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# New Paradigm in Additive Manufacturing: Utilization of Computed Tomography

## It's well known in the world of industrial engineering that additive manufacturing, commonly known as "3D printing," is no longer confined to the realm of hobbyists and university laboratories.

It is increasingly being used in industrial settings and as a production method rather than for merely prototyping and sampling. Particularly in the last decade, AM technology has made significant strides, inspiring and complementing other new techniques in the manufacturing sector such as digital threads and more broadly, Industry 4.0.

# A Brief History of Additive Manufacturing

**While the additive manufacturing concept was first proposed in the 1940s, and a U.S. patent for a 3D printing process was granted in the early 1970s, serious application of the technique really started in the early 1980s.**

Significant developments occurred in subsequent decades. In the 2000s, advances were such that 3D printing became much more accessible, and gave rise to many hobbyists and even a subculture of "maker labs" that provided participants with access to 3D printers and other tools. At the same time, research in academic and other institutions yielded advances that could be increasingly applied in industry. While initially used for pre-production prototypes and post-production sampling, AM is starting to emerge as a viable large-scale manufacturing process.

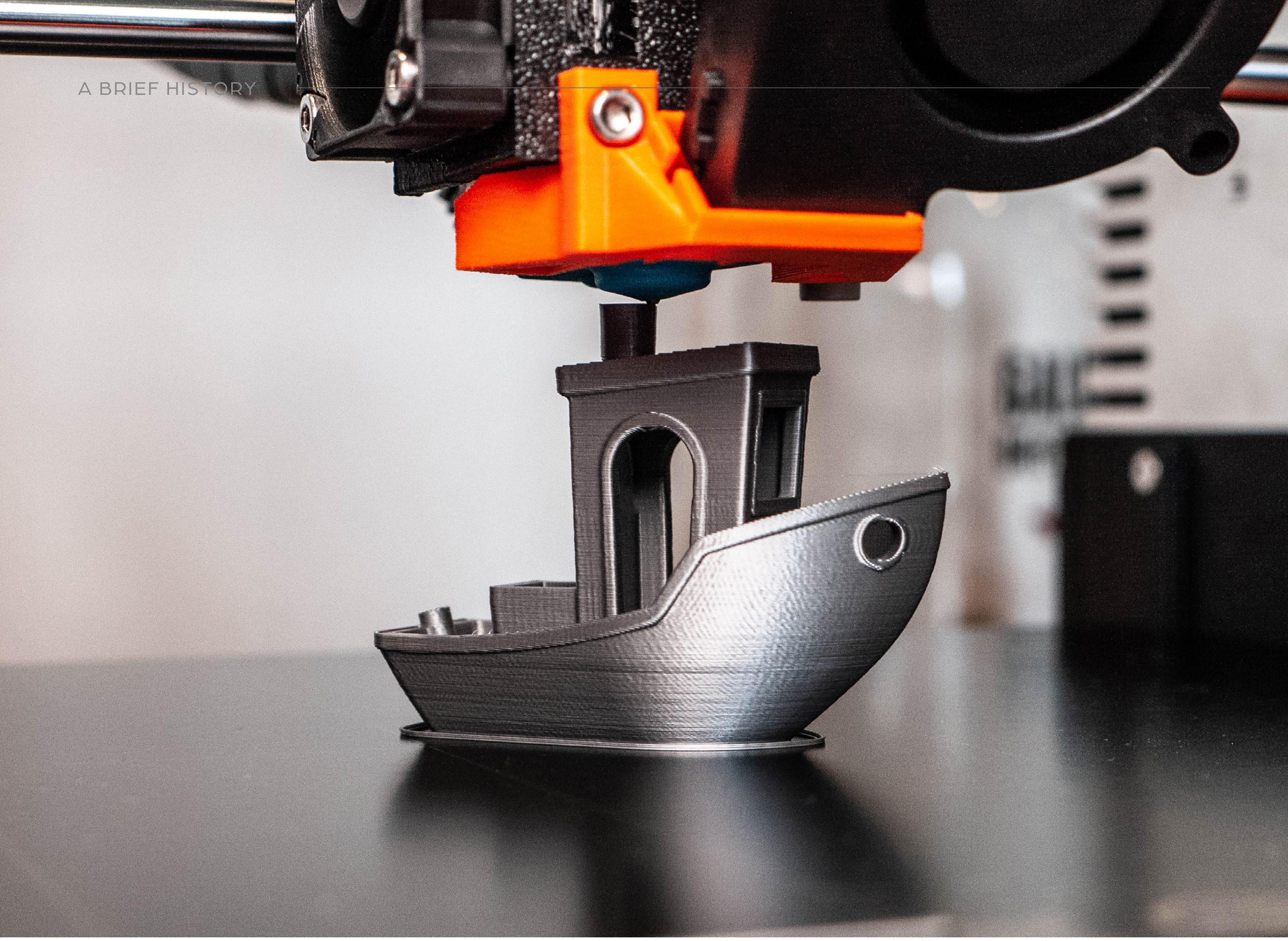
With this expansion has also come growth in methods and materials. Now, AM encompasses a wide variety of methods, among them electron-beam melting and selective laser melting. The spectrum of substances used for AM has also broadened from its beginnings with extruded polymers to composites, ceramics, and metals.

