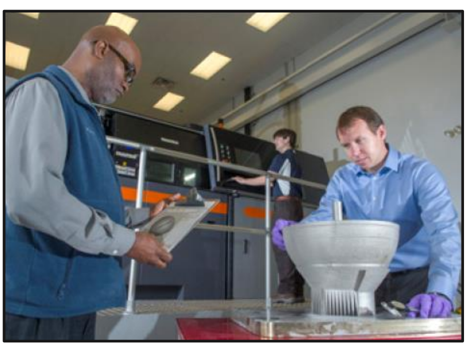
National Aeronautics and
Space Administration



advanced manufacturing branch

Marshall Space Flight Center

EM42 Advanced Manufacturing Branch

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The Advanced Manufacturing Branch, EM42, has two teams: the Additive Manufacturing and Digital Solutions Team (AMDST) and the Advanced Composites Manufacturing Team (ACMT).

The AMDST provides various capabilities and services that span the entire product life cycle. The team's major capabilities are additive manufacturing, digital manufacturing, structured light scanning, manufacturing execution systems, and various other digital tools that support the development and manufacture of hardware.

The ACMT provides advanced composites structures development utilizing state-of-the art methods available to private industry. This includes: Fiber placement, tape laying, filament winding, compression molding, resin infusion, vacuum bagged hand layup, oven curing, and autoclave curing. The team also provides other diverse capabilities and services that include materials development for radiation shielding and rocket nozzles, as well as providing autoclaves, walk-in coolers and freezers.

Together these teams are able to provide engineering solutions, manufacturing development, and full-scale hardware production of the most complex size and shape. Team experience ranges from test and flight articles down to manufacturing enhancements and materials development using on-site equipment. The resources and facilities on-hand have been utilized for numerous NASA, private industry, and other government agencies' programs, projects, and tasks. With collaboration efforts ever expanding and capabilities keeping up with the very latest state-of-the art, this organization is well equipped and has the right personnel mix and expertise to efficiently respond to the demands of today's affordable manufacturing requirements.

EM42 Advanced Manufacturing Branch Contacts

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Additive Manufacturing and Digital Solutions Team

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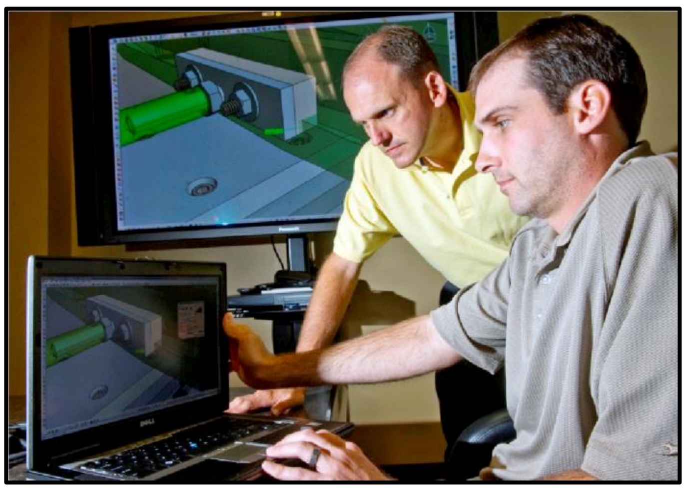
The Additive Manufacturing and Digital Solutions Team, within the Advanced Manufacturing Branch, provides various capabilities and services which span the entire product lifecycle. The capabilities within the team encompass such disciplines and technologies as Digital Manufacturing, Manufacturing Execution Systems, Structured Light Scanning, In-Space Manufacturing, Additive Manufacturing, and Digital Thread activities and efforts. As a whole, this team is dedicated to developing, improving, and delivering the additive manufacturing and digital solutions needed to meet NASA's various goals and missions. This brochure only elaborates on a subset of these capabilities. For further information, please contact the team lead listed above.



