Aviation Workshop. The workshop began with a series of plenary presentations by leaders in the field of structures and materials, followed by concurrent symposia focused on forecasting the future of various technologies related to rapid manufacturing of metallic materials and polymeric matrix composites, referred to herein as composites. Shortly after the workshop, questionnaires were sent to key workshop participants from the aerospace industry with requests to rank the importance of a series of potential investment areas identified during the workshop. Outcomes from the workshop and subsequent questionnaires are being used as guidance for NASA investments in this important technology area.

1. Introduction

This report is based on the outcomes of a workshop held in Tysons Corner, VA, on November 14-15, 2018. The workshop, Materials and Methods for Rapid Manufacturing for Commercial and Urban Aviation Workshop, was focused on identifying and assessing the state of technology areas relevant to rapid/advanced manufacturing, understanding critical technology gaps and identifying high-priority investment areas for NASA. One hundred twenty-two participants attended, including materials and manufacturing professionals, original equipment manufacturers (OEMs), material suppliers, researchers, government agencies and academia.

The workshop was inspired by several related factors, including the growing worldwide demand for personal and business travel. To meet this growing demand, commercial aircraft manufacturers need to double production rates within the next 20 years while the emerging urban air mobility (UAM) manufacturers are developing vehicles for passenger and package delivery, requiring high efficiencies while still meeting strict regulatory structures and materials performance requirements similar to those of commercial aviation. If the aviation industry is to meet production needs at per unit costs and factory floor space that are equivalent or less than today's costs and floor space requirements, the advanced manufacturing technologies being developed will require corresponding advances in materials, processing and certification technologies.

The purpose of the workshop was to obtain information from subject matter experts on the technical challenges and the high-payoff technical focus areas that can accelerate the implementation of rapid manufacturing methods by the aviation industry. The workshop focused on understanding emerging and envisioned developments in advanced manufacturing; design and development of materials that are optimized for specific manufacturing approaches; the unique design possibilities associated with advanced manufacturing; computational simulation of material processing and performance; and

development of the future qualification, certification and sustainment technologies that are needed to ensure safety throughout the vehicle's lifecycle.

The workshop was the beginning of a collaborative transformation by NASA, industry, academia and other government agencies to better understand production and certification challenges while building and strengthening the enduring relationships needed to keep NASA at the forefront of capability development. The event was sponsored by John Cavolowsky, director of the Transformative Aeronautics Concepts Program (TACP) in the NASA Aeronautics Research Mission Directorate and hosted by George Finelli, director of NASA Langley Research Center's (LaRC) Aeronautics Research Directorate. Other key personnel included members of the LaRC planning committee, including Jonathan Ransom (General Chair), Michelle Ferebee (General Co-Chair), Ed Glaessgen (Technical Program Chair), Brian Jensen (Technical Program Chair), Andrea McAlister (Logistics Coordinator) and the NASA Inter-Center Planning Team, including Sean Swei (Ames Research Center), Tim Risch (Armstrong Flight Research Center), James Zakrajsek (Glenn Research Center (GRC)) and Joyce Dever (GRC).

First, the workshop topic areas and a summary of observations from the workshop are briefly described. Next, a description of the two symposia, the Metals Symposium and the Composites Symposium, upon which the workshop was organized is given. The survey results of workshop-identified potential investment areas are discussed. Finally, a summary of the workshop is provided. For completeness, Appendix A is provided that contains a complete list of symposia session presentation titles and presenters.

Since the requirements of the metals and composites communities differ slightly, the organization of the corresponding workshop discussions also differed. Hence, there is some minor variability in the format of the Metals and Composites sections in this document. Although the certification process contains a regulatory component, the terms certification and qualification were used interchangeably during the workshop discussions. Hence, they are used interchangeably throughout this document.

2. Topic Areas and Summary Observations

This section briefly outlines the topics considered during the plenary, metals and composites symposia as well as some summary observations about the future of aircraft materials, design, certification and manufacturing including NASA's potential role. Note that throughout this report, composites refers to polymer matrix composites (PMC).

Plenary speakers representing the Federal Aviation Administration (FAA), NASA and aircraft manufacturers presented their views of the future of materials, manufacturing and qualification. Summary notes are given in Table 1.

Table 1: Plenary Speakers

Organization	
Speaker	***Summary Notes***
Federal Aviation Administration Perspective on Rapid Manufacturing	
Michael Gorelik - Chief Scientific and Technical Advisor for Fatigue and Damage Tolerance **Larry Ilcewicz** - Chief Scientific and Technical Advisor for Advanced Composite Materials Federal Aviation Administration	• The focus of the presentation was on rapid qualification, a large part of the material development cycle. • FAA plans to proactively address emerging safety risks including establishment of a new organizational structure to support emerging innovations. • FAA's 14CFR Part 25 regulations for Materials – fundamental based on experience and test – no mention of models yet - "test article should be full scale." • PMP model – process, microstructure, properties. Damage tolerance is considered by Dr. Gorelik to be a model-friendly domain; however, there are few current examples of certification by analysis. • Southwest Research Institute's Darwin code may be a platform that can deal with effect of defects. • There is no regulatory oversight of material development or material qualification; oversight starts at product qualification. • Another topic of interest was process parameter control to produce known microstructure which defines properties. • Metallic additive manufacturing is good case to work model-based qualification. • No FAA safety critical part certified yet, but this could happen within a year. • Need more focus to connect microstructure to properties. • New technologies are not aligned with a specific product line, but cross many; the new FAA organization helps deal with that. • Design includes materials and manufacturing. • Integrated product development, co-located through development effort, is essential. • A total certification direct operating costs savings of 5-8% is possible with composites. • Produce parts at scale when implementing new rapid manufacturing processes.
NASA's Manufacturing Development Activities and Capabilities	
Richard Russell - Technical Fellow for Materials, NASA Engineering and Safety Center National Aeronautics and Space Administration	• Presentation provided an overview of NASA materials processing/manufacturing capabilities. • Focus of the effort is toward advanced manufacturing technology and certification requirements for space structures, not specifically related to rapid manufacturing technologies.
Advanced Composites and Rate	
Gerould Young - Senior Director Advanced Manufacturing & Materials Product Development Boeing Commercial Airplanes	• Design and production are intertwined and cannot be separated. • View of requirements dictates how structural design is optimized. • For composites, performance other than weight savings is important, including fatigue, inspectability, etc. • Production of 50 – 60 million pounds of composites (Airbus and Boeing) in the ~2015 timeframe.

	• Doubling the amount of composite aircraft structure used by ~2030. • Some topics of interest to Boeing include thermoplastics, fast curing resins, thermoforming, high stiffness fibers, stamping, over-molding, reduction of composite processing time (heat/cool, cure, bagging), laydown rates, tooling, forming, painting, sealing, cladding, drilling, fastening, shimming, quality assurance, nondestructive inspection and system installation.
Rapid Manufacturing for Aviation: a DOD OEM Perspective	
Richard Barto - Senior Manager of the Lockheed Martin Advanced Technology Labs Lockheed Martin Corporation	• Doing nothing is the greatest risk; need to change the way that we certify; need to embrace new manufacturing technologies, improve design methodologies and rapid introduction of new materials. • Opportunities include leveraging probabilistic and multiscale models. • The most promising emerging manufacturing technologies are: out-of-autoclave and resin transfer molding for polymer matrix composites, thermoplastic automated fiber placement and dispersion of large filament count carbon fiber tows.
Prototype and Production Paradigms	
Glenn Isbell, Jr. - Vice President, Rapid Prototyping & Manufacturing Innovation Bell	• New technology unlocks innovation. • 4 frameworks are colliding – operations, certification, manufacturing, and technology. • Digital fabric needed in the design process. • Considering all of the information and digital advances, product development times have gotten slower. • Interactive design and virtual validation, enterprise digital mock-up (EDMU) is desired.
Development of Next Generation Aerostructures and Production Systems	
Eric Hein - Senior Director - Research and Technology, Spirit Aerosystems, Inc	• Spirit is a global company with 15,000 employees that supplies components to both Boeing and Airbus. • They focus on cost and need meaningful investment in product design that rapidly spans low Technology Readiness Level (TRL) to high TRL. • Key challenges include advanced architectures, system focused product development, material system optimization, development of ultra-competitive composite airframe structure and lean metallic structures, increased buy-to-fly ratio.
An Urban Air Mobility Vehicle Developer Perspectives	
Joe Brennen - Manufacturing Lead Joby Aviation	• Joby is developing an all-electric vertical take-off and landing (VTOL) vehicle with a 100-150 mile range for multiple (handful) occupants; expecting a “large” market. • Technologies of interest include additive metallic materials manufacturing, rapid (30 minute) cycle times for parts, snap curing, injection molding, weldable thermoplastics and lightning strike mitigation. • Energy density of current batteries motivates structural performance that is at least as good as current aircraft structures.

Concurrent symposia focused on forecasting the future of various technologies related to rapid manufacturing of metallic materials and composites followed the plenary session. Topic areas and specific sessions for the workshop are presented below.

2.1. Topic Areas

Session Topic Areas included:

- Manufacturing/processing methods
- Materials designed/developed for specific manufacturing/processing methods
- Design for specific manufacturing/processing
- Certification for materials, manufacturing/processing and application

The specific Sessions for each day of the metals and composites symposia included:

Day 1

- Metals: Manufacturing and Materials - Manufacturing/Processing Methods
- Metals: Manufacturing and Materials - Design/Development of Materials for Specific Manufacturing Methods
- Composites: Advanced Manufacturing Methods - Thermosets
- Composites: In-process Monitoring and Nondestructive Evaluation

Day 2

- Metals: Component Design and Certification - Component Design/Development that Exploits Manufacturing/Processing Methods
- Metals: Component Design and Certification - Certification for Materials, Manufacturing/Processing and Application
- Composites: Advanced Manufacturing Methods – Thermoplastics
- Composites: Process Modeling and Simulation of Advanced Manufacturing
- Composites: Panel Session on Testing Requirements for Advanced/Rapid Manufacturing Processes

2.2. High-Level Observations

The workshop resulted in numerous observations that may inform NASA decision making at various levels. While specific observations and recommendations from the workshop are included in the following sections of this report, several summary observations are given here:

Future Aircraft Materials, Design, Certification and Manufacturing

- Future aircraft will be heterogeneous with a combination of metals and composites that are manufactured using a myriad of approaches.
- Future production rates require improvements and streamlined relationships in aircraft design, materials, certification and manufacturing methodologies.

- Design, certification and manufacturing are inseparable and have to be considered as a unit.
- The commercial and urban aviation markets have similar challenges. While the rate of production and manufacturing approach is different, neither market can sacrifice structural performance to achieve faster production rates.
- Rapid manufacturing-related technology development is required as a national asset; manufacturing approaches and forms will evolve significantly during the next 20 years.
- The materials and methods identified for rapid manufacturing are broadly applicable to both the commercial and urban aviation markets. However, the specific materials and manufacturing needs for urban aviation are evolving as these vehicles continue to be defined whereas the needs are well known for the commercial aviation market.
- Maturity of required capabilities (manufacturing through certification) for new metallic forms lags that for composites; simulations are performed at different length scales for metals and composites. Multi-scale understanding of metals and composites is critical for rapid insertion of emerging materials/process methods.

NASA's Role

- NASA must understand key steps (sensitivities) in the specific manufacturing process to ensure that NASA investment is high payoff.
- NASA should invest in advanced materials and foundational methods (experimental and simulation) that are broadly applicable.
- NASA should focus on providing well-validated modeling tools to the community.
- NASA must strengthen its ability to transition from fundamental research to engineering and manufacturing capabilities; strengthen ties with academia and with industry, increase workforce training, internships and co-ops.