Additive manufacturing can be considered a transformative method of industrial engineering. It facilitates the nearly instantaneous building of machine parts, and is a more sophisticated approach to component construction compared to traditional die-casting methods. AM enables the construction of parts that were once deemed extremely difficult or impossible to build, such as complex hollow meta-structures[1] or organically inspired structures such as those generated from topology optimization[2].


*The boundaries of the technology are constantly expanding as new innovations emerge.*

As practitioners envision more possibilities, finer features, smoother surfaces, higher geometric complexity, and new material choices are also being demanded at faster printing speeds with less material waste.

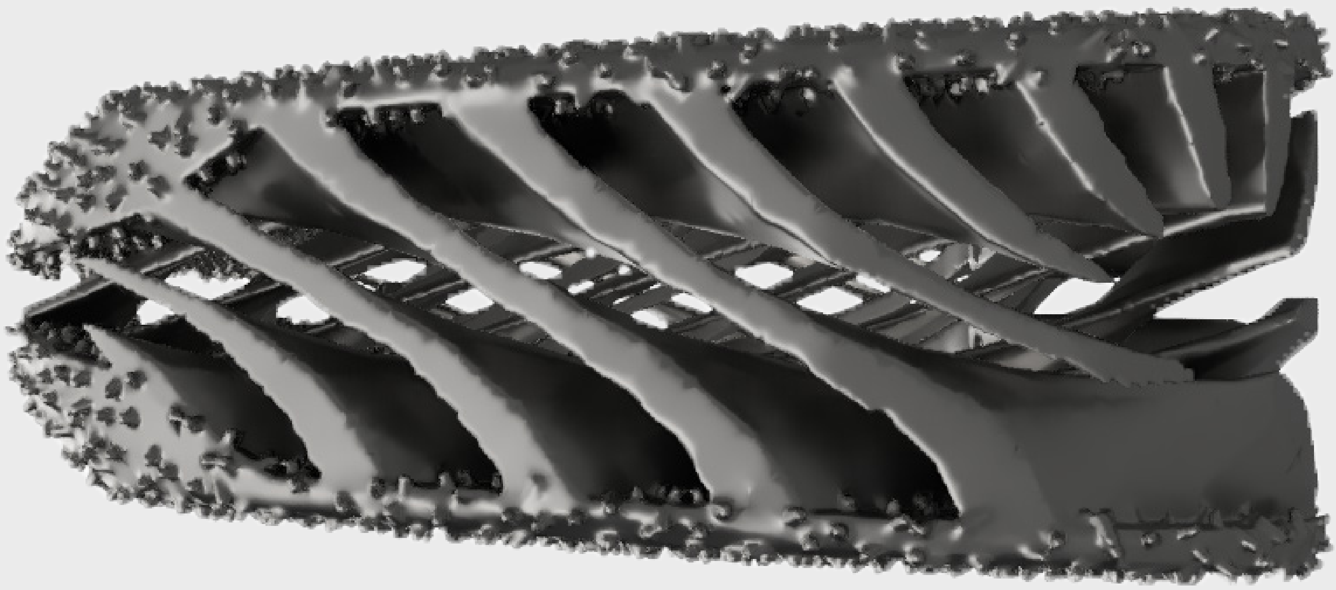
Rapid progress is being made to industrialize AM. It has been particularly successful in the aerospace and aviation industries. For example, since 2015 General Electric has been mass producing its LEAP engine fuel nozzle using AM. In the commercial aerospace industry, additive manufacturing has become second nature. Leaders such as SpaceX, Blue Origin, and Virgin Orbits are regular designers of large-scale machine parts fabricated using AM.



These advances are extraordinary, but a significant limitation to the use of large-scale AM has been the need for reliable quality assurance and control (QA/QC) of the manufactured parts. Understandably, the required concomitant advances in QA/QC lag behind advances in fabrication. As AM becomes more prevalent in various industries, there is a need to expand the scope of existing QA/QC techniques, particularly when failure of the component leads to unacceptable or untenable consequences.

