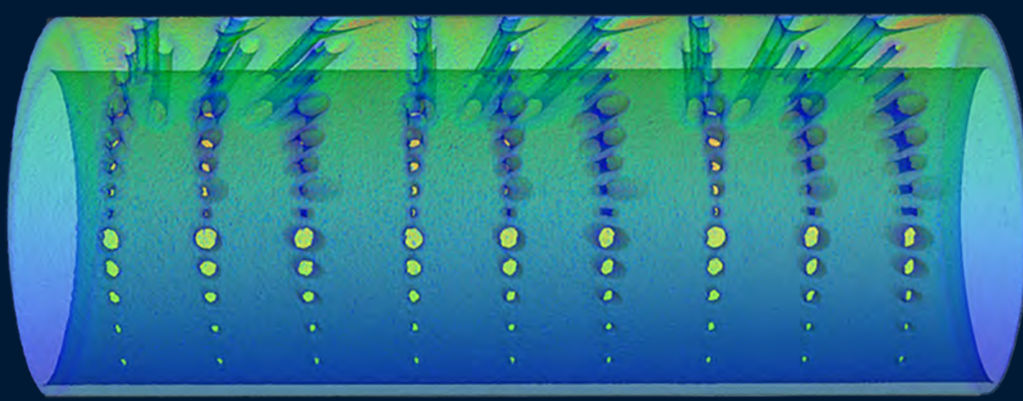
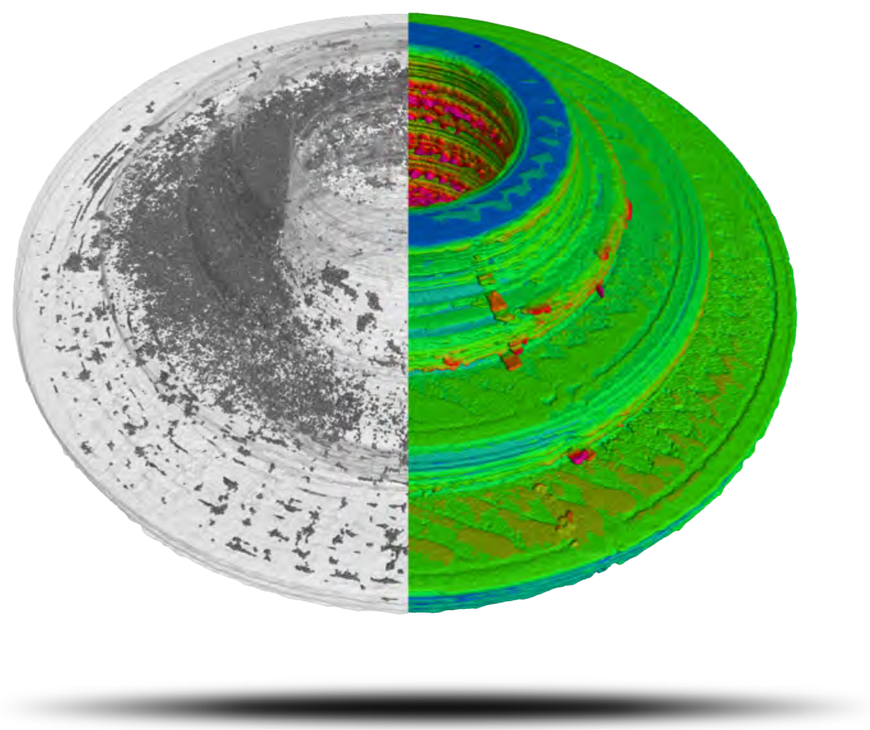


BACK TO THE FUTURE:

How CT Can Predict the Performance of Agile Additive Manufacturing Designs

What you will learn in this paper:

- CT: from a quality inspection to an informational tool
- Testing materials before production with CT
- Reducing cost, risk and time in manufacturing
- CT in research and development



Additively manufactured valve spring retainer

BACK TO THE FUTURE:

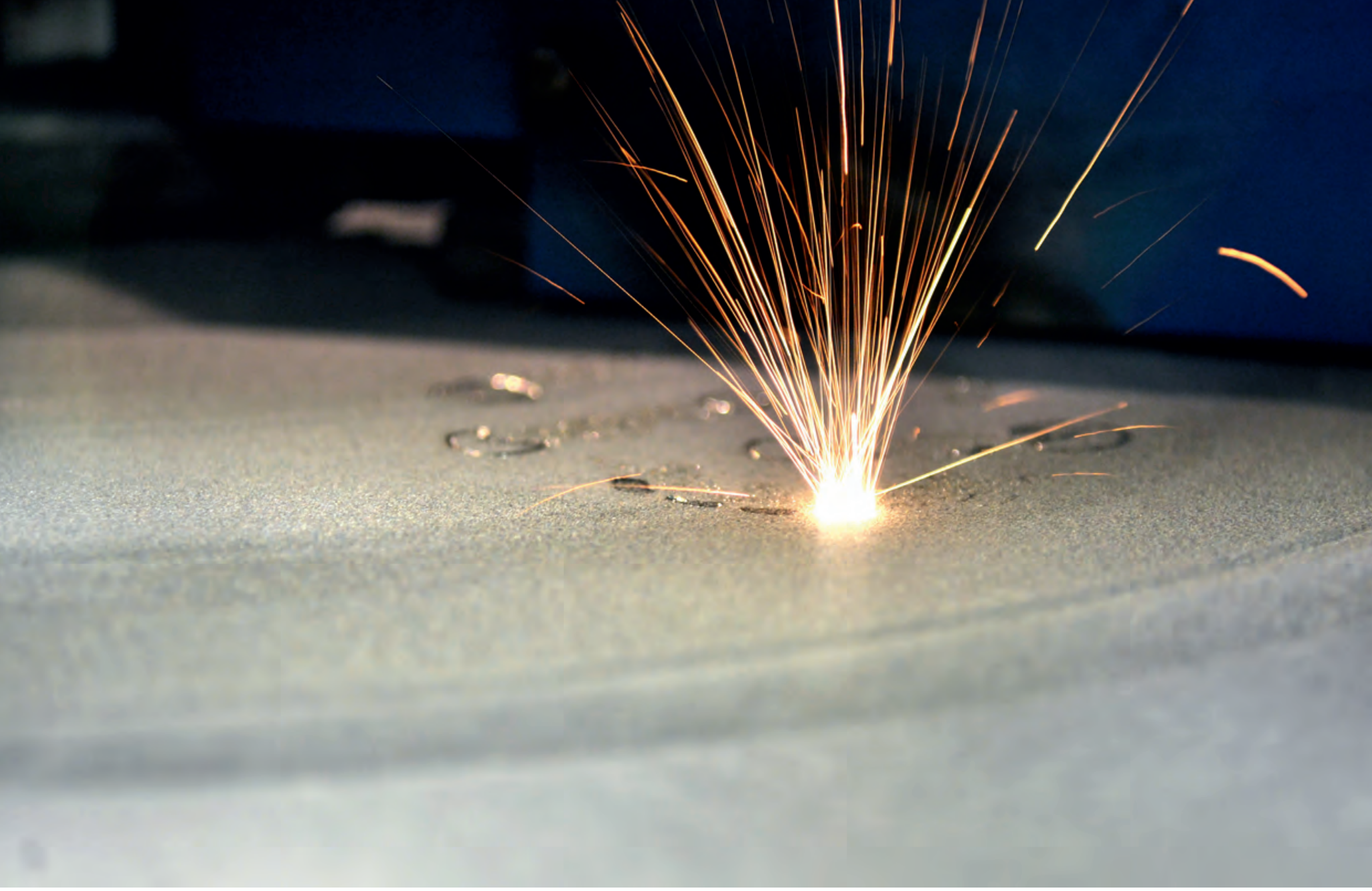
How CT Can Predict the Performance of Agile Additive Manufacturing Designs

Additive manufacturing (AM) is one of the most revolutionary processes to come along in many years, making a dramatic impact on the industrial market. Also known as 3D printing, AM is a manufacturing technique that builds objects layer by layer using materials such as polymers, metals, and composites. This fast-evolving technology is changing the way engineers think about product design by offering enormous flexibility in what is geometrically possible. However, the more complex the design, the more challenging (and necessary) it can be to inspect in the quality control process.

Many additive manufacturers and designers have adopted industrial computed tomography (CT) to perform non-destructive testing (NDT) on the part to ensure quality throughout the R&D and production processes. A CT scan produces a 3D volumetric density map. The 3D-volume is generated by the reconstruction of a high number of 2D x-ray images. Many 2D projection images can be combined by powerful software to produce a 3D volume of practically any part, object, or product. This is critical for any application for which a manufacturer wishes to see inside an object without destroying it – and the inside is where the complexity is increasing with this new manufacturing process.

While CT technology has taken its rightful place as a viable NDT tool, many engineers may not realize what an important role it can play in the discovery phase of research and development. Utilizing CT in R&D can avoid many issues later in the production process by identifying key information about part design, raw materials and how well it matches the intended geometry, all of which are vital to the success of the product. Once designers discover the power that CT can enable as an informational tool rather than just a quality tool, they will never look at CT the same way again. This white paper will help to educate design engineers on the benefits of CT in evaluating part designs to determine how the part will perform, if it is fit for purpose, and if there are any variables in measurement. As with all good things, the information retrieved at the very beginning can help the designer to be more agile and to avoid costly downtime later in the design and eventually production stages. It will also clear up any misconceptions about CT and clarify how recent technology improvements in CT scanning speed, resolution and price-performance ratios make it a great tool for use in the early R&D phase.

Learn more about CT in AM:
www.yxlon.com/additive_manufacturing



The Future of Manufacturing: Industry 4.0

Industry 4.0 is transforming industry by changing the way industrial companies operate from day-to-day, by efficiently and effectively leveraging new digital and robotic techniques into the manufacturing process.