3. Metals Symposium

This section briefly outlines the topics considered during the four sessions of the metals symposium as listed in Appendix A1 (i.e., Manufacturing/Processing Methods, Design/Development of Materials for Specific Manufacturing Methods, Component Design/Development that Exploits Manufacturing/Processing Methods, and Certification for Materials, Manufacturing/Processing and Application). The Metals Symposium was organized into four inter-related sessions that included approximately 50 representatives from government (NASA, Department of Energy (DoE), National Institute of Standards and Technology (NIST), FAA, Department of Defense (DoD)), academia, and industry consisting of material producers, manufacturers and OEMs. Several pervasive observations, comments and themes were repeated throughout the four metals-related sessions. These included:

- Metals use continues … but their forms looking out to 2040 are not well defined.
    - Manufacturing approaches will evolve significantly during the next 20 years.

- NASA should invest in foundational capabilities that are broadly applicable; provide well-validated modeling tools.
- Rapid manufacturing means more than just faster fabrication (machine speed).
    - The entire design, manufacturing, certification cycle must be considered.
    - Ex. Time to field the GE Aviation Leading Edge Aviation Propulsion (LEAP) engine additively manufactured nozzle.
- Inter-relationship between design, material, manufacturing, certification.
    - True for composites…also true for new approaches for manufacturing metallic materials.
- As analysis capability has increased, it has slowed product development time.
    - How to reverse this trend?
- Design materials specifically for new advanced manufacturing methods rather than continuing to use legacy materials.
- Move toward designs that exploit advanced manufacturing.
- Understand key process parameters as a function of the production hardware.
- Need more communication between manufacturing, modeling and simulation communities.

In the remainder of this Section, an overview of the respective sessions in the Metals Symposium is given and the discussion topics relevant to the sessions are outlined. Based on the session presentations and the ensuing discussions among the participants, the following questions are addressed

- What are the most important factors or requirements that drive technology decisions?
- What are the biggest technology gaps? What are the barriers to adoption of new manufacturing processes?
- What is required to close these gaps? What should NASA contribute?

The discussion topics and responses to the aforementioned questions were used to identify potential areas of future NASA investments.

3.1 Manufacturing/Processing Methods

The focus of the session on Manufacturing and Processing Methods was to forecast emerging and envisioned metallic manufacturing and processing methods for advanced and rapid production of aircraft components. The session was chaired by Corbett Battaile from Sandia National Laboratories and Karen Taminger from NASA LaRC. Three speakers were invited from industry to highlight opportunities and directions from a forming producer (Scot Forge), an aerospace OEM (General Electric Aviation), and an automotive OEM (General Motors). Afterwards, discussion ensued on the topic of metallic manufacturing and processing methods with participation from the speakers and the audience.

3.1.1 New Manufacturing Approaches Discussed

To achieve high rate production of transport-scale aircraft, unitized structures, automation, eliminating part count and fasteners all contribute to reducing weight, increasing

production rates, and reducing cost. When considering high rate production and cost metrics, both the material and the processing costs must be considered together. For example, although aluminum is more expensive than steel, it has completely replaced steel in beverage cans due to lower process costs and time. Improving processing operations such as high precision castings, flow forming and forging can be used to form large-scale, near net-shape integral structures. Future opportunities strive towards net shape of advanced aircraft alloys, to reduce material waste and eliminate subsequent operations such as finishing and assembly. Assembly approaches, including welding, joining, and bonding, are candidates to eliminate fasteners and increase assembly time. Much of the discussion focused on topics related to additive manufacturing (AM). The primary discussion points included:

- Welding/joining/bonding – eliminate fasteners.
- Forming – flow forming, forging – forms large scale, near net-shape integral structures (towards net shape).
- AM – currently extensive activity in laser powder bed fusion-type methods; future will be more diverse with larger scale directed energy/wire or solid-state AM approaches becoming increasingly relevant in the next 10-15 years.
- Hybrid manufacturing – e.g., additive and subtractive manufacturing combined to produce net shape parts with good surface finish.
- Combined manufacturing – e.g., forming/forging combined with welding or AM.

3.1.2 What are the most important factors or requirements that drive technology decisions?

Technology decisions are driven by the OEMs, where in today's competitive environment, the primary focus is cost. There is an immediate need to improve production rate for commercial transport aircraft because the demand is projected to increase significantly in the foreseeable future. Although technology decisions are typically driven by performance, cost and rate, it may be impossible to simultaneously optimize all three. Key aerospace OEMs are willing to accept current materials or same weight (performance) to keep costs down and increase production rates. Costs are also weighed when adopting new technologies. For example, GE incurred very high costs to certify a new AM fuel nozzle in their LEAP engines. Some performance benefit was gained by the unique complexity and greatly reduced part count from using AM, but that did not offset the costs for this particular part. However, GE viewed the certification as a strategic investment which will pave the way for designing and building other components with AM. The primary themes are summarized as follows:

- Driven by OEMs; currently, the primary focus is cost (production rate is a cost).
- The industry is willing to accept current materials or performance to keep costs low.
- Performance can also be a constraint for specific applications (e.g., GE AM fuel nozzle in LEAP engine).

3.1.3 What are the biggest technology gaps? What are the barriers to adoption of new manufacturing processes?

The biggest technology gaps for adoption of new manufacturing processes are related to understanding new processes, availability of tools and cost to adopt. New materials and manufacturing processes are closely linked. Understanding the process physics and how key processing parameters influence resulting microstructures, mechanical properties and defects is necessary to be able to assess risks and rewards, and reduce uncertainty in new manufacturing methods and resulting materials. Product variability and incomplete understanding of new processes and materials are high barriers for obtaining qualification or certification for placing these new technologies onto commercial products. While new technologies are being assessed, conventional practices, such as machining, are continuously being improved. This has the net effect of reducing the benefits of cost or production rate with new technologies relative to conventional practices. Availability of appropriate modeling tools and real time sensors for in-situ process monitoring and post-fabrication inspection are also barriers to adoption of new technologies. Finally, the cost of capital equipment for manufacturing is very high. The more expensive the equipment, the more limited accessibility to use that equipment for research, because suppliers have to ensure capital investments produce return on the investment. In contrast, AM machines have become sufficiently affordable to allow many organizations to conduct research on AM. There is a need for modeling tools associated with high cost processes (such as forming and forging operations), which can significantly improve the production quality and rate if used appropriately. The primary themes are summarized as follows:

- Qualification and certification requirements
- Understanding of process, microstructure, property relationships
- Availability of tools (modeling and real-time sensors/inspection) to improve all manufacturing processes, not just AM

3.1.4 What is required to close these gaps? What should NASA contribute?

High speed, low cost sensors for real-time process monitoring, temperature management during forging, and die design for flow modeling material are helpful in all production steps and may be able to reduce post-fabrication inspection. Investment in advanced manufacturing equipment that is focused on research helps enable understanding of the interrelationships between materials and manufacturing on high-value equipment that is not accessible to most research groups. In addition to exploring new manufacturing methods, a business case needs to be made for new manufacturing methods, accumulating an experience "library" to help support decisions to adopt new manufacturing technologies. Technology and tool development to support aircraft applications, integration and model/data availability can accelerate product development cycles by modeling and simulation, and experimental validation and verification. The primary themes are summarized as follows:

- High speed, low cost sensors for real-time process monitoring is helpful in all production steps (can reduce post-fabrication inspection).

- Build business case for new manufacturing methods – accumulated experience "library" to help decision to adopt new manufacturing technologies.
- Technology and tool development is needed to support aircraft applications, integration and model/data availability.

3.2 Design/Development of Materials for Specific Manufacturing Methods

The focus of the session on Design and Development of Materials was to forecast emerging and envisioned metallic material forms that are designed and developed to be compatible with new methods for advanced and rapid production of aircraft components. The session was chaired by Eric Lass from NIST and Tim Smith from NASA GRC. Four speakers were invited to highlight opportunities and directions from the perspective of academia (Carnegie Mellon University), materials suppliers (Arconic and Constellium) and a NASA flight center (Jet Propulsion Laboratory). Afterwards, discussion ensued on the topic of material requirements and development with participation from the speakers and the audience.

3.2.1 New Materials Development Approaches Discussed

The industry experts who attended this workshop were adamant that more work was needed from research entities, such as NASA, in investigating other avenues of rapid manufacturing. Examples presented on numerous occasions were wire-fed processes and friction stir techniques. The idea that powder-bed processes alone would be the future of manufacturing was widely disputed. In fact, it was suggested that hybrid manufacturing processes (additive and subtractive) may have more potential as time progresses. The primary themes are summarized as follows:

- Currently, there is a strong focus among academia and government labs with powder bed processes, while new technologies (e.g., wire feed etc.) are ignored.
- There is a need for government labs to explore the less trendy manufacturing technologies.
- Can a model-focused approach (optimization, microstructural, etc.) lower future alloy development costs?
- Alloy systems for graded composition, location-specific properties, and multifunctional materials could be highly desirable for future AM applications.
- Hybrid AM technologies (additive and subtractive) are promising for improving quality and reliability of AM components (e.g. surface defects in fatigue-critical components).

3.2.2 What are the most important factors or requirements that drive technology decisions?

It was clear that cost was the main driver in technology decisions among industry. If a new manufacturing techniques could not immediately reduce costs for a company, then it would not be used/investigated. This included new alloy development. Even if a new alloy could be shown to have superior properties, participants of the session suggested a company would still balk at investigating it if they could still use the cheaper, inferior alloy instead. Another concern explored during the discussion was how resource intensive qualifying a

new alloy or manufacturing technique was. If the process could be optimized, requiring less time or money, then industry would be more willing to invest in new technologies. The primary themes are summarized as follows:

- Currently, cost is more important to industry than performance considerations.
- A new manufacturing technology must lower costs in order to be implemented by industry.
- Qualification and certification of new materials and component designs are extremely costly, creating a significant activation barrier to overcome for implementation.
- Current technologies work…why spend the money for incremental improvements.

3.2.3 What are the biggest technology gaps? What are the barriers to materials development?

Though current computational models are improving every year, they still lack the consistency and accuracy needed to independently improve or create new manufacturing processes and/or materials. A significant portion of this session's discussion focused on the lack of a coherent digital thread between different processes or models. It is still difficult to incorporate different length-scale models into a single effort. Another concern was the loss of academically produced modeling tools due to lack of funding or publicity. Could NASA work to provide a database where these tools could be uploaded, shared, and stored? Also, since these models are produced by separate groups that rarely communicate, their codes also do not communicate. This lack of communication means it is incredibly difficult to link different models together to improve the manufacturing process. Could a single language be adopted across industry, academia, and government labs to address this? The primary themes are summarized as follows:

- Industry did not appear to have a strong interest in specific alloy development.
- Cost seems to be a major barrier to materials development in industry.
- In AM, residual stress models appear to be somewhat mature. Need a stronger focus in thermodynamic/physical prediction models for rapid manufacturing applications and alloy development.
- Need improved mesoscale models on microstructural and alloy development for each new manufacturing method.
- Academia-developed modeling tools are powerful, but are often lost because of lack of sustainable resources, thus further development into something useful for industry rarely occurs.
- The computational modeling needs cannot be satisfied by a single code, but rather a series of modeling tools are required to cover the necessary time and length scales.
- Communication and exchange of data between modeling tools (i.e. output used as input in another) is currently very difficult, making it nearly impossible to link various tools, if they do exist.

3.2.4 What is required to close these gaps? What should NASA contribute?

From this session, a few opportunities arose where NASA may be able to have an impact. Improving and connecting the modeling tools used in these new manufacturing techniques represents a low risk but potential high reward endeavor. If these tools can be made reliable, then industry can reduce the resources necessary to qualify new alloys or manufacturing techniques. In addition, if NASA could qualify new alloys which are optimized for these new manufacturing techniques, then industry could employ them in new products at a much faster and cheaper rate. In the end, the American public would benefit from both endeavors. The primary themes are summarized as follows:

- The overall consensus throughout the discussion was that the modeling tools are likely to be the most impactful over the whole design space (Low risk – High reward).
- The modeling tools have the potential to transcend any specific focus.
- Could NASA act as a bridge between academia and industry for model development?