Principles of quality control and assurance that apply to other modern manufacturing methods also apply to AM. However, traditional QA/QC techniques may be insufficient or fail to adequately inspect AM components due to their structural criticality or uniquely complex geometries. For example, a complex heat exchanger built by AM might have internal cooling channels that are not visually observable or inspectable without sectioning the part, and in so doing, destroying it. Topological optimization can reduce the amount of material used or wasted. However, less material and same or better performance often means the part is more sensitive to structural defects, making requirements stricter. Traditional QA/QC would require that the components be destructively characterized in order to observe the features or defects of interest. Obviously this cannot be done for every produced component, and with such strict tolerances, sampling won't provide complete assurance that every part is acceptable.

What might be the solution? QA/QC for AM components must make use of nondestructive testing (NDT) and evaluation techniques in order to preserve the produced parts. One technology that lends itself remarkably well to this area is 3D computed tomography.



# Additive Manufacturing and Non-Destructive Testing (NDT)

It's clear that for reliable quality assurance of additive-manufactured parts, non-destructive inspection is necessary. 3D computed tomography, also referred to as 3D CT or just CT, is an effective tool for NDT. Over the last decade, improvements in CT scanning speeds, image accuracy and resolution, and operational efficiencies have led to inline CT, in which inspection occurs practically at the same time as the production line is producing the machine part. This has made CT viable for large-scale automated defect recognition (ADR) in a production environment.

*3D CT is a method of creating 3D images from a set of transmission radiographs (X-rays).*

The radiographs are acquired with a known geometry of the key components and for a selected set of scan parameters. During a CT scan, an object is rotated and thousands of pictures are taken at a variety of comprehensive angles, creating a 3D volumetric data set.

| | X-ray Computed Tomography (CT) | Metallography | Coordinate Measurement Machine (CMM) | Blue Light Scanning |
|---|---|---|---|---|
| Measures component external geometry | X | | X | X |
| Measures engineered holes in component | X | | X | X |
| Measures non-orthogonal features | X | | | X |
| Measures component hidden features | X | | | |
| Detects material flaws | X | X | | |
| Yields results that can be directly compared with CAD model | X | | | X |

Table 1. Comparison of Non-Destructive Testing Methods[4]

This data set consists of voxels (volumetric pixels), where each voxel is a measure of the X-ray attenuation for that scan of the object at that 3D location. After image acquisition, sophisticated software combines the acquired data, imaging geometry, and scan parameters selected by the user to create a 3D volume of the piece.

Additive manufacturers need to analyze many aspects of their processes, among them feedstock characteristics, material characterization, porosity, lattice structure visualization, and surface roughness. They may also need to perform nominal actual comparison (NAC), finite element analysis (FEA), or reverse engineer a part[3]. CT can assist with all of these, but the aspects most frequently requested for production processes fall into two categories – discontinuity analysis and dimensional measurements.

While there are a number of traditional methods for NDT, most of them are limited in what they can detect, so they must be used in conjunction with one another. On the other hand, 3D CT is ideal for addressing all of the needs of NDT. Table 1 compares 3D CT with other NDT characterization techniques:

As the table shows, CT is suited to multiple QA/QC evaluation tasks — a one-stop shop for AM components. By using a single technology, rather than needing several different types of equipment and staff with varied operational and interpretive skillsets, CT analysis could well present a cost-effective alternative to using multiple other NDT methods.