Digital Manufacturing

Digital Thread

The team supports various efforts to define and establish a Digital Thread which links together mission concepts, design, manufacturing and test. Efforts are currently focused on linking Product Data Management systems to Manufacturing Execution Systems so that product data can automatically flow to manufacturing, and vice versa, through a standards-based interface. These efforts are aimed at eliminating manual, paper-based processes and reducing the chance of human error. The end goal is to establish a digital thread that allows non-homogeneous software tools to retrieve, modify and seamlessly share data across multiple disciplines.

Digital Manufacturing

Our Digital Manufacturing tools focus on the design and manufacture of a product, looking for ways to optimize manufacturing operations using three-dimensional manufacturing simulations. These simulations contain a wide range of geometrical data, such as buildings, cranes, tooling, fixtures, platforms, and machines. Several analyses are performed which allow for problems to be identified early in the design cycle. The three most often performed analyses are interference analysis, kinematic verification, and simple human factors. Other capabilities include off-line programming of robots. These tools have been used to support development and flight programs. The problems identified through the use of digital manufacturing tools have produced a cost avoidance in the millions of dollars.

Automated Part Inspection

Electronic Work Instructions

Manufacturing Execution System (MES)

The MES allows for the electronic creation and delivery of work instructions to the shop floor. It maintains configuration control of process plans and captures all critical data that is used, generated, or created on the floor, i.e. the as-built record. In the Process Planning phase, the MES allows for:

1) eBOM to mBOM planning and reconciliation
2) Creation of rich work instructions which include CAD models, drawings, movies, documents, etc.
3) Routing and approval of plans before they can be released to the shop floor
4) Assigned effectivity and full configuration control of process plans

During the Process Execution phase, the MES allows for:

1) Process sequence enforcement
2) Electronic buyoffs
3) Capturing of as-built data, such as serial number, temp, humidity, or any other process data
4) Redlining of work orders
5) Superceding of work orders

Structured Light Scanning and Photogrammetry

Our Structured Light Scanning tools are used to capture as-built 3D surface geometry of hardware. These models are used to identify deviations from the as-designed part/assembly, and they become the input for additional analysis.

The use of these techniques has provided a wealth of information about our tooling, equipment, and products that was previously unavailable. Through the use of optical measuring techniques, CAD models can be generated which represent the as-built parts. These CAD models can then be used for as-designed/as-built comparisons so that deviations can be identified. Since each as-built part is unique, this approach has allowed us to modify processes on-the-fly so that parts can be built within specification.

As each part of an assembly is scanned, a corresponding digital assembly is created. This digital assembly can be used to check for assembly problems of large scale structures, such as the mating of different stages of a vehicle. It also allows for analyses to be performed on the as-built assembly, such as determining engine turbo pump performance, holding capacity of a cryogenic fuel tank, or erosion rate of a nozzle after each engine test.

Heritage hardware exists which has no drawings or 3D models. Scanning techniques have been used to reverse engineer hardware so that CAD models can be generated. This allows for design engineers to update or modify heritage hardware to increase capabilities or performance. One such example is the F1 Engine.

Structured Light Scanning

Photogrammetry

Additive Manufacturing Certification and Materials Development

Additive Manufacturing (AM) technologies provide advanced techniques for creating prototype, test, and functional parts, which do not require tooling development. Instead, physical geometries are constructed directly from 3D computer aided design (CAD) models by adding layers from the bottom up, essentially growing the part from the inside-out. Materials range from tough plastics to full-strength metals. The team also provides critical engineering support to projects developing AM technologies for use in long-duration space missions and planetary habitats.

At MSFC, a world-class AM facility is available. Systems in operation include the following:

- Selective Laser Melting (SLM) is a powder based additive manufacturing process that uses a high power laser to fuse small particles of metal to build parts up to 400 x 800 x 500 mm with a +/- 0.1 mm accuracy. SLM parts typically exhibit wrought-like properties in alloys including Nickel Alloy 718 (Inconel 718) and Copper-8 Chromium-4 Niobium (GRCop84), and Copper-4 Chromium2 Niobium (GRCop42). Processes are currently being developed for hydrogen resistant alloys such as JBK-75 and NASA HR1. Efforts are currently focused on creating key mechanical properties databases of materials for design allowables for flight hardware.