3.3 Component Design and Development that Exploits Specific Manufacturing and Processing Methods

The focus of the session on Component Design and Development was to forecast emerging and envisioned design paradigms that exploit new methods for advanced and rapid production of aircraft components. The session was chaired by Eddie Schwalbach from the Air Force Research Laboratory (AFRL) and Chris Lang from NASA LaRC. Four speakers were invited to highlight opportunities and directions from the perspective of academia (Johns Hopkins University and the University of Pittsburgh), other government agencies (Sandia National Laboratory) and an OEM (Boeing). Afterwards, discussion ensued on the topic of design and development with participation from the speakers and the audience.

3.3.1 Design Approaches Discussed

This session focused on the application and limitations of advanced design tools, such as topology optimization capabilities, for aerospace applications. Such capabilities have been under development for many years, and, while they can produce novel, highly optimized solutions to solve multi-physics design problems, a common challenge has been that the designs are not always practically realizable via conventional manufacturing methods due to geometric constraints. Advancements in additive manufacturing methods are easing some of these constraints with more widespread interest in application of advanced design methods, though new challenges are being uncovered. These issues were discussed in the current conventional approaches to design, and existing certification and qualification procedures described by industry participants. Some issues considered include:

- Largest benefit for cases requiring integration of multiple disciplines for design optimization and/or incorporation of numerous and appropriate design constraints for a given manufacturing process.

- Computational tool development with broad application across manufacturing processes (beyond additive manufacturing).
- Move away from deterministic designs, more explicit incorporation of uncertainty and robustness.
- Required level of testing to be guided by design, particularly for certification and the exponential growth in design complexity.

3.3.2 Most Important Factors/Requirements for Technology Decisions

The methods discussed above are primarily exercised during the design phase, but they ultimately impact costs and performance over the life-cycle of the component. As such:

- Design tools must incorporate aspects of the entire development and manufacturing cycle, including inspectability, manufacturability, and certification requirements.
- Component performance is not always the biggest driver; cost and lead-time for manufacturing and qualification can be significant.
- Process specifications are needed for design requirement.

3.3.3 Biggest Gaps/Barriers to Adoption

A number of technical gaps and barriers limiting the potential application of advanced component design methods were identified, including:

- Methods Development: Integration across design, manufacturing processing details, microstructure, and performance as well as verification and validation for optimization approaches.
- Certification: Lack of appropriate controls and standards for material, microstructure, process variation as well as inspectability of complex designs, including effectiveness of in-process inspection to reduce post-build testing.
- National Security: Maintaining technology development as a national asset.
- Hardware/Software Requirements: Availability of computing resources, secure access, and data format and translation.
- Education and Training: workforce training, adoption of methods in design practices, and building appropriate student expertise at universities.

3.3.4 Actions to Close Gaps

The vast majority of the work to advance automated design capabilities has been done in an academic sphere. Transitioning developments from this realm into industrial application will require a number of actions beyond continued maturation of design capability. Primary among these is bidirectional transfer of knowledge between industry and academia: better education of the industrial/applied workforce on design tool capabilities *and* limitations, as well as better informing the academic community about current design and qualification practice, including regulatory aspects. Specific actions include:

- Development of realistic *complex* problem definitions for the research community to address and develop, and test methods (e.g., a canonical example problem optimizing deflection performance in the linear elastic regime is not sufficiently realistic or complex).
- Bridging the gap between the research community and industrial design and development practices (e.g., technical interchange meetings, partnerships, industry participation at academic conferences).
- Fostering relationships between basic research and application through internships/cooperative education opportunities.

3.4 Certification for Materials, Manufacturing/Processing and Application

The focus of the session on certification was to forecast new certification paradigms that exploit deployment of components produced using rapid manufacturing methods. The session was chaired by Somnath Ghosh from Johns Hopkins University and John "Andy" Newman from NASA LaRC. Four speakers were invited to highlight opportunities and directions from the perspective of a NASA flight center (Marshall Space Flight Center), other government agencies (Sandia National Laboratory and the National Institute for Standards and Technology), and a public-private partnership (the Commonwealth Center for Advanced Manufacturing). Afterwards, discussion ensued on the topic of certification with participation from the speakers and the audience.

3.4.1 Challenges to Qualification and Certification of New Manufacturing Processes

Novel manufacturing processes like 3D printing and additive manufacturing (AM) are bringing dramatic changes to the manufacturing industry through their competency in near net-shape production of complex, customized parts and structures. These processes are able to fabricate finished products conforming to 3D computerized designs, while avoiding the need to engage expensive cutting tools, dies or molds. The unprecedented agility of these processes is enabling the realization of novel innovations in advanced design by methods such as topology optimization, and on-demand products. Furthermore, these processes are capable of delivering location-specific material microstructures that may result from concurrent structure-material optimization.

Despite their significant progress and promise, the qualification and certification of many of these processes in industrial applications have been impeded by serious challenges, such as variability in mechanical performance of components produced by nominally identical processes. These inconsistencies are typically attributed to subtle, yet characteristic variations in the material microstructure and defects, as well as imperfect surface topologies, which are consequences of input material impurities and/or fluctuations in process parameters. Improving product quality with a range of functionalities demands robust understanding of the connection between performance and life, material microstructure, and processing parameters. An important step towards this goal is the establishment of a robust digital thread framework, comprising physics-based multi-scale computational models coupled with structure-material design. This framework should be

able to quantify the process-material-performance/life linkage leading to better design of structure-material ensembles, along with the process to achieve this. It is necessary to efficiently integrate this process-material-product design framework with the certification process of high performance, multi-functional structural systems.

A step towards comprehensive qualification and certification that NASA can undertake is to build an integrated, multi-disciplinary computational modeling-design platform bridging multi-physics domains that transcend multiple length and time scales and efficient solution methodologies. Ubiquitous models, delineating common threads in the multi-physics problems will be pursued to create a unifying framework. Uncertainties in problem specification, related to process conditions, loading and material representation will be quantified and correlated among process and performance variables, and hierarchically transferred across scales. Advanced concepts of data analytics and machine learning should be an integral part of this framework. To meet demands of the large-scale computational problems, their iterative solutions and associated large data-sets, combined with highly optimized efficient codes with large computational resources, should be developed.

3.4.2 Areas Where NASA Should Invest for Visionary Advances

Qualification and certification technology areas in which NASA should consider investment, include:

- Develop efficient, validated spatial and temporal multi-scale, physics-based computational simulation-design framework for processing, materials, performance and life. Reduced order multi-scale models are necessary for cost-effective predictive and design capabilities, compatible with the certification process. Advanced methods of machine learning and data analytics should be integrated with this framework for comprehensive, yet optimal, constitutive and process models.
- Integrate rapid and effective uncertainty quantification with this framework to account for variabilities in material and process conditions on the structure-material design process.
- Integrate multi-scale modeling with structure-material design for location-specific material design in topologically optimized structures, along with process design for optimal performance and life in structure-material ensembles.
- Develop simulation-based methods for design and control of process parameters and routes to minimize variations and inconsistencies in material properties, especially extreme properties.
- Use this computational platform to develop new alloys optimized AM-compatibility, rather than continued use of wrought alloys developed for traditional manufacturing processes.
- Integrate this computational platform with multi-physics capabilities for effective NDE and certification of NDE methods.
- Engagement of industry in the development of the comprehensive platform for quick deployment in specific applications.

4. Composites Symposium

This section briefly outlines the topics considered during the five sessions of the Composites Symposium as listed in Appendix A2 (namely Advanced Manufacturing Methods – Thermosets, In-Process Monitoring and Nondestructive Evaluation, Advanced Manufacturing Methods – Thermosets, Process Modeling and Simulation of Advanced Manufacturing, Composites Materials Testing Requirements for Advanced/Rapid Manufacturing Processes). The Composites Symposium was organized into five inter-related sessions that included approximately 70 representatives from government (NASA, DoE, NIST, FAA, DoD), academia, and industry consisting of material producers, manufacturers and OEMs. Several pervasive observations, comments and themes were repeated throughout the five composites-related sessions. These included:

- Expanded use of unitized composite structure, which combines current smaller components and reduces part count, is required to meet rapid manufacturing and aircraft production goals.
- High rate infusion processes utilizing fast cure, stable, low viscosity resins combined with automated building of textile preforms is needed.
- Out-of-autoclave processing using advanced materials and prepreg technology will contribute to improvements in manufacturing rates.
- High rate automated tape placement (ATP) will be achieved with advanced materials designed for ATP, increased automation and real time process monitoring and control.
- Rapid, full scale inspection techniques with automated in-situ defect recognition and quantification/characterization is required for increase manufacturing rates.
- Increase use of continuous fiber thermoplastic materials manufactured by in-situ consolidation will provide primary structure at increased rate.
- Aligned, discontinuous fiber, thermoplastic materials should be utilized for critical secondary structure.
- Improved modeling and simulation technologies will benefit material and process selection to deliver high rate, complex unitized composite production.
- Modeling and simulation can be used to predict process parameters, effects of defects, and cure/consolidation quality.
- Generally, current testing methods will apply to rapidly manufactured composites, but new design concepts of complex unitized structure or new materials forms may require advanced test development (adhesive bonding, stitched then infused preforms, z-pinned reinforcements, thermoplastics with discontinuous fiber).
- Manufacturing processes must be stable and result in reproducible, high quality composites.

In the remainder of this Section, an overview of the respective sessions is given, followed by a summary of the session presentations. Based on the presentations and the ensuing discussions among the participants, discussion topics and potential areas of future NASA investments for each session are provided.

4.1 Advanced Manufacturing Methods - Thermosets

The Thermoset Advanced Manufacturing Session addressed the issues and opportunities for advancement/development of thermoset PMC manufacturing to afford increased production rates. The session was chaired by Dave Bertino from the Boeing Company along with Roberto Cano and Brian Grimsley from NASA LaRC. The session consisted of six presentations from industry leaders which addressed the following topic areas: Unitization of Composite Structure (which applies to any composite resin type), Infusion Processes, Out-of-Autoclave (OOA)/ Oven Cure, Rapid Cure/ OOA Materials, High Rate Processes such as Automated Fiber Placement (AFP) and Increased Cure/ Consolidation Rate Needs.

4.1.1 Summary of Presentations

The "State of Unitization of Composite Structure" was presented by Dan Hansen from the Boeing Company. From the commercial aircraft industry perspective, all current aircraft have the same low level of unitization. The low level of unitization results in the need for extensive assembly processes which not only require time, but also lead to increased weight from the assembly joints themselves. There is a significant need for much more unitization which requires both structural design and manufacturing advances. Current examples of unitized structures that are flying on commercial aircraft are limited to parts like the 787 Horizontal Stabilizer and C17 Doors. Increased unitization will result in more complex parts. In a current manufacturing process like AFP, the geometry of the part plays a significant role in the amount of steering required to maintain the fiber design angle, or rosette. Increased steering and complexity during placement of unitized structure will increase the risk of out-of-plane defects like puckers and wrinkles especially if the tow width is increased to improve production rates. These changes in manufacturing conditions will necessarily increase the value of validated physics-based process models to simulate the AFP process for the purpose of optimizing both the manufacturing process and probable need for new material development to improve placement (tack) characteristics.

"Technology Needs to Enable High Rate Infusion Processes for Aerospace" was presented by Wendy Lin from GE Aviation. This talk was focused on jet engine applications, which utilize much smaller parts than commercial transport aircraft. Notwithstanding focus of the talk, industry needs for increasing production rates with infusion processes such as resin transfer molding (RTM) include: advanced pick and place of textiles for RTM and new resins with long processing windows, low viscosities, increased toughness and fast cure rates. There is currently a large technology gap in resin infusion with current quick cure resins. These resins do not possess the required characteristics for structural applications. There is also a need for improved tackifier technology to aid in lay-up as well as improved stitching/knitting yarn technology for preform manufacture. It is important to note that the current size of infused structural parts being fabricated using this technology are on a smaller scale than other processes.