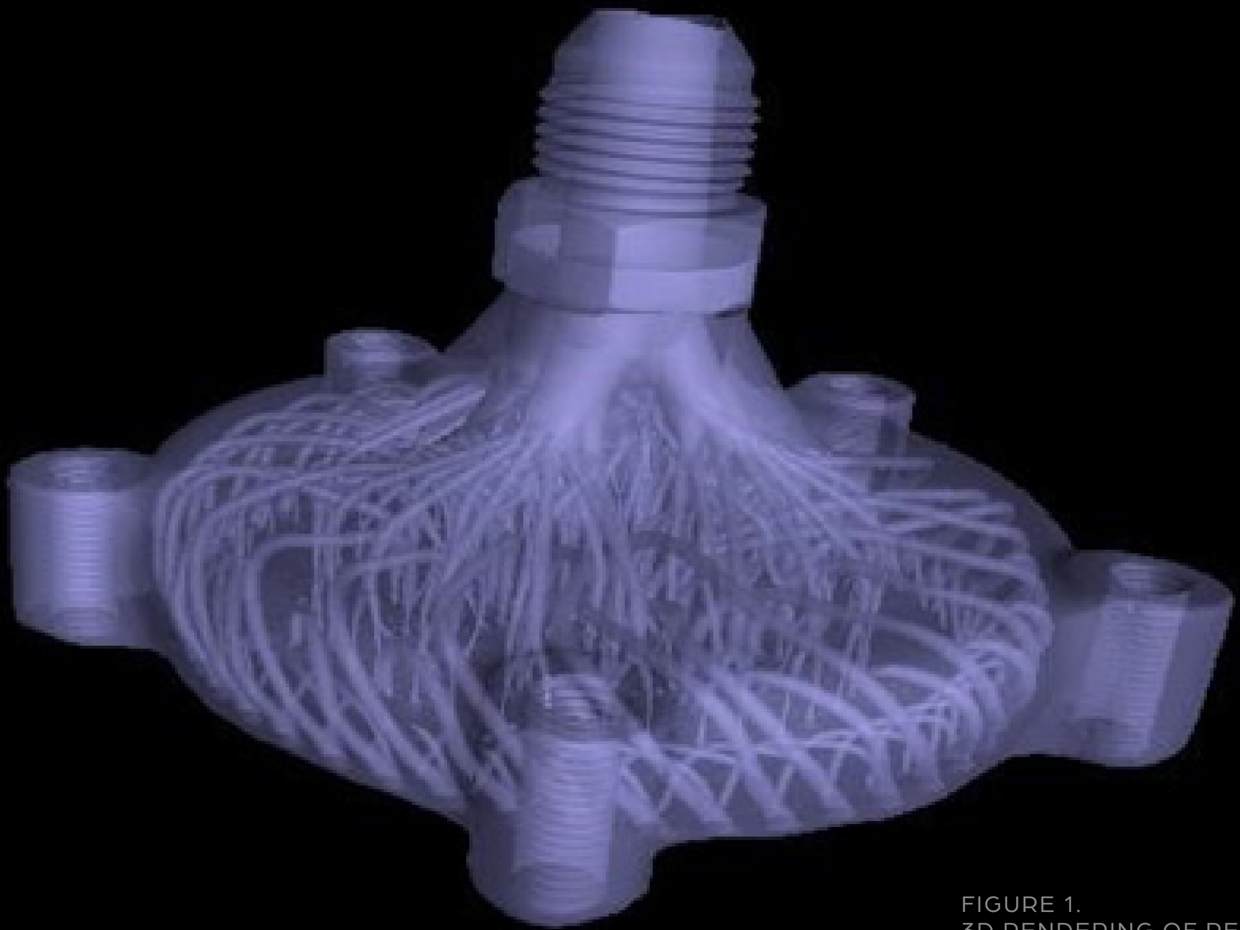


FIGURE 1.
3D RENDERING OF RESIN-PRINTED FUEL INJECTOR[5]

# Analyzing AM components with CT: Some Examples

**An illustrative example of the use of CT for QA/QC of a commercial product is of a resin-printed fuel injector made by Additive Rocket Corporation (Figure 1).**

The part has two types of inspection requirements: defects identification and geometry measurements. For defects, material requirements are localized. Material near the exterior bolt holes and in the body have different measurement criteria: The degree of porosity is important for material surrounding the bolt holes, to meet strength requirements, but what's most important for the interior channels is wall thickness and channel diameter at various points, because the dimensions are carefully designed to control the flow of the high-pressure liquid going through them. Without CT, multiple methods and equipment types would have to be used to determine these characteristics, possibly including destructive ones like cross-sectioning.

*AM manufacturing technology has progressed to the point where fabrication speed might be only a few minutes per part.*

Increasingly, CT scans can achieve the high throughput needed to keep up. In addition, CT is valuable for "before and after" testing, in which after post-fabrication initial testing, a completed part is subjected to environmental stresses such as simulated low temperatures and the vacuum of space for rocket components, to see if the part holds up.

Another example is from the medical arena. At Worcester Polytechnic Institute, 3D-printed porous silicone, essentially a foam, is being explored as drug-loaded scaffolding for localized drug delivery and for tissue regeneration. The porous structure is the frame for tissue to grow onto. Researchers use CT to examine critical cell characteristics such as size, sphericity, contact surface, and curvature. The material has extremely low density and easily gets dehydrated in the air, so cell structure information must be obtained quickly after fabrication. This can be achieved with CT equipment that is immediately available in the same location.