Such technologies include cloud services, IoT sensors and activators, robotics, wireless networking and more. These would be intelligently combined with manufacturing machines to create what one might call a SMART factory.

AM is one of the key technologies that could help revolutionize the manufacturing value chain with the onset of Industry 4.0 because the new technologies it brings lend themselves to the customization that can be done with AM. This will bring about a shift from mass production to full customization, and from centralized to distributed production. Further, AM offers a potential to change the supply chain as we experience it today. It extends the current concept of product development and enables people not only to develop customized products, but also to manufacture them more efficiently.

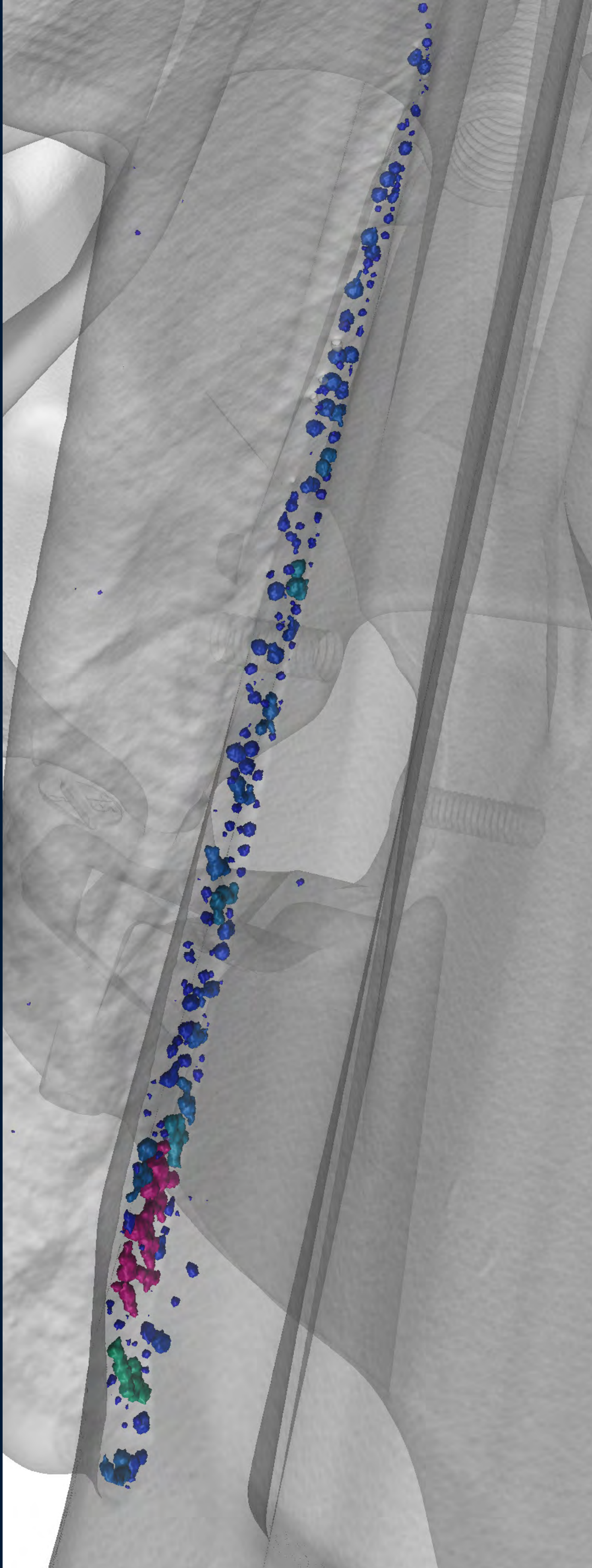
Additive Manufacturing – A Growing Industry

Starting out mainly as a prototyping technology, additive manufacturing has gained tremendous momentum for use in industrial applications during the last 5 years. For highly demanding functional parts, laser beam powder bed fusion (LB-PBF) became the most dominant AM technology. In the past two years, binder jetting technology (BJT) and fused deposition modeling (FDM) of metal components raised end user expectations to enable new applications by massively reducing cost.

Conventional manufacturing techniques can produce a great range of shapes and designs, but additive manufacturing takes production design to the next level. One of the greatest benefits of this more modern technology is the greater range of shapes and inside features that can be produced. Designs that can't be manufactured in one entire piece with traditional means can easily be achieved. For example, shapes with a scooped out or hollow center can be produced as a single piece, without the need to weld or attach individual components together, and weight can more easily be reduced by internal structural design changes. This has the advantage of being stronger, with no weak spots which can be compromised or stressed.

Before AM, the limitations of production all too often influenced design, ruling out ideas because they weren't practically achievable. The introduction of this technology and its development means the process has been turned upside down with design now driving the production.

YXLONs 3D-printed specimen for internal tests and developments in the field of Additive Manufacturing



Systematic porosity in a hybrid part (metal casted base part with additively manufactured structures). The CT scan offered deep insights into the interdependencies between two different manufacturing technologies. The processes could be adapted accordingly to eliminate the root cause of the porosity.