Industry has looked at utilizing infusion for larger scale composite structure but has not had reliable success (due to high scrap rates). There is a clear need for further development for commercial aircraft and a huge potential for urban air mobility which will utilize smaller structure.

"Out-of-Autoclave/Oven Cure Prepreg Technology for Composite Manufacturing" was presented by Kyle Magnuson from RUAG US. Although some companies like RUAG are embracing OOA composite technology, OOA technology and composites in general still require more buy-in within NASA and industry. Increased pull and industry available technology such as public databases can increase the use of composite technology outside aerospace, which in turn generates innovation from these other industries. There is still a need for new and improved resin technology, especially resin systems with faster cure cycles that maintain the needed processing characteristics and provide the required mechanical properties. NASA has a history of, and can serve an important role in, structural resin development and characterization.

An assessment of "Rapid Cure/Out of Autoclave Material Development" was presented by Damon Call from Toray Composite Materials America. Toray and others in industry are willing and eager to help develop materials for specific needs including faster cure resins and materials specifically designed for AFP. However, these types of material development efforts require a clear market pull from industry and government. Without a well-defined market, it becomes difficult to commercialize new material products. As noted above, NASA has demonstrated expertise in development and characterization of high-performance aerospace resins and PMCs. In partnership with resin suppliers and the OEMs, NASA could play a significantly useful role in resin characterization and screening of PMCs fabricated using these new resin candidates and help fill this persistent gap of identifying new product concepts that meet the requirements of industry.

"High Rate Lay-up Processes for Composite Needs" was presented by Keith Young from the Boeing Company. The simple message from industry is "less people and more automation." Current manufacturing of aircraft relies heavily on labor. Increasing the use of automation during manufacture can greatly enhance production rates. However, to realize increased automation in composite manufacturing, two areas must be addressed. First, materials specifically designed for automation must be developed. Currently, most automated processes utilize material initially developed for hand lay-up or slightly modified versions of these same materials. Second, there is a need for process models for lay-down/manufacturing. Developing materials specifically designed for automation and developing the model capability to accurately simulate manufacturing technologies would aid greatly in increasing production rates. As industry pushes for more automation, this will drive requirements to fabricate more complex-curvature parts that are defect-free, or with acceptable AFP defect specifications. Currently, the effects of these types of out-of-plane defects on mechanical performance are not well understood, and therefore result in highly conservative design. To increase the use of AFP, the manufacturing process needs to be optimized and the effect of manufacturing defects needs to be better understood so that industry can make better use of design tools which incorporate manufacturing defects, i.e. Design for Manufacturing (DFM). In addition, the push

towards higher automation, provides a "digital thread" that increases the value and utility of validated physics-based process models to simulate the AFP process for the purpose of optimizing both the manufacturing process and possibly requires new material development to improve processing characteristics. Results from validated physics-based process models can be linked with existing design simulation tools to close the loop on DFM. DFM is readily applicable to the AFP process because of the digital thread but can also be applied to any manufacturing process that is defined by the laws of physics and polymer material behavior.

An industry assessment of "High Cure/Consolidation Rate Processes for Composite Needs" was presented by Blake Slaughter of the Boeing Company. To increase composite process rates, industry requires new fast cure resins with current state-of-the-art (SOA) mechanical properties. Current fast cure materials do not meet the mechanical property requirements of primary aerospace structure. Increased production rates could also benefit from the ability to cure resins based on the state of the chemistry (percent cure) instead of the current processes based on time. Also, there is a need for OOA-oven cure resins specifically designed for automated processes like AFP. Another area of development that would greatly increase composite production rates is fast heat-up/cool-down tooling technology. The time to heat-up and cool-down parts/tooling are a large portion of the production time for curing composite structure. In recent work to understand the physics guiding the AFP process, the tack of the composite slit-tape has been identified as playing a major role in the formation of defects during this process. An aerospace polymer resin possessing tack characteristics, including flow and cohesion strength that can be more readily tailored to the placement temperature range between 70 and 150°F would be of significant benefit to optimizing the AFP process. Combined with improved control of the material heating during the process, the AFP lay-down rates would be significantly increased.

As pointed out by all the industry speakers, increased production rates for thermoset composite structure require a suite of advanced technologies that work together to improve production rates at various stages. Unitization, increased robust automation with higher throughput, and improved fast cure resin technology are three critical areas of need for improved production rates. However, these improved technologies will also need improvements in other areas such as tooling technologies that can fully utilize their advantages. Eliminating the need for an autoclave is also a very key component since it often is a limiting step in terms of time and part size. An underlying need for all these technologies is enhanced simulation/modeling capabilities. To reach the type of production rates envisioned to meet future needs, all these areas must be advanced. NASA has expertise in all these areas and can help advance unitized structural design, increased production rate fabrication technologies and fast cure OOA structural resin development. It should be noted that although most of the discussion in this session revolved around commercial aircraft, urban air mobility vehicles would need/benefit from similar types of advancements.

4.1.2 Discussion Topics and Potential Areas of Future NASA Investments

Several topics were identified for future NASA investment, including:

State of Unitization of Composite Structure:
- Current aircraft have the same low level of unitization and need much more.
- The Boeing 787 horizontal stabilizer and C17 doors are examples of unitized structures.

Technology Needs to Enable High Rate Infusion Processes for Aerospace:
- Advanced pick and place of textiles for RTM
- New resins: long processing windows, low viscosities, increased toughness, fast cure
- Large technology gap in infusion with current quick cure resins
- Improved tackifier technology
- Stitching/Knitting yarn technology for preform manufacture

Out-of-Autoclave Prepreg Technology in Composite:
- More buy-in to composites within NASA and industry
- Public databases
- New resins, faster cure, improved mechanical properties

Rapid Cure/ Out of Autoclave Material Development
- Toray is willing to help develop materials for specific needs, faster cure resins, materials designed for AFP.
- Developments require industry/government pull (clear market) to commercialize new products.

High Rate Lay-up Processes for Composite Needs
- Less people, more automation.
- Materials specifically designed for automation.
- Process models for lay-down/ manufacturing.

High Cure/ Consolidation Rate Processes for Composite Needs
- New materials, fast cure resins with SOA mechanical properties.
- Cure to state, not time.
- OOA-Oven cure resins specifically designed for AFP.
- Fast heat-up/cool-down tooling technology.

4.2 In-Process Monitoring and Nondestructive Evaluation

The “In-Process Monitoring and Nondestructive Evaluation” session was chaired by Todd Rudberg from Electroimpact along with Tyler Hudson and Peter Juarez from NASA LaRC. The session consisted of three presentations from industry leaders which addressed the following topic areas: In-situ Quality Assurance (QA), Digital Manufacturing & Structural Health Monitoring, Fiber Placement, Industry Standards, Predictive Maintenance and

Reduced Inspection Requirements, and Automated Technologies for Manufacturing, Material Characterization, and Structural Certification.

4.2.1 Summary of Presentations

"Composites Circle of Life" was presented by John Tyson from Trilion Quality Services. The talk was focused on four areas: i) The composite build with in-situ quality assurance using 3D shape detection and defect detecting primarily using digital image correlation (DIC) and photogrammetry; ii) Digital assembly/digital twin with precision guided assembly and an as-built digital thread; iii) Structural testing to reduce schedule and costs by improving the amount and quality of the data collected; iv) Structural health monitoring using enhanced visual inspection with history and predictive maintenance.

"Electroimpact's Vision for Fiber Placement, Industry Standards, Predictive Maintenance and Reduced Inspection Requirements" was presented by Todd Rudberg from Electroimpact. He discussed AFP capacity and management as well as current developments to double machine utilization. A significant portion of this presentation was focused toward on-head inspection for laps, gaps, and tow add/cut locations. A salient point made in the presentation was that AFP cell time utilization currently (typical and exemplary) is significantly less than the utilization needed by industry. The typical cell time per build currently is 42% for inspection and data review, 8% for operator breaks, 17% for reliability recovery, 17% for tool moves/wait, and only 19% for layup time. Even exemplary present-day performance has 28% for inspection and data review and 42% for layup time. The utilization that industry needs is 8% for inspection and data review, 0% for operator breaks, 8% for reliability recovery, 8% for tool moves/wait, and 76% for layup time.

"Automated Technologies for Aerospace Structures: Manufacturing, Material Characterization, and Structural Certification" was presented by Waruna Seneviratne from the National Institute of Aviation Research (NIAR), Wichita State University. He provided an overview of the work going on at NIAR. For in-process inspection tools, current research projects are focusing on digital manufacturing twin/digital thread framework, increasing manufacturing efficiency, and machine learning algorithms for process optimization.

Topics discussed in detail during the open floor discussion included:

- Real Time Process Monitoring and Control: Material tracking/process monitoring/digital thread at every step from material acceptance/screening through delivery/service is needed. For incoming raw material, in-situ process monitoring is needed to reduce material variability because small material variability per ply can have compounding effects on thick laminates. During laydown, in-situ, automated foreign object debris (FOD) (e.g., net poly backing paper) detection is critical. During cure, in-situ cure process monitoring is needed especially with regard to new material systems (e.g., rapid cure) and architectures (e.g., Out-of-Autoclave, stamping, RTM).

- Tools for more rapid assembly: i) Rapid assembly of parts with real-time feedback maintaining correct positioning/quality; ii) Geometry, dimensioning, and tolerance tracking throughout assembly via computer vision/photogrammetry analysis.

- Rapid NDE Techniques: Techniques included large scale automated thermal inspection of structures, computer simulation aided inspection of problematic inspection use cases, and use of simulation for design-for-inspectability.

- Inspection Data Analysis Automation: Automated data analysis is critical for rapid manufacturing with high quality. Tools needed include automated, in-situ, defect recognition and quantification/characterization, linking nondestructive inspection (NDI) results to material state or material strength to make quicker and more informed decisions, and machine learning based parameter estimation for process efficiency improvement/variability reduction.

- Summary: Provide the technology to enable better process development and monitoring by delivering new data on process inputs/outputs at each step of the manufacturing process (i.e., material screening, laydown, cure, and assembly).

4.2.2 Discussion Topics and Potential Areas of Future NASA Investments

Several topics were identified for future NASA investment, including:

Real Time Process Monitoring and Control
- Material tracking/process monitoring/digital thread at every step from material acceptance/screening through delivery/service
- In-situ process monitoring for raw material production to reduce material variability (small material variability per ply can have stack-up effects on thick laminates)
- In-situ FOD detection during laydown (such as net poly backing paper)
- In-situ cure process monitoring especially with regard to new material systems (e.g., rapid cure) and architectures (e.g., OOA, stamping, RTM)
- Quantifying the process variability and final part mechanical properties relationship
- Real-time feedback/tools for more rapid assembly of parts while maintaining correct positioning/quality.
- Geometry, dimensioning, and tolerance tracking throughout assembly via computer vision, photogrammetry analysis

Rapid NDE Techniques
- Large scale automated thermal inspection of structures
- Computer simulation aided inspection of problematic inspection use cases
- Use of simulation for design-for-inspectability

Inspection Data Analysis Automation
- Automated in-situ defect recognition and quantification/characterization
- Linking NDI results to material state or material strength to make quicker and more informed decisions

- Machine learning based parameter estimation for process efficiency improvement/variability reduction

Overarching requirement

- Provide the technology to enable better process development and monitoring by delivering new data on process inputs/outputs.