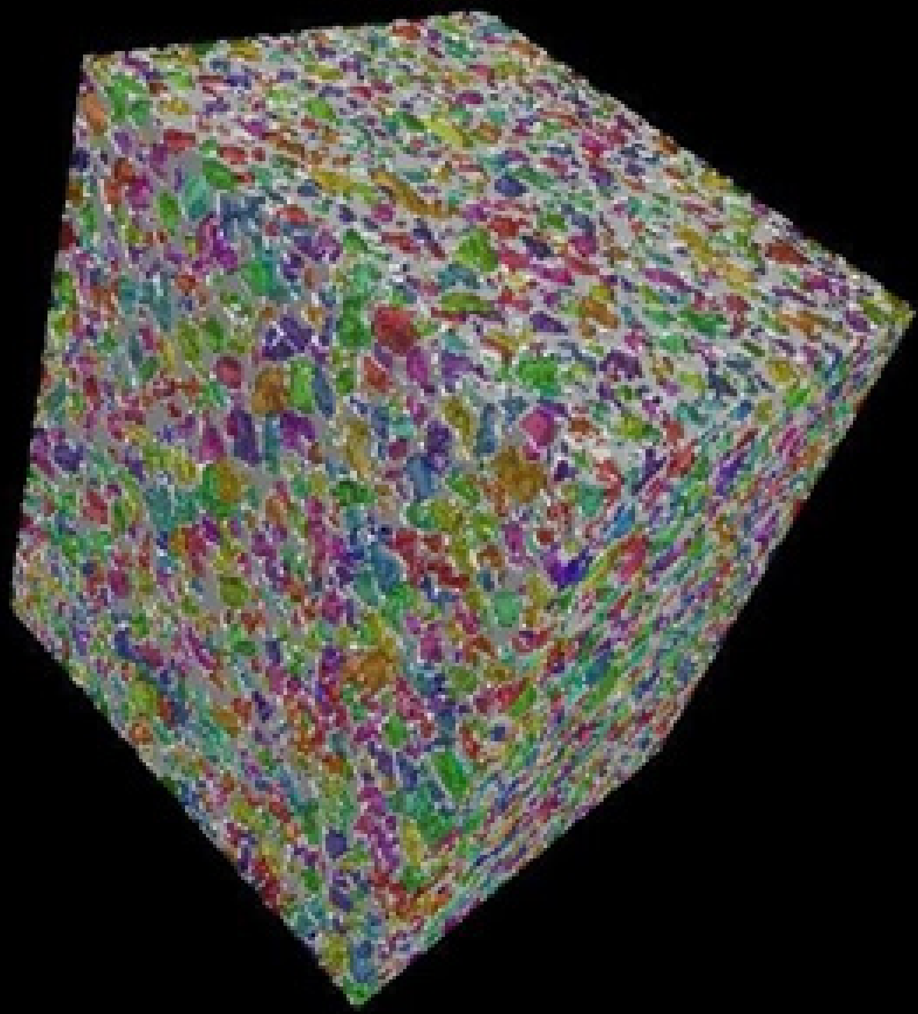
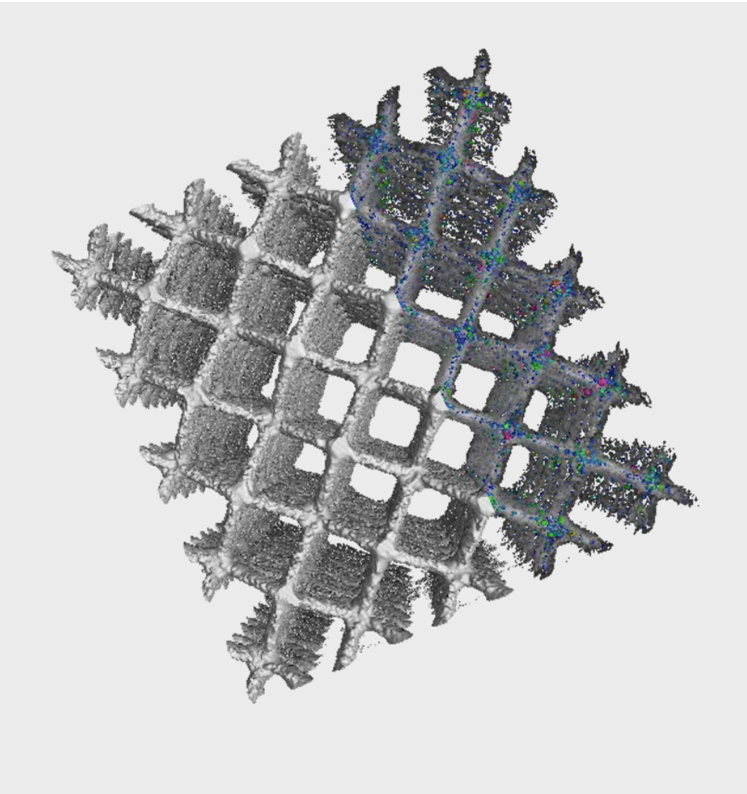
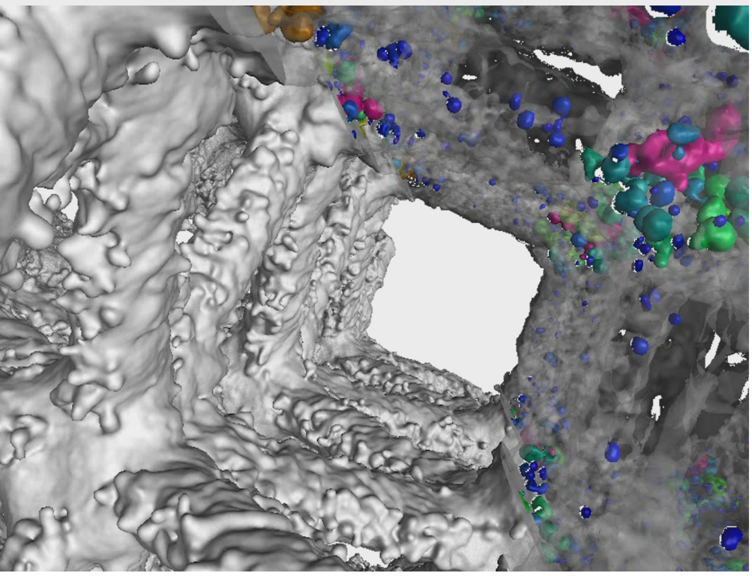