Test Hardware Made Via Selective Laser Melting

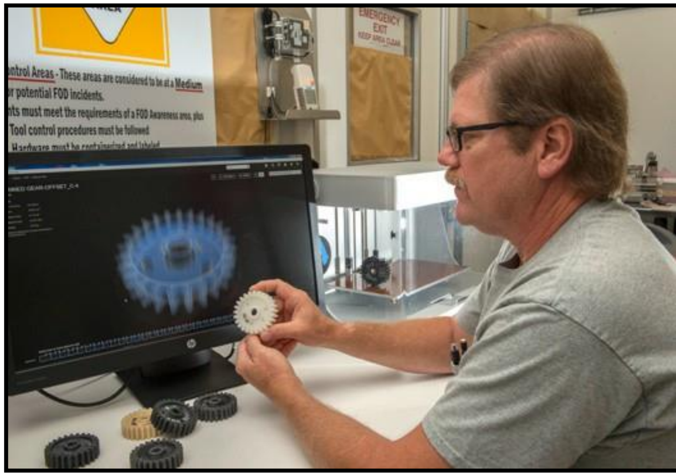
Powder Bed Fusion Parts

- Stereolithography (SLA) is a process in which an ultraviolet laser is used to solidify or selectively cure a vat of liquid photo-polymer resin into the desired shape. At MSFC, the SLA Viper system can build components up to 10 x 10 x 10 in, with a tolerance of about 0.001 in. The SLA 5000 system has a build capacity of 20 x 20 x 23 in, with a tolerance of about 0.008 in. SLA parts typically exhibit tensile strengths near 7 ksi and heat deflection near 130 °F.

Powder Bed Fusion Parts

- Blown Powder Directed Energy Deposition (BP-DED) is a powder-based AM process that injects metal powder into the path of a high powered laser in order to build a part layer-by-layer. The laser used in the process is mounted at the end of a robotic arm, facilitating the production of much larger parts than are possible by SLM. This process is well suited to produce rocket engine components such as nozzles in Inconel 625, JBK75, and the NASA developed HR1 alloy. With the help of on-going development and certification efforts, this process has an exciting and promising future in space flight

Directed Energy Deposition



Carbon Fiber Reinforced Plastic Parts

- Fused Deposition Modeling (FDM) is an extrusion process that forms a desired geometry by depositing thin layers of semi-molten ABS, polycarbonate or Ultem plastic from a traversing orifice. At MSFC, the FDM Fortus system can be used to build components up to 36 x 24 x 36 in, with a tolerance of about 0.007 in. FDM parts exhibit the highest toughness of the plastic AM systems, as well as tensile strengths ranging from 5 ksi to 8 ksi, and heat deflection from 230 °F to 320 °F.

Testing of Selective Laser Melting
Lattice Structures

- The nScrypt multi-material 3D printer is a ground-based development platform for developing materials and processes for the In-Space Manufacturing FabLab capability planned for the International Space Station. This machine has a 3D print envelope of 300mm x 300mm x 150mm, with single-digit micron positioning accuracy. Processes are being developed to print metals such as aluminum, Inconel, and titanium, as well as a wide range of printed electronics materials. Capabilities include micro-mill removal of material as well as in-situ laser sintering.