4.3 Advanced Manufacturing Methods - Thermoplastics

The "Advanced Manufacturing Methods - Thermoplastics" session was chaired by Sam Tucker from the Boeing Company and Rob Bryant from the NASA LaRC. The session consisted of five presentations from industry leaders which addressed the following topic areas: Thermoplastic Composites, Tool-less Thermoplastic Manufacturing Utilizing Continuous Fiber, Thermoplastic Composite Tapes for High Speed Manufacturing, Rapid Manufacturing of Composites for Aerospace Applications and Innovations in Automated Fabrication of Composite Structures.

Over the past decade, there have been dramatic improvements in both the quality of thermoplastic prepreg tape and ATP robotics. This has allowed the advantages of fiber reinforced thermoplastic composites (FRTCs) and OOA in-situ processing to be used for aerospace FRTC structures. This technology continues to grow due to the economic advantages associated with reduction of scrap, near infinite shelf life, reusability, reduction in manufacturing equipment investment, higher rates of production from tape to part, and increased structural customization. These factors have allowed overseas technology investments for the production and supply of structural FRTCs to surpass that of the US aerospace industry.

As an example, FRTC panels produced by the European-based GKN are used by Airbus and Gulfstream, and advanced manufacturing of FTRCs continues to increase in the aerospace/non-aerospace sectors. In fact, Europe has targeted the year 2025 for introduction of a commercial transport into the market that relies on FRTCs. This places the US aerospace industry in a precarious competitive situation of either playing catch-up, or figuring out a way to displace the current SOA composites with a technological advancement providing a greater economic advantage.

The major advantage of using FRTCs as a cornerstone of rapid advanced manufacturing technology are the economics associated with equipment investment, idle inventory, production throughput, labor (automation), and lifecycle (service life, disposal, reuse). However, there are several challenges associated with the implementation of FRTCs when displacing or augmenting their thermosetting and metallic counterparts. The challenges consist of:

- Making FRTC structures with performance properties equal or better than current materials offer, at lower cost.
- Integration with current materials and manufacturing processes.
- Certification of new manufacturing processes using alternate materials.
- Geometry-independent build consistency.

- Maintaining dimensional control by removing the effects of thermally induced strain resulting from coefficient of thermal expansion (CTE) anisotropy and resin crystallization.
- Incorporation of different material forms.
- Direct incorporation of subcomponents reducing manufacturing steps.
- Using reusable scrap for aerospace applications.

This framework of rapid advanced manufacturing of FRTC technology relies on quality weld bonding to reduce the need for hard tooling, and the ability to integrate patch or part placement as needed. This places emphasis on allowing for in-situ rework and build adjustments during production using process monitoring with closed loop feedback. By combining the advantages of FRTC with rapid advanced manufacturing results in the cost effective mitigation of post-processing, hard tooling, manufacturing support infrastructure, and reusability.

4.3.1 Summary of Presentations

John Geriguis (General Atomics) outlined their developments in an automated tool-less manufacturing process to create complex structural components using two robots working in tandem. There were several key aspects indicated:

- The developmental steps demonstrating the automated "tool-less" process was done outside the US.
- The process technology did not have in-situ process feedback control.
- The process demonstrated the use of a variety of thermoplastic resin prepregs.
- The fabrication of a complex geometrical FRTC was demonstrated.

General Atomics view FRTC as a cost effective way to reduce weight, increase durability and longevity, and lower the costs of manufacturing and customization of their airframes. Additionally, advancement of the rapid economic manufacture of aerospace FRTCs in the US requires collaborative partnerships. An example was that General Atomic's "Tool-less" thermoplastic manufacturing concept started in 2010, but until NASA took an interest in its development, there was no significant momentum or progress from the private sector.

Jim Mondo (Tencate/Toray) discussed the advances made in thermoplastic tape, both in quality and resin chemistry and the benefits of durability, superior strength and toughness of composite structure, and lower costs associated with tape production. Currently, thermoplastic tape optimization continues in concert with the increased use of advanced manufacturing processes allowing for the increased incorporation of thermoplastic composites into the current generation of air vehicles. Within the US aerospace industry, the current use of FRTCs is in secondary structural applications for large transports. These include brackets and other support structures that require increased shear strength without a weight penalty. Also shown were large structural panels, the required technologies used to produce them, and where future primary FRTC structures will be used on next generation aircraft.

Jim Pratte (Solvay) outlined developments in engineering thermoplastic-based production resins to support aerospace FRTCs. Detailed process technology growth achieved by combining continuous process technology with "autoclave quality" parts was discussed. Their value proposition is:

- Decreased cycle time reducing manufacturing costs.
- Reduction in parts count via 'weld" building and integration of components.
- Potential recycle and repair.
- As a base and formatted material supplier, Solvay is in support of all thermoplastic production processes as the fabricators decide what process is best for their parts:
  - In-Situ (tool-less)
  - ATP (tool supported)
  - Press and stamp molding
  - Welding (joining of individual subcomponents)
  - Continuous compression molding
- Solvay is investing in thermoplastic technology as the best future option for commercial aerospace in terms of cost and weight savings and is moving towards production of large structural FRTCs.

John Melilli (Composite Automation) outlined current developments in automation based on in-situ robotic placement and consolidation of thermoplastic composite tape and patches to build structural components. The current issue is that complex composites require extensive hand labor, which introduces workmanship variability, increased time, and cost. Large thermoplastic aerospace parts (made mostly in Europe) are made using ATP OOA technology, along with parts using thermoplastic prepreg patches. Also discussed were ATP consolidated FRTCs with void contents of approximately 1.2% (<2% is aerospace standard) by volume. There were several specialized robotic head systems shown that were application specific and used for specialized geometric applications.

Wenping Zhao [United Technologies Research Center (UTRC)] discussed both current and future products, manufacturing technology, and potential implementation of FRTC that will benefit their aerospace products. Several issues that address the technology needs required to continue the advancement of FRTCs were discussed. These include:

- UTRC's strong interest in in-situ FRTC processes.
- Challenges with current thermoplastic composites such as comprehensive and quantitative understanding of the effects of in-situ processing defects.
- Enabling technology development areas such as fusion welding, NDE, process modeling, etc.

UTRCs current outlook for air vehicles is the increased production of aircraft based on Boeing and Airbus market analyses. The future need of increased air mobility will require methods that increase the economic rate of production of aircraft.

Summary:
Several advantages for using advanced manufacturing robotics has resulted in aerospace FRTCs gaining increased use. This increased use directly relates to out-of-autoclave (OOA) processing in combination with the unique chemistry of thermoplastic materials that:

- Allows the consolidation of FRTCs without additional complex post-layup processing.
- Allows reforming, recycling, and reuse of FRTCs.
- Increases overall parts production since layup rates are part independent.
- Demonstrates a "tool-less" manufacturing process.
- Reduces part count and the ability to integrate subassemblies into structural components.

The presenters indicated that they are investing in thermoplastic composites, and welcome NASA's assistance in collaboration with industry and academia to provide the following:

- The implementation and oversight of a Public/Private research program similar to Europe's highly successful ThermoPlastic Composites Research Center (TPRC). Several US institutions are paying members to this international consortium, as none exists in the US.
- Assistance in locating at least one research facility that would allow for workforce training and prototyping.
- Help in increasing the acceptance rate of thermoplastic composites or thermoplastic-based hybrid parts and structures into the aerospace market.
- Co-development of tools for closed loop process monitoring, in-situ inspection, and certification.

NASA does not have the equipment or specific expertise to help conduct all areas of this research at any facility. Therefore, this capability needs to be internally funded, co-funded as a partnership within the US, or both. To this end, the industrial/academic partners indicated that they are willing to help develop critical areas specific to NASA needs. This is in concert with the proposed NASA composites investment portfolio; see sub-section below.

4.3.2 Discussion Topics and Potential Areas of Future NASA Investments

Several topics were identified for future NASA investment, including:

- Thermoplastic tape enhancement and post process quality assurance
- Rapid layup resin chemistry/surface preparation
- Closed loop welding, in-process control, inspection, and repair
- Integration of different materials to develop hybrid/multifunctional structures
- Monitoring and modeling process effects on in-situ consolidation
- Scalable part manufacture
- Out-of-autoclave processing
- Lower cost tooling and hybrid molding
- Direct integrating of other components

- Repair and recycling
- Rapid certification methodology

4.4 Process Modeling and Simulation of Advanced Manufacturing

The Process Modeling and Simulation of Advanced Manufacturing Session addressed the issues and opportunities for advanced materials modeling and composite manufacturing simulation to afford increased production rates. The session was chaired by Bryon Pipes from Purdue University and Frank Palmieri from NASA LaRC. The session consisted of two presentations from industry and academic leaders which addressed the following topic areas: Simulation/Process Modeling for Improved Manufacturing Rate and Modeling/Simulation of Liquid Composite Molding Processes for Advanced Manufacturing.

4.4.1 Summary of Presentations

The process modeling session focused on i) understanding how computer-aided simulation of composites manufacturing processes can improve overall manufacturing rates and ii) identifying the greatest barriers preventing process models from full success. Sam Tucker, manager of the Boeing Company Next Lab, presented information on modeling needs and areas of potential impact on manufacturing. Professor Suresh Advani of the University of Delaware presented recent developments in modeling to improve RTM processing of complex parts with reduced development time. The subsequent discussion, led by the session chairs, covered the following topics and observations. Although the process modeling session was brief, the audience and speakers were highly interested in the topic.

The session highlighted, in multiple ways, how process modeling is expected to reduce the time and cost associated with developing new manufacturing processes. An accurate and detailed process model (for any given process) could greatly reduce the number of large-scale/full-scale development trials needed for process development. The models themselves do not necessarily increase the ultimate rate of manufacturing, but new manufacturing technologies designed to increase manufacturing rate may be developed, qualified, and brought online much faster when supported by simulation than using a traditional, experimental only approach to process development. Moreover, new technologies with the potential to increase manufacturing rate may be too complex and costly to develop solely by experimental means. Therefore, accurate and comprehensive process modeling may be critical to developing certain, high-rate manufacturing technologies. In other words, the technical barriers to process modeling translate into cost barriers to develop high-rate composites manufacturing methods.

Manufacturers need accurate, validated models to predict laminate defects that occur during composite fabrication stages such as deposition, RTM, cure, and bonding. Although NASA is not a leader in developing simulation software for these processes, NASA has exceptional expertise in fabrication, characterization, and metrology

technologies needed to develop and validate models developed by external partners. Simulation technology is needed to predict how defects that occur during manufacturing, such as fiber placement defects, porosity, and fiber waviness, effect the structural properties of the final part. NASA has expertise in characterizing and testing composite structures and material properties to develop and validate an effects-of-defects simulation whether it is developed in-house or in cooperation with external partners.

In some cases, simulation tools are available to manufacturers, but potential users lack the material property databases for the specific material systems they are using. Property characterization of materials (mechanical, physical, environmental) is a slow and expensive task for manufacturers because of the costly characterization equipment and expert personnel required for the work. NASA maintains laboratories with state-of-the-art tools and capable staff to properly characterize new materials. Multiple comments were made during the session about the generation of "material cards" using a process analogous to National Institute of Aviation Research's (NIAR) National Center for Advanced Materials Performance (NCAMP), which resulted in the generation of a public database of properties used widely by the modeling community.

Atomistic-scale models can rapidly predict material properties of nano-scale systems without the need for experimentation, but methods are lacking to integrate atomistic models into micro-scale and continuum level models needed by manufacturers. NASA is committed to multi-scale modeling development and has recently released the Vision 2040 report*, which describes the path to full integration of nano-scale modeling into full-scale structural analysis.

Related specifically to parts fabricated by RTM, process models have been developed to reduce process development time and to improve product quality. These models determined that successful resin infusion processes (number and location of infusion and bleed ports on a part) can be predicted with little or no experimental testing required. The models used algorithms to predict where race-tracking of resin (flow around instead of into the carbon fiber preform) will occur and where slow resin filling is expected. Some of the results were highly non-intuitive, but shown to be correct upon experimental validation.