FIGURE 2. 3D RENDERING OF PRINTED SCAFFOLDING FOAM[6]

# New Frontiers: Challenges in to Using 3D CT for AM





**As the use of AM increases as a large-scale manufacturing technique, opportunities abound for parallel growth in the use of CT.**

At the same time, identifiable challenges remain. Some are physics based — for instance, how X-rays interact with different materials — while others are technologically based, such as when current diagnostic systems are too small or not fast enough. And finally, there is also a human element. CT systems are complex, scientific instruments. CT imaging typically requires well educated, highly trained specialists to correctly operate, maintain, modify and troubleshoot the machines. One of the biggest challenges with automated CT today is the need to simplify the operation so that less specialized users can operate machines just as effectively.

Some challenges are moving targets. For example, thanks to ongoing research, it's becoming possible to 3D print larger and larger parts in shorter times, meaning that CT machines need to both accommodate larger parts and have faster throughput. Some researchers and practitioners are challenging the current ASTM definition of AM by printing 3D shapes all at once, rather than by a gradual layering process, which would also mean that CT evaluation of each part needs to occur more quickly.

Due to experimentation and success of using new materials for AM, some parts are now being made of heavier and denser elements than before. This introduces more physics-based challenges because such materials require high acceleration voltages for X-rays to penetrate them, and high current settings to get an acceptable transmitted signal on the other side of the part. As a result, a relatively large focal spot size is generated, which results in less clear images.

Other issues involve current testing paradigms. Typically, AM test artifacts are not designed with CT in mind. For example, a NIST (U.S. National Institute of Standards and Technology) artifact originally designed to test AM printer capabilities has too high an aspect ratio, causing difficulties in CT imaging. Conversely, many existing CT "phantoms" (objects used as stand-ins to test and calibrate CT machines) were not created using AM, so are not suitable for tuning CT machines for their designated AM uses.

*Imaging at the speed of production remains one of the most significant blockages in 3D CT scanning today.*

This is mainly because CT analysis itself comprises sets of complex software algorithms that process large amounts of data collected by X-ray detectors.

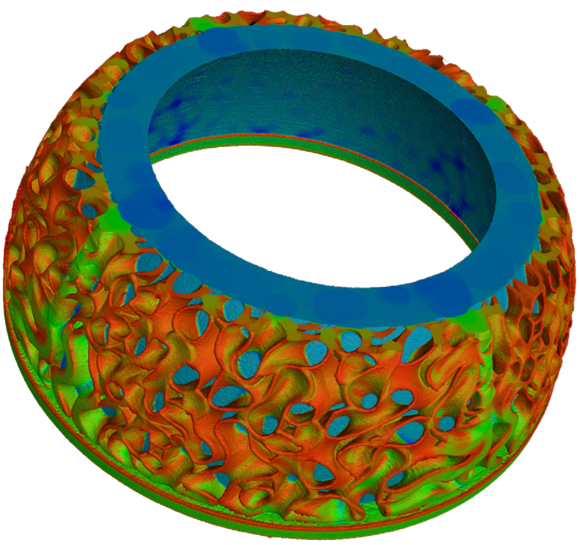
Inline production and inspection means that critical components with complex material structures or internal geometries are inspected at the same rate they are being produced. No time-lag occurs, maximizing production and product sign-off efficiency. So, if a production line is making a part every 30 seconds, maximum efficiency would require an automated inspection to take place within that same 30 seconds. Technologies that enhance both speed and function at that the development of automated inspection are, in some ways, still in their infancy.

Yet, it's possible. Just five years ago, it could have taken hours, even days for detectors to run their software algorithms, create 3D images and analyze the data. Now, days have become hours and hours have become minutes, so it's not unreasonable to expect those minutes to be further reduced to seconds.

*The technological hurdles we've described can be overcome, as they have in the past, by cooperation among CT manufacturers, systems integrators and their customers.*

Researchers and industry advocates who understand the intersection of these two complementary technologies — AM on the one hand, and CT, on the other — are beginning to work together to solve these issues and push the technology further.