Multi-Material 3D Printer

Process	Model	Material	Build Chamber Size
Stereolithography (SLA)	3D Systems/Viper SLA	DMX Somos (White)	10 x 10 x 10 in
Stereolithography (SLA)	3D Systems/5000 SLA	Somos Watershed 11122 XC	20 x 20 x 23 in
Fused Deposition Modeling (FDM)	Stratasys/Fortus 900 FDM®	ABS, Polycarbonate, Ultem	36 x 24 x 36 in
Selective Laser Melting (SLM)	Concept Laser/M1	Inconel 625/718	9.5 x 9.5 x 9.5 in
Selective Laser Melting (SLM)	Concept Laser/M2	Copper, Titanium, other	9.5 x 9.5 x 11 in
Selective Laser Melting (SLM)	EOS/M100	Various	Ø 3.94 x 3.74 in
Selective Laser Melting (SLM)	EOS/M290	Inconel 625/718	9.5 x 9.5 x 11 in
Selective Laser Melting (SLM)	Concept Laser/ XLINE1000R	Inconel 718	24 x 15 x 19 in
Selective Laser Melting (SLM)	Concept Laser/ XLINE2000R	Inconel 718	31 x 15 x 19 in
Directed Energy Deposition (DED)	DM3D Technologies	JBK75, NASA HR1, Inconel 625/718	12 x 8 x 10 ft

Advanced Composites Manufacturing Team

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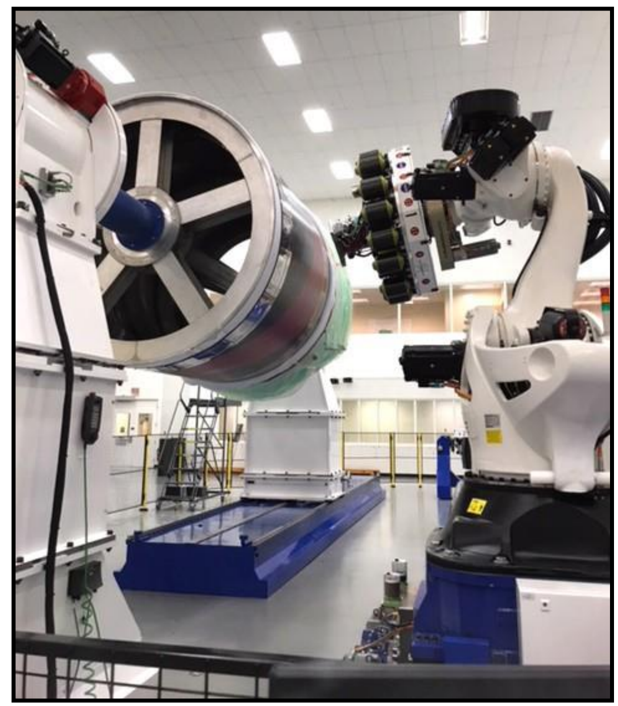
The Advanced Composites Manufacturing Team (ACMT), within the Advanced Manufacturing Branch, provides advanced composites structures development utilizing state-of-the art methods. This includes fiber-placement, filament winding, compression molding, resin infusion, vacuum bagged hand layup, oven curing, and autoclave curing. This team develops a broad spectrum of hardware from telescope tubes to large-scale composite tanks, motor cases, and fairings for large scale launch vehicles.


Automated Fiber Placement of Composite Shell
Buckling Knockdown Factor Barrel

Composite Overwrapped Pressure Vessel

Filament Winding

Our filament winding facility is rather versatile and has produced structures from many programs. This capability was first established in 1985 during the composite solid rocket motor-case development effort for the Space Shuttle. This capability has expanded into many programs, including a large, cost effective, disposable RP-1 engine developed for the X-34 program. This involved the tape wrapping of an ablative liner followed by a composite overwrap that was filament wound. The structure was cured in our 9 x 12-ft autoclave. Filament winding is also an integral enabling technology in the development of cost effective solid rocket motor cases. Composite Overwrapped Pressure Vessels (COPVs) have been developed for many programs and research efforts. This can vary from small ultralight vessels to in-space applications to larger vessels used as fuel tanks in a propulsion test bed.

The filament winding process is ideal for structures that are symmetric about an axis. This process has also been used for composite telescope tubes, optical benches, and struts on various programs. MSFC has two modern four-axis filament winding machines that are outfitted with state-of-the-art fiber tensioning systems. Structures can be made that are 1 inch in diameter up to a tube structure that is 4 feet diameter x 15 feet long.