4.4.2 Discussion Topics and Potential Areas of Future NASA Investments

Several topics were identified for future NASA investment, including:

Industry needs:

- Models to advance rate of manufacturing through selection/development of high rate processes.
- Prediction of processing defects during laydown, molding, cure, fabrication, etc.
- Prediction of material properties from process parameters and effects of defects.

* Vision 2040: A Roadmap for Integrated Modeling of Materials and Systems, Prepared by NASA, Pratt & Whitney, Nexight Group, BlueQuartz Software, and ESI Group

Modeling improvements needs:

- Bridging between molecular and continuum mechanics (NASA's Vision 2040 aligned).
- Continuity between models: outputs don't convey to inputs easily.
- Capability to merge physics-based and data-based modeling methods.

Areas to be addressed by NASA to enhance materials modeling include:

- Documentation of open-source software?
- New materials characterized for models (material card generation).
- Extension of NCAMP-like materials database to enhance simulation capability.
- Troubleshooting guide for model-to-process matching "Rosetta Stone".
- Application of process models is limited by integration (software) and ignorance (lack of physical understanding).
- NASA as a pathway to disseminate and integrate modeling and material data for the industry.

4.5 Composites Materials Testing Requirements for Advanced/Rapid Manufacturing Processes

The Composites Testing Requirements Panel Session was chaired by Steven Wanthal from the Boeing Company, Waruna Seneviratne from the National Institute for Aviation Research, and James Ratcliffe from NASA LaRC and explored issues pertaining to the effect of implementing rapid manufacturing techniques, including use of new materials, on testing requirements for composite materials. The session was conducted in an open panel format, covering various topics on testing of composite materials, including additive manufacturing, new materials, Integrated Computational Materials Engineering (ICME), AFP materials, and the building block design approach. The panel session was tailored by the chairs on the basis of details gleaned from the preceding sessions of the workshop.

4.5.1 Summary of Presentations

The panel session, opened by Steve Wanthal and Waruna Seneviratne, began with a discussion covering general concerns regarding the implementation of significantly enhanced airframe production rates and methods to enable such production rate enhancements. An initial concern is that the resulting manufacturing process must be stable and result in a repeatable structure that is designed using a validated analysis framework that can account for expected manufacturing variations. Failing to ensure this may lead to reduction in target production rates due to additional testing possibly required to substantiate components at various stages of the building block approach that do not meet design requirements.

Discussion took place concerning the possibility that new manufacturing processes, including materials needed to help affect a production rate enhancement, may require development of new test methodologies. The general consensus was that existing test

methods (used in the production of conventional structures) would likely be applicable to any other manufacturing process and material system, although some manufacturing techniques (resin film infusion (RFI), non-riveted adhesive bonding, stitching) and certain material systems may require modification of existing test methods to ensure proper and accurate measurement. An example of this is the generation of input data for analysis frameworks being applied to stitched or z-fiber reinforced laminated structure. In these cases, certain test methods based on linear material models, such as those for measuring interlaminar fracture toughness, may require modification to accommodate for behaviors such as large-scale crack bridging or large deformations. Possible nonlinear behavior of certain thermoplastic-based material systems may also present challenges to established test methods that assume linear, time-independent material behavior. Such issues will be readily avoided by assessing the suitability of established test methods for these cases.

Additive manufacturing techniques may yield structure that exhibit material properties that vary with the nature of a build (for instance, if properties become functions of part volume), and thus additional testing may be required to establish these properties on a build-by-build basis. Additionally, material property databases will be required for new material systems implemented as part of a strategy of increasing production rates. The cost and time of associated coupon testing will have to be reduced.

ICME practices that are being proposed as part of an enhanced production rate manufacturing process will require empirical input data, possibly necessitating development of new test methods. Validation test campaigns will also be required. A clearer understanding of the testing burden associated with ICME is needed.

The impact of the use of unitized structure on the testing burden was also discussed. Such structure, consisting of non-riveted, adhesively bonded joints, in addition to the associated adhesive materials, will require suitable characterization testing methods.

The remaining discussion centered around the overall impact of the above issues on the nature of the design building block approach and whether or not the approach needs to be reimagined in light of possible testing challenges faced with increasing production rates. First, additional layers to the building block may be needed to accommodate testing required to validate new analysis methods, particularly those involving length scales not considered in conventional design approaches (such as with molecular modeling techniques). Second, merging of some building block levels may be required in order to include necessary details at the would-be coupon level. This will depend on the strategies adopted in the design analysis framework. For example, approaches that smear through-thickness properties of stitched structure will require modified test coupons that include a sufficient amount of detail (e.g., stitching detail, z-fiber detail, etc.) to allow for the required quasi-coupon level property to be captured. Lastly, the upper levels of the building block may be affected by the need for comprehensive testing of as-built parts under realistic loading conditions in order to evaluate unitized structural components. Such testing will require extensive integration of NDE methods and will pose a cost risk

to the design and certification process. Steps needed to mitigate this possible issue will have to be considered.

4.5.2 Discussion Topics and Potential Areas of Future NASA Investments

Several topics were identified for future NASA investment, including:

- A validated analysis framework that accounts for expected manufacturing variations providing a stable manufacturing process and repeatable structure.
- New test methods that support design concepts, materials and manufacturing methods wherein methods that have been developed for conventional structures are not applicable.
- Assessment of the effect of alternative manufacturing techniques (RFI, non-riveted adhesive bonding, stitching, etc.) on current testing practices.
- Determination of new test methods and/or modifications of existing methods required to generate experimental input data for a design analysis framework, e.g., measuring effective properties needed for analysis of stitched or other z-reinforced structures.
- Additive manufacturing.
  - Material property measurement representative of a build.
  - Testing of gradient structures.

4.6 Composites Symposium Wrap-up Discussion Summaries

In an effort to organize the meeting wrap-up composites discussion into a manageable set of topics, a suggestion was made to develop categories that describe all the activities that can be considered elements of rapid manufacturing. The workshop attendees agreed to categorize composite rapid manufacturing into seven elements. During the discussions, sub-elements were identified for each major element. A list of these is shown below. In addition, during this discussion, a list of potential research activities of which NASA can make a contribution to the rapid manufacture of composites was assembled. This list is also shown below.

Structural Architectures – Structures Designed for Efficient Manufacturing, Reduced Part Count, Unitized Structure

- Architectures including unitized concepts
- Welding, bonding, stitching, fastening, co-curing, over molding
- Complex curvature composite design and manufacturing
- Rapid joint assembly concepts, automated/reproducible/qualified surface treatments for bonded structures
- Nonlinear stiffeners or minimally stiffened composite structures
- Aggressive, non-traditional laminates
- Architectures designed for rapid manufacturability
- Analytical validation & testing at multiple scales

Research activities where NASA can contribute:

- Architectures including unitized concepts
- Welding, bonding, stitching, fastening, co-curing, over molding
- Complex curvature composite design and manufacturing
- Rapid joint assembly concepts
- Minimally stiffened structures
- Aggressive non-traditional laminates
- Design for rapid manufacturability
- Analytical validation & testing at multiple scales

Material Development – New Materials for Rapid Cure and/or Process Methods

- New and advanced thermosets (infrared, ultraviolet, thermally conductive, quick cure)
- New and advanced thermoplastics (low melting, amorphous, low viscosity, repairable, recyclable)
- Formable materials (new weaves, braids, and preforms)
- Lower cost fibers and hybridized composite layups
- Mechanical testing of new material forms and concepts

Research activities where NASA can contribute:

- Advanced resins (infrared, ultraviolet, conductive, quick cure)
- Formable materials (New weaves, braids, and preforms)
- Lower cost fibers and hybridized composite layups
- Carbon fiber tows with high fiber counts (24K, 36K, 48K)

Laydown Rate and Forming – Fast Ply-by-Ply Builds and Complex Structure Forming/Stamping

- Simulation and process modeling
- Effects of defects and tolerances
- Material forms, non-traditional laminates
- Advanced instrumentation and test methods for material characterization
- Material equivalency or benchmark testing
- Structural element level fabrication and testing

Research activities where NASA can contribute:

- Simulation and process modeling
- Effects of defects and tolerances
- Material forms, non-traditional laminates
- Mechanical testing of new material forms and concepts
- Advanced instrumentation and test methods for material characterization.
- Material equivalency or benchmark testing
- Structural element level fabrication and testing

Cure Cycle, Consolidation and Tooling – Rapid Cure Thermosets or Thermoplastics, Low Consolidation Pressures, Intelligent Tooling, Modeling

- Simulation and process modeling
- New/improved resins and computational materials
- Rapid out of autoclave cure
- Resin infusion methods for complex structures
- Tooling concepts including thermal management
- Mechanical testing of new materials and concept
- Automated, thermoplastic tape in-situ consolidation processing
- Bag-less consolidation
- Process optimization including thermal effect for rapid cure
- Low-cost reconfigurable tooling
- Rapid tools cycle (clean, prep, heating, and cooling)

Research activities where NASA can contribute:

- Bag-less consolidation
- High rate processes for composite consolidation/cure
- Process optimization including thermal effect for rapid cure
- Low cost reconfigurable tooling
- Rapid tools cycle (clean, prep, heating, and cooling)

Assembly – Accurate Structural Dimensions, Precise Fit-Up, Unitized Structures

- Manufactured structure with precise dimensions
- One-sided fastening
- Predictive part spring back and variability
- Rapid joint assembly/bonding concepts
- Production system design and simulation tools

Research activities where NASA can contribute:

- One-sided fastening
- Predictive part spring back and variability
- Rapid joint assembly concepts
- Production system design and simulation tools

NDE and In Process Quality Control – Accurate Material Process Models and In-Line/Real-Time Nondestructive Evaluation

- Real time process monitoring and control
- Rapid NDE techniques
- Inspection data analysis automation
- NDE data linked to material state/strength
- Use of simulation for design-for-inspectability

Research activities where NASA can contribute:

- Real time process monitoring and control
- Rapid NDE Techniques
- Inspection data analysis automation

Paint, Prep and Application – Process/Tool/Surface Quality Relationship, Automated/Reproducible/Qualified Surface Treatments

- Process/tool/surface quality relationship
- Automated/reproducible/qualified surface treatments
- Weight efficient lightning strike protection
- Rapid coatings and livery applications

Research activities where NASA can contribute:

- Rapid coatings and livery applications
- Weight efficient electric-magnetic-electric (EME)
- Appliques.

5. Results of Industry/Government/Academia Survey of NASA Identified Potential Investment Areas

During the weeks after the workshop, numerous OEMs and Tier 1 suppliers were asked to complete a survey related to potential NASA investment areas in both the metals and composites symposia. Each of these surveys contained specific questions that were extracted from the *Discussion Topics and Potential Areas of Future NASA Investments* sections discussed previously. In these surveys, a rating of 1 indicated a task that was deemed to be very important for NASA to do to support US industry, whereas a rating of 5 indicated a task that was deemed to be unimportant for NASA to do to support US industry. Rather than show individual values, average/consensus values are indicated by green (very important), yellow (somewhat important) or red (unimportant). *Hence, these are the recommendations from the OEMs and Tier 1 suppliers as potential investment areas for NASA.*

5.1 Potential NASA Investment Areas for Rapid Manufacturing of Metals

Table 2 shows the outcomes of the metallic materials sessions at the workshop including an aggregation of the technology areas and tasks that the workshop participants thought NASA should develop in order to close the corresponding technology gaps. This table was sent to 6 OEMs/Tier 1 suppliers with a request to rate each task numerically from 1 to 5 as previously discussed. Although the individual responses are intentionally obscured by this format, some general observations regarding industry priorities can be made. *As seen in the table, all tasks that resulted from the metals symposium were viewed by the OEMs as being either very important or somewhat important investment areas for NASA.*

Most of the tasks in the focus area related to evaluating **emerging metals manufacturing methods** were rated as being somewhat important by industry. The exception to this observation is for the specific task related to bridging the gap between the research community and industry's design and development practices that was considered to be very important. This task represents a high-payoff role for NASA toward transition of capabilities.