For example, the Advanced Casting Research Center (ACRC) at the University of California, Irvine, a consortium of over 30 manufacturers and research entities, is engaged in projects as diverse as innovative AM techniques and the application of big data to manufacturing process improvement. Collaboration is also growing among traditionally separated AM and CT research and standards groups such as in subcommittees of the ASTM. Work of this sort will do much to iron out existing and future issues.



# Taking Advantage of CT for Large-Scale AM

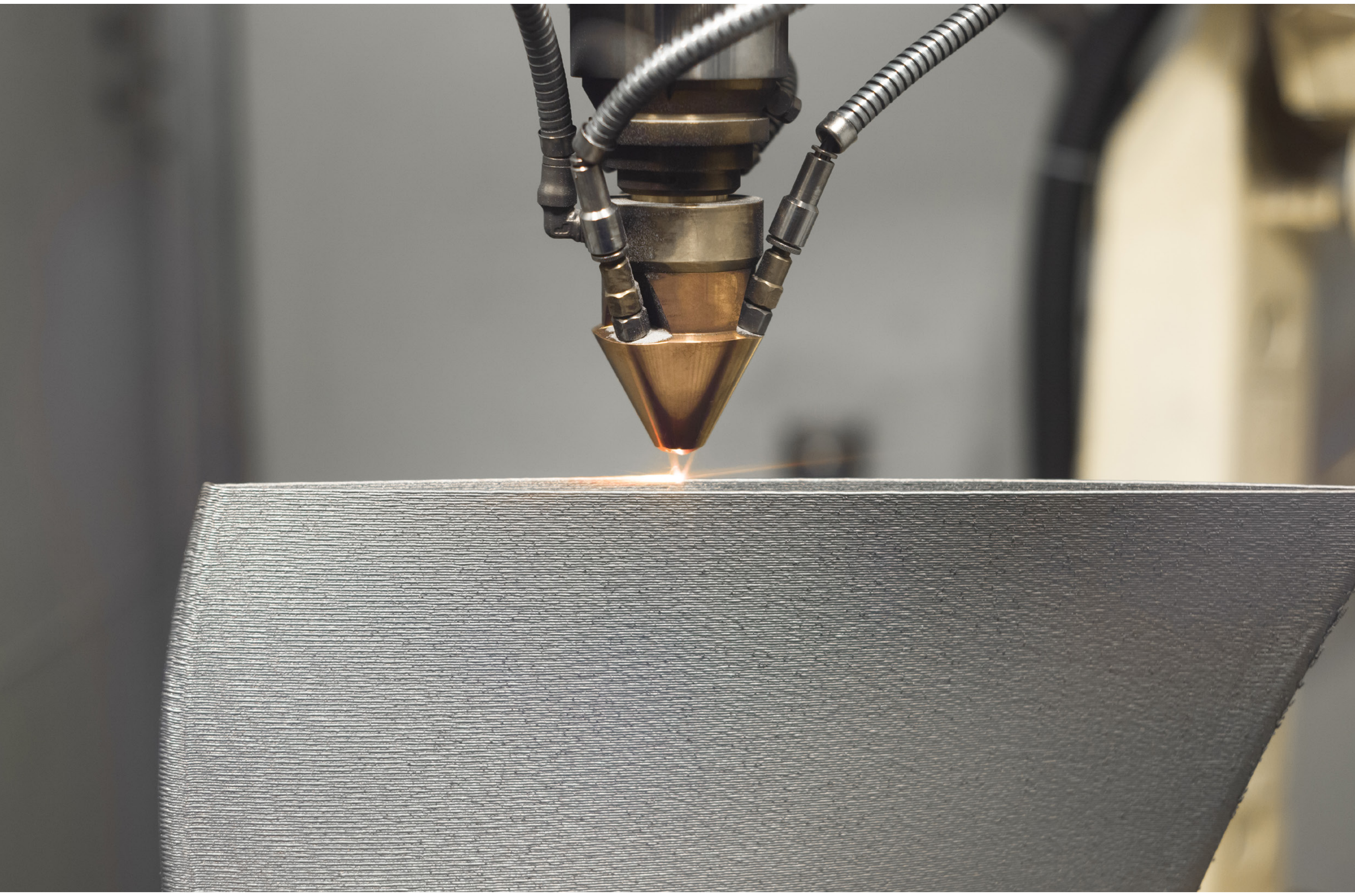
**Additive manufacturing at scale is in and of itself is revolutionary. It encompasses multiple methods and technologies, from laser-induced techniques to large material welding, and gives manufacturers the ability to develop and fabricate from new materials that match the requirements of any given component.**

At the same time, the advantages of automated inspection can't be understated, and the utilization of 3D CT precision scanning for repeated, dependable, automated defect recognition may well be the evolution catalyst for many industries to fully enter the AM space.