60K, Carbon Fiber Overwrapped, Chamber/Nozzle

Computational Volumetric Inspection of Automated Fiber Placement Robot

Automated Fiber Placement

The composites manufacturing area contains a state-of-the-art robotic automated manufacturing cell that has produced many large complex composite structures and research test articles. This equipment has also been used with industry partners to develop new hardware while they wait for the delivery of their own equipment. This facility has the advantage of not being burdened about production flow. MSFC also has access to larger fiber placement machines located at the Michoud Assembly Facility (MAF) in New Orleans, LA. These machines have supported the following:

- Fiber placement of several different composite tank components needed by various programs
- Development of in-house flight hardware

The same automated equipment is used to make test panels for materials property databases and in-process damage assessments as well as Nondestructive Evaluation (NDE) studies. The fiber placement machines can make parts up to 16 feet in diameter x 25 feet in length. This unique equipment is also supported by large autoclaves and a new seven-axis machining center.

Automated Filament Winding

Hand Lay-Up and Compression Molding

MSFC has clean facilities used for a variety of non-automated processes that involve hand layup of material, vacuum bagging and oven/autoclave curing. These include the following:

Composite Process Development

- The hand layup process is frequently used to develop composite test panels for research and development (R&D) studies or material property databases. These panels are made under strict process control, and tests are supported by a complete mechanical test laboratory. Very complex structures are made by hand that are too complex for automation. Other structures, like optical benches, may utilize materials that are not suited for automation.

Composite Manufacturing

- The non-automated methods are also used for development efforts where only one article is needed and investments in tooling and equipment are not feasible. MSFC has a variety of large work spaces that also have access to ovens, autoclaves, and heated presses.

Supporting Facilities and Infrastructure, Including a Large-Scale Clean Room for Composite Structure Assembly

The ACMT maintains a large-scale clean room capable of assembling 27.5-ft diameter structures. The clean room exhibits the following features:

- 5,000ft^2 clean work area
- 10-ton monorail crane
- 20-ton bridge crane
- 400ft^2 airlock with 2-ton electric hoist
- 1,600ft^2 tooling/prep area

In addition, the ACMT maintains and provides training for several autoclaves used in high temperature and pressure materials processing. Other facilities include cold storage areas that are constantly monitored for out-of-temperature limits.

Autoclaves

- 18 x 20 ft (maximum operating pressure/temperature: 300 psi/400°F)
- 9 × 12 ft (maximum operating pressure/tempera ture: 150 psi/600°F)
- 4 × 6 ft (maximum operating pressure/temperature: 240 psi/650°F)

18 x 20 ft Autoclave

Out-of-Autoclave Bonding Development

Ovens

There are several ovens, varying in size, used to cure vacuum bagged parts and wrapped pressure vessels. The largest oven onsite is 36ft x 18ft in size with a max operating temperature of 500F. It has been used to cure large scale hardware and has an integrated rotisserie.

Cutting Tables and Laser Positioning

- Computer controlled cutting tables are used to accurately cut a variety of different composite materials.
- A laser positioning system supports putting broad goods in place.

Freezers

- 400ft^2 Bethlehem -20/+10°F
- Bldg. 4707: 600ft^2 walk-in coolers (+25/+50°F, +40/+75°F, and +30/+40°F)
- Bldg. 4720: 536ft^2 walk-in cooler (+34/+35°F) and 584ft^2 walk-in freezer (25/+20°F)
- Bldg. 4778: Walk-in freezer (-20/+10°F)

Composite Hot Bonder

- 6 zone heating channels
- Max operating temp 1400°F
- Upper Blanket Limitation @ 5 watts in^2 @ 220V
- Hot Bonder can be used to cure out-of-autoclave composites, bonded joint development, secondary bonded components, and for composite panel repair.

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