Nearly all of the tasks in the focus area on developing **capabilities to support certification of rapid manufacturing** were viewed as being very important for NASA to pursue. Current capabilities for certification typically require an extensive test matrix wherein similitude between the test coupons and the production article is assumed. This paradigm allows no flexibility beyond the specific conditions (e.g., material composition, machine settings) that were certified; hence, any variation requires that a new test matrix be undertaken. The tasks listed in the table contribute to a paradigm change by focusing on systematically developing an understanding and validating the processing-microstructure-property-performance (PSPP) relationships, including understanding the effects of manufacturing defects, for each rapid manufacturing process of interest. The final step of this new paradigm is to transition high-fidelity simulation and characterization outcomes to engineering capabilities.

Nearly all of the tasks in the focus area on developing **capabilities for design and optimization of materials and structures** for rapid manufacturing were also viewed as being very important for NASA to pursue. In aggregate, these tasks enable the inherent flexibility of several rapid manufacturing methods (e.g., powder bed AM, powder feed AM) to be realized. Among these are development of methods for manufacturing-method-specific alloy development and integrated design practices. The most far reaching of these tasks, focused on integration of structural optimization and material optimization, was considered to be too aggressive by some of the OEMs; as a result, it is rated as somewhat important.

Capabilities for **in-situ non-destructive evaluation (NDE)** were the most often discussed topic in the metals symposium. As indicated by its rating, this work appears to be widely recognized as being critical to the future of many of the rapid manufacturing methods being considered. Additionally, the OEMs rated computational NDE as being very important while work on new sensors was considered somewhat important.

The final technology focus is development of a **comprehensive physics-based/machine learning-informed computational framework (digital thread)** for processing, materials, performance and life. Although development of a robust digital thread framework is a lofty goal, the OEMs considered it to be a very important investment area for NASA.

Table 2: Potential NASA Investment Areas for Rapid Manufacturing - Metals

Technology Focus	Focus Area	Detail Task
Evaluate emerging metals manufacturing methods	Manufacturing	Evaluate the potential efficacy of the broad range of advanced manufacturing technologies
		Develop an accumulated experience "library" to inform decisions about adoption of new manufacturing technologies
		Develop an industry-responsive business case for down-selection of new manufacturing methods
		Bridge the gap between the research community and industry design and development practices
Develop capabilities to support certification of rapid manufacturing	Certification	Characterize and catalog microstructures and defects for a broad range of advanced manufacturing technologies
		Develop foundational multi-scale/multi-physics simulation and characterization capabilities w/standardized data formats
		Understand process-microstructure-performance relationships over entire design space; quantify uncertainties
		Focus on effect of manufacturing defects on material performance
		Develop effective reduced order models for cost-effective predictive capabilities
		Transition high-fidelity simulation and characterization outcomes to engineering capabilities
Develop capabilities for design and optimization of mtl and struct for rapid manufacturing	Materials & Structures	Develop capabilities for development of application-specific alloy systems and location-specific (structural and material) optimization, including graded compositions, location-specific properties, and multifunctional materials
		Develop and validate computational materials methodologies for alloy development - broadly applicable where possible, specific to each new manufacturing method where necessary
		Integrate design capabilities for the entire development and manufacturing cycle, incorporating inspectability, manufacturability, certification requirements; incorporate uncertainty and robustness within the design process
		Develop concepts for closer integration of the manufacturing process with structural and material design
Develop improved capabilities for NDE and in-situ monitoring	NDE	Develop high speed, low cost sensors for real-time process monitoring throughout production (to reduce post-fabrication inspection)
		Develop new capabilities for in-process inspection to reduce post-build testing
		Develop computational models for effective NDE and its certification
Develop a comprehensive physics-based/machine learning-informed computational framework (digital thread) for processing, materials, performance and life	Digital Thread	Integrate process-material-component design and certification

5.2 Potential NASA Investment Areas for Rapid Manufacturing of Composites

Table 3 shows the outcomes of the composite materials sessions at the workshop including an aggregation of the technology areas and tasks that the workshop participants thought NASA should develop in order to close the corresponding technology gaps. As with the metals sessions, this table was sent to over twenty attendees representing 6 Tier 1 OEMs, materials suppliers, academia, and the FAA with a request to rate each task numerically from 1 to 5 as previously discussed. Once again, the individual responses and the specific numerical averages are intentionally omitted by this format. *Here, an important original observation is that there was a significant range of ratings provided by the twenty plus responders.* A limited number of tasks received ratings that ranged from 1 to 5, with

importance of a particular task appearing to naturally align with specific industry or academic interests. Rather than show individual values, average/consensus values are indicated by green (very important), yellow (somewhat important) or red (unimportant). For Table 3 – Composites, light green and light red colors were added to help further classify survey results. *Hence, these are the recommendations from the OEMs and Tier 1 suppliers as potential investment areas for NASA.*

The first technology focus area, "design and analyze **unitized and bonded structural concepts**," had half of the potential detailed tasks rated as highly important. It became obvious from the workshop that participants viewed unitized structural concepts and manufacturing of complex structure, which will limit part count, component fit-up and fastener operations, as critical to rapid manufacturing success. Robust and certifiable bonding techniques along with the ability to non-destructively evaluate the quality of the structures are highly important components of this technology focus area.

The second technology focus area, "develop technologies to increase **thermoset** composite production rates," also had half of the potential tasks rated as highly important. The survey showed that physics-based modeling of both resin infusion and OOA vacuum bag only processing is needed. The variability in part quality for these processes compared to those built by prepreg/autoclave methods (high consolidation pressure available) require a much better understanding of process parameters/part quality relationships. Fast curing matrix resins for both prepreg/AFP and vacuum assisted resin transfer molding (VARTM) processes were identified as necessary to reduce autoclave or oven curing times.

The third technology focus area, "develop technologies to increase **thermoplastic** composite production rates," showed over half the potential tasks rated as highly important. Two of these areas involved the thermoplastic tape provided by the material suppliers to the manufacturers. Tailored matrix resins and tape quality (consistent width and thickness, low void content, and smooth, resin available surfaces) are critical for successful in-situ automated placement processing. In addition, a closed loop control system for real time build inspection/validation is important to rapidly manufacture thermoplastic composites.

The fourth technology focus area, "develop **in-process monitoring/NDE** technologies," had all but one task rated as highly important. Both workshop discussions and survey results highlight the need for manufacturing composites with consistent part quality and low scrap rates and for rapid, large scale inspection methods. The ability to identify off nominal process parameters in real time, and to quantify the effects to part quality to determine need for rework or not, will play an important role in increasing manufacturing rates. Current off-line, relatively slow NDE techniques also slow production rates, so implementation of in-situ NDE will help significantly.

The fifth technology focus area, "develop **process modeling and simulation** technologies," had one task rated as highly important. Tools to predict processing defects, including tape deposition, matrix curing, resin flow and forming, for each of the desired composites processing methods will reduce time and cost for introduction of new materials/processes or to better optimize current manufacturing rates.

The sixth technology focus area, "develop **testing requirements** for rapid manufacturing/increased production rates," rated all tasks as moderately important. The survey requested input on the suitability of current test methods and the need for new methods relative to composites made by rapid processing methods. There was a general consensus that the processing method most likely doesn't affect specific composite test requirements, but an emphasis on more rapid certification and more complex unitized structures will require advanced test methodology development for substantiating such structures. In addition, an increased emphasis on computational modeling of materials and processes will require new input property data tests and model validation tests. Bonded structure and new material forms, such as resin infused three dimensional preforms, will require new approaches for materials performance characterization. The need for immediate investment in this area was indicated as lower than some of the other focus areas.

The seventh and last technology focus area, "develop **cross-cutting technologies** to increase composite production rates," produced high importance ratings for bonding both thermoplastics and thermosets. The actual surface treatment process and the methodology to quickly and accurately analyze the quality and contamination of the treated surfaces are highly important to improved production rates. The development of a rapid surface treatment for bonding metallic materials was rated as moderately important.

Table 3: Potential NASA Investment Areas for Rapid Manufacturing – Composites
Remove rating column from this table to match the corresponding metal's table.

Technology Focus	Focus Area	Detail Task
Design and analyze **unitized and bonded structural concepts**.	Unitization	Conduct trade studies with industry to determine most promising use of unitization for rapid manufacture of CFRP structure needed for next gen 737 which meets throughput while minimizing defects/ repairs/and scrap rates.
	Unitization	Develop NDE techniques for assessment of complex unitized structure.
	Unitization	Develop robust and certifiable bonding techniques for bonded structure. (see also "Cross-Cutting Technologies" below)
	Unitization	Develop tooling concepts and processing techniques for rapid manufacture of unitized structure.
Develop technologies to increase **Thermoset** composite production rates for aerospace structure.	Theromosets	Conduct trade studies to determine most promising processes to rapidly manufacture thermoset CFRP structure for next gen aircraft while minimizing defects/repairs/scrap parts.
	Theromosets	Further develop/tailor existing COTS physics-based process models to identify key thermoset material properties for rapid AFP manufacturing.
	Theromosets	Further develop/tailor existing COTS physics-based process models to identify key thermoset material properties for rapid infusion manufacturing.
	Theromosets	Further develop/tailor existing COTS physics-based process models to identify key thermoset material properties for rapid Out Of Autoclave Vacuum Bag Only manufacturing.
	Theromosets	Partner with OEM and Material Suppliers to develop fast curing thermoset resins tailored for AFP with autoclave cure.
	Theromosets	Partner with OEM and Material Suppliers to develop fast curing resins tailored for AFP with OOA VBO processing.
	Theromosets	Partner with OEM and Material Suppliers to develop fast curing resins tailored for the RTM infusion process.
	Thermosets	Partner with OEM and Material Suppliers to develop fast curing resins tailored for the VARTM infusion process.
Develop technologies to increase **Thermoplastic** composite production rates for aerospace structure.	Thermoplastics	Partner with OEM and Material Suppliers to develop thermoplastic resins tailored for in-situ automated placement processing.
	Thermoplastics	Demonstrate closed loop control for in-situ process fabrication for real-time build inspection, geometric accuracy, and rework/repair for thermoplastic CFRP structure.
	Thermoplastics	Demonstrate tool-less OOA fabrication of a representative complex aerospace-quality thermoplastic structure.
	Thermoplastics	Determine effect that thermoplastic prepreg tape surface has on bond quality of the composite during build lay-up.
	Thermoplastics	Demonstrate the integration of prefabricated components into a thermoplastic composite, multi-material structure during build. Examples include thermoset parts, metal parts, etc. as subcomponents of a thermoplastic structure.