In fact, automated defect recognition done via CT brings qualitative advantages to the QA/QC process that might not be immediately obvious. We like to say that "ADR" actually stands for Automated Deviation Recognition, because besides identifying flaws in the actual manufactured part, it can also help flag undesired changes in the manufacturing process; for example, if unexpected material, say dust due to a manufacturing error, is embedded in the part. 3D CT will also identify misalignment of the scanning equipment itself.

Continuing advances in CT equipment advancements in recent years show that it will continue to evolve and be refined to meet the developing needs of handlers of CT for AM – from scanning speed to image accuracy, from labor intensity to operational efficiency.

In support of additive manufacturing at scale, ideally suppliers will leverage their expertise and develop and improve automated software algorithms that analyze defects using 3D instead of 2D data. There is demand for 2D technologies to grow into the 3D CT space – and who better to set new expectations for inspection than users of additive manufacturing and consumers of NDT CT themselves?



# 3D CT and Beyond

**As industry turns its attention more and more to AM in the coming years, the need for 3D CT will increase exponentially, enabling the development and production of AM components quickly, cost-effectively, and of uncompromised quality.**

As with other Industry 4.0 advances, CT, as a modern digital inspection tool, will support cost reduction, quality improvement, and enhanced output.

We foresee many 2D applications being replaced with CT in next 5-15 years. There is little reason to only look at a machine part in 2D when 3D provides more data with minimal logistical or cost imperatives. For both AM parts and more traditionally manufactured objects, the future of X-ray inspection will be in the 3D space.

When investing in best-in-class 3D CT for automated inspection, the initial outlay may appear daunting and costly, but when we consider how technology assists manufacturers in making the right decisions quickly, the longer-term cost-savings become evident.

# VJ Technologies, part of the VJ Group

**Founded in 1987, VJ Technologies is a leading global provider of X-ray inspection solutions. We apply our radioscopic digital imaging expertise to government agencies and nondestructive testing markets throughout the world.**

VJT imaging systems are used for radioscopic inspection of products and assemblies to detect defects or foreign matter, reducing cost and time while increasing quality and safety. VJT delivers a competitive advantage and superior customer service through our network of global offices.

*Together with VJ Electronix and VJ X-Ray, its companion divisions of the VJ Group, VJ Technologies continues to develop new X-ray based inspection systems and solutions that exceed our customers' needs and provide product development and application-specific solutions.*

With more than 30 years of solving the toughest challenges at the world's top companies, we've developed the relationships and expertise to choose the correct combination of imaging components to deliver the perfect system to meet your project's requirements, processes and budget. And our work with industry partners as a member of the ACRC consortium enables us to better anticipate and meet ever-evolving inspection challenges. VJT's best-of-class imaging toolsets and ability to develop proprietary, custom and configurable solutions is what makes VJ Technologies unequaled in the industry.

VJT X-ray products and inspection services comply with ASME, ASNT, EN and all other relevant global industry standards, as well as give you the ability to meet even higher internal compliance standards. VJT equipment is used around the world every day to verify the safety, efficiency and performance of AM and non-AM components in aerospace, automotive, electronics, medical devices, defense, and consumer products.

# Veda CT Family of Products

**VJT's Veda family of products includes the VedaPro.**

VJT's VedaCTPro, with the dual tube 450kV/225kV Option, satisfies the requirements of AM NDT through its delivery of dependable customized 3D CT solutions – advanced CT that is set to transform automated inspection through its unwavering capabilities in speed and high-resolution imaging. Granite-based and well-known for its effective absorption of vibrations, the VedaCT meets all expected world standards and, utilizing industry-leading hardware, supports a wide range of applications, including AM.

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VJT develops and manufactures a complete line of automated, manual, and turnkey X-ray inspection systems for a wide variety of industries. Our primary market sectors include aerospace, automotive, electronics, remediation, nuclear, oil & gas, and pipe & weld applications. VJT Inspection Services provides a full range of expert Inspection Services (IS) to meet your needs, In-house or in-the-field.


[1] X. Wu, Y. Su, and J Shi, "Perspective of additive manufacturing for metamaterials development", Smart Materials and Structures, 28, 093001 (2019).

[2] F. Mezzadri, V. Bouriakov, X. Qian, "Topology optimization of self-supporting support structures for additive manufacturing", Additive Manufacturing, 21, 666682 (2018).

[3] R. Biswal, X. Zhang, M. Shamir, A. A. Mamun, M. Aud, F. Walther, and A. K. Syed, "Interrupted fatigue testing with periodic tomography to monitor porosity defects in wire + arc additive manufactured Ti-6Al-4V", Additive Manufacturing, 28, 517-527(2019).

[4] Dai, Chen, and Boguski, Robert, "New Paradigm in Additive Manufacturing: Utilization of Computed Tomography," Proceedings of SMTA International, Nov. 15- Dec. 31, 2021, p. 290.

[5] Ibid, p. 290.

[6] Ibid, p. 289


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