Develop **In-Process Monitoring/NDE** technologies to increase composite production rates for aerospace structure.	NDE	Develop Real Time Process Monitoring and Control for material tracking/process monitoring/digital thread at every step from material acceptance/screening through delivery/service. In-situ process monitoring is needed to reduce material variability, to detect FOD (e.g., net poly backing paper) during lay-down and to perform cure monitoring especially with regard to new material systems and architectures.
	NDE	Develop tools for more rapid assembly of parts with real-time feedback maintaining correct positioning/quality, geometry, dimensioning, and tolerance tracking throughout assembly via computer vision/photogrammetry analysis.
	NDE	Develop rapid NDE techniques including large scale automated thermal inspection, computer simulation aided inspection of problematic geometries, and simulation for design-for-inspectability.
	NDE	Develop automated inspection data analysis tools for rapid manufacturing including automated in-situ defect recognition/quantification/characterization, linking NDI results to material state for quick/informed decisions, and machine learning based parameter estimation for process efficiency improvement/variability reduction.
Develop **Process Modeling and Simulation** technologies to increase composite production rates for aerospace structure.	Simulation	Develop software tools to predict processing defects (deposition, cure, forming, resin transfer, etc.) to reduce time and cost to develop new composite manufacturing processes and to optimize current processes for rate and yield.
	Simulation	Develop and validate tools to predict material properties using atomistic to continuum level modeling. Characterize new materials for implementation in modeling tools (NCAMP-like task) and validation of material models.
	Simulation	Provide a stable source for storage and distribution of available software tools. Manage documentation of software manuals, training and data for software tools.
	Simulation	Development of software tools to create a contiguous digital thread for aircraft manufacture from design through product service.
Develop **Testing Requirements** for Rapid Manufacturing/ Increased Production Rates	Testing	Determine new test methods and/or modifications to existing methods required to generate experimental input data for design analysis framework.
	Testing	Assess the suitability of existing standards and develop new methods where needed to fully characterize materials for rapid manufacturing.
	Testing	Develop test methods required for input properties for multi-scale model validation.
	Testing	Develop advanced testing methodology to reduce the time/cost of coupon test programs for new materials insertion.
	Testing	Develop test methodologies to characterize bonded joints.
Develop **Cross-cutting Technologies** to increase composite production rates for aerospace structure.	X-Cutting	Develop high throughput, rapid surface treatment process for bonding composites (thermoplastics and thermosets).
	X-Cutting	Develop high throughput, rapid surface treatment process for bonding metals (Ti, Al, stainless steel, inconel).
	X-Cutting	Develop integrated surface treatment/analysis capability to measure residual surface contamination.

6.0 Summary

This report documented the goals, organization, and outcomes of the NASA Aeronautics Research Mission Directorate's Materials and Methods for Rapid Manufacturing for Commercial and Urban Aviation Workshop that was held in Tyson's Corner, VA, on November 14-15, 2018. The workshop was focused on identifying and assessing the state of technology areas relevant to rapid/advanced manufacturing, understanding critical technology gaps and identifying high-priority investment areas for NASA. One hundred twenty-two participants attended, including materials and manufacturing professionals, original equipment manufacturers, material suppliers, researchers, government and academia.

The workshop began with a series of plenary presentations by leaders in the field of structures and materials, followed by concurrent symposia focused on forecasting the future of various technologies related to rapid manufacturing of metallic materials and polymeric composites. The Metals Symposium was organized into four inter-related sessions that included approximately 50 representatives from government, academia, and industry consisting of material producers, manufacturers and OEMs focused on future manufacturing approaches, design and development of materials for those manufacturing methods, design approaches that exploit emerging rapid manufacturing, and related capabilities for qualification and certification. Similarly, the Composites Symposium was organized into five inter-related sessions that included approximately 70 representatives from government, academia, and industry consisting of material producers, manufacturers and OEMs focused on rapid manufacturing of thermoset resin-based composites, rapid manufacturing of thermoplastic resin-based composites, in-process monitoring/NDE technologies, process modeling and simulation of advanced manufacturing, composite materials testing requirements and a wrap-up discussion.

Shortly after the workshop, questionnaires were sent to key workshop participants from the aerospace industry with requests to rank the importance of a series of potential investment areas. Areas surveyed for metals included manufacturing, certification, material and structural design, non-destructive evaluation, in-situ monitoring and development of a digital thread for metals. Areas surveyed for composites included unitized structures, thermoset and thermoplastic material development, non-destructive evaluation and in-situ monitoring, process modeling, testing and cross-cutting technologies. Responses were received and subsequently aggregated by the workshop organizers. Outcomes from the workshop and subsequent questionnaires are being used as guidance for NASA investments in this important technology area.

The following technologies were identified as the most promising and high impact potential NASA funded activities to meet the needs of future aircraft production rate and were included in the OEM survey of potential investment areas.

Potential Investment Areas for Metals

- Objectively **evaluate emerging metals manufacturing methods** for their efficacy and potential impact as means of rapid manufacturing of flight certified aerospace structures.
- Develop computational materials-based capabilities to support **qualification and certification** of the most viable rapid manufacturing methodologies to enable their use in production environments.
- Develop capabilities for **design and optimization of materials and structures** for rapid manufacturing including materials that are designed to be compatible with rapid manufacturing processes, optimized structures that exploit new and emerging manufacturing capabilities and structural systems that integrate both technologies.
- Develop improved capabilities for **NDE and in-situ monitoring** that are compatible with computational materials-based certification.
- Develop a comprehensive physics-based/ machine learning-informed computational framework (**digital thread**) for processing, materials, performance and life.

Potential Investment Areas for Composites

- Design and analyze **unitized and bonded structural concepts** (low part count/reduced assembly/minimal mechanical fastening) optimized for rapid manufacturing methods.
- Develop fast curing **thermoset** (TS) resins tailored for out-of-autoclave (OOA) processes including automated fiber placement (AFP) w/vacuum bag only (VBO) curing and resin infusion with VBO curing.
- Develop in-situ consolidation of continuous carbon fiber **thermoplastic** (TP) matrix resins by defining relationship of TP tape quality requirements and process parameter optimization for quality part production. Evaluate thermoforming of flat, continuous fiber panels to wing skin curvatures.
- Develop advanced **in-process monitoring and real-time nondestructive inspection** (fiber placement/FOD/autonomous defect recognition) and cure monitoring of material state (chemistry required for mechanical properties) methodologies.
- Develop robust **process modeling and simulation** technologies that can be used to predict defects and material properties for varying process parameters.
- Develop advanced **test methodologies** for lower cost/rapid certification of new materials/processing methods and model development validation.
- Develop high throughput **cross-cutting technologies**, including a rapid surface treatment process with integrated surface analysis to measure residual contamination for adhesive bonding which will minimize drilling and mechanical fastener use.

Appendix A1. Sessions in the Metals Symposium

This appendix contains a list of the sessions in the Metals Symposium along with the associated presentations and speakers.

Session 2a Metals: Manufacturing and Materials I - Manufacturing/Processing Methods
Session Chairs: Corbett Battaile (Sandia), Karen Taminger (NASA)

Scot Forge's Aerospace Footprint- Past, Present and Future
Andre Wilson (Scot Forge)

Aerospace Propulsion Materials and Manufacturing: A Look Ahead
Mike Peretti (GE Aviation)

Materials Opportunities in Metal Additive Manufacturing for Automotive Applications
Anil Sachdev (General Motors)

Session 3a Metals: Manufacturing and Materials II - Design/Development of Materials for Specific Manufacturing Methods
Session Chairs: Eric Lass (NIST), Tim Smith (NASA)

Control of Defect Formation for Qualification in Metals Additive Manufacturing
Tony Rollett (Carnegie Mellon)

*Application of Digital Technologies for Rapid Materials Manufac*turing
Brandon Bodily (Arconic)

Replacement of Legacy Alloy 2219 with Airware 2050 on Complex Formed/Machined Monolithic Space Structures and Fiber/Aluminum Hybrid Aircraft Wing Cover Design
Michael Niedzinski (Constellium)

Functionally grade materials – unique properties for difficult problems
Andrew Shapiro (NASA JPL)

Session 4a Metals: Component Design and Certification I – Component Design/ Development that Exploits Specific Manufacturing/Processing Methods
Session Chairs: Eddie Schwalbach (AFRL), Chris Lang (NASA)

Re-Imagining Design with Manufacturing-Aware Topology Optimization
Jamie Guest (Johns Hopkins)

Toward an Integrated Manufacturing, Mechanical, and Materials Engineering Computational Engineering (ICM^{3}E) Design Framework
Albert To (University of Pittsburgh)

Multidisciplinary Design Optimization: A Forward-looking Perspective
Miguel Aguilo (Sandia)

Qualification and Certification of Additive Manufacturing

Rigo Perez (Boeing)

Session 5a Metals: Component Design and Certification II - Certification for Materials Manufacturing/Processing and Application
Session Chairs: Somnath Ghosh (Johns Hopkins), Andy Newman (NASA)

Forward Considerations in Methodologies for Qualification and Certification of AM Parts
Doug Wells (NASA)

Microstructure-Focused Metal Additive Manufacturing Process Simulations for Qualification
Theron Rodgers (Sandia)

Benchmark Measurements for Validating Additive Manufacturing Simulations
Lyle Levine (NIST)

Inspection Challenges for LPB-fusion Additive Parts and Trends in In-process Monitoring
Yuri Plotnikov (Commonwealth Center for Advanced Manufacturing)

Appendix A2. Sessions in the Composites Symposium

This appendix contains a list of the sessions in the Composites Symposium along with the associated presentations and speakers.

Session 2b Composites: Advanced Manufacturing Methods - Thermosets
Session Chairs: Dave Bertino (Boeing RT), Roberto Cano (NASA), Brian Grimsley (NASA)

Unitization of Composite Structure
Dan Hansen (Boeing RT)

Technology Needs to Enable High Rate Infusion Processes for Aerospace
Wendy Lin (GE Aviation)

Out-of-Autoclave (OOA)/Oven Cure Prepreg
Kyle Magnuson (RUAG US)

Rapid Cure/Out of Autoclave Materials
Damon Call (Toray Composite Materials America)

High Rate Processes for Composite Lay-Up
Keith Young (Boeing RT)

High Rate Processes for Composite Consolidation/Cure
Blake Slaughter (Boeing RT)

Session 3b Composites: In-process Monitoring and Nondestructive Evaluation

Session Chairs: Todd Rudberg (Electroimpact), Tyler Hudson (NASA), Peter Juarez (NASA)

Composites Circle of Life: In-situ QA, Digital Manufacturing & Structural Health Monitoring
John Tyson (Trilion)

Electroimpact's Vision for Fiber Placement, Industry Standards, Predictive Maintenance and Reduced Inspection Requirements
Todd Rudberg (Electroimpact)

Automated Technologies for Advanced Structures: Manufacturing, Material Characterization, and Structural Certification
Waruna Seneviratne (National Institute for Aviation Research)

Session 4b Composites: Advanced Manufacturing Methods - Thermoplastics
Session Chairs: Sam Tucker (Boeing RT), Robert Bryant (NASA)

Tool-less Thermoplastic Manufacturing Utilizing Continuous Fiber
John Geriguis (General Atomics)

Thermoplastic Composite Tapes for High Speed Manufacturing
Jim Mondo (TenCate)

Rapid Manufacturing of Composite for Aerospace: Thermoplastic Composites
Jim Pratte (Solvay)

Innovations in Automated Fabrication of Composite Structures
John Melilli (Composite Automation)

United Technologies and Thermoplastic Composites
Wenping Zhao (United Technologies)

Session 5b Composites: Process Modeling and Simulation of Advanced Manufacturing
Session Chairs: Byron Pipes (Purdue), Frank Palmieri (NASA)

Simulation/Process Modeling for Improved Manufacturing Rate
Sam Tucker (Boeing RT)

Challenges and Benefits of Modeling and Simulation of Liquid Composite Molding Processes for Advanced Manufacturing
Suresh Advani (University of Delaware)

Session 6b Composites: Panel Session on Testing Requirements for Advanced/Rapid Manufacturing Processes
Discussion Leaders: Steven Wanthal (Boeing RT), Waruna Seneviratne (NIAR), James Ratcliffe (NASA)

Topics: (include but are not limited to)
Qualification Testing

Certification Testing for Manufacturing Processes
Testing for Certification of Structure
Validation Testing
General Test Requirements

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14. ABSTRACT

This report is based on the outcomes of a NASA Aeronautics Research Mission Directorate (ARMD)-sponsored workshop held in Tysons Corner, VA, on November 14-15, 2018. The workshop, Materials and Methods for Rapid Manufacturing for Commercial and Urban Aviation Workshop, was focused on identifying and assessing the state of technology areas relevant to rapid/advanced manufacturing, understanding critical technology gaps and identifying high-priority investment areas for NASA. One hundred twenty-two participants attended, including materials and manufacturing professionals, original equipment manufacturers, material suppliers, researchers, government agencies and academia.

15. SUBJECT TERMS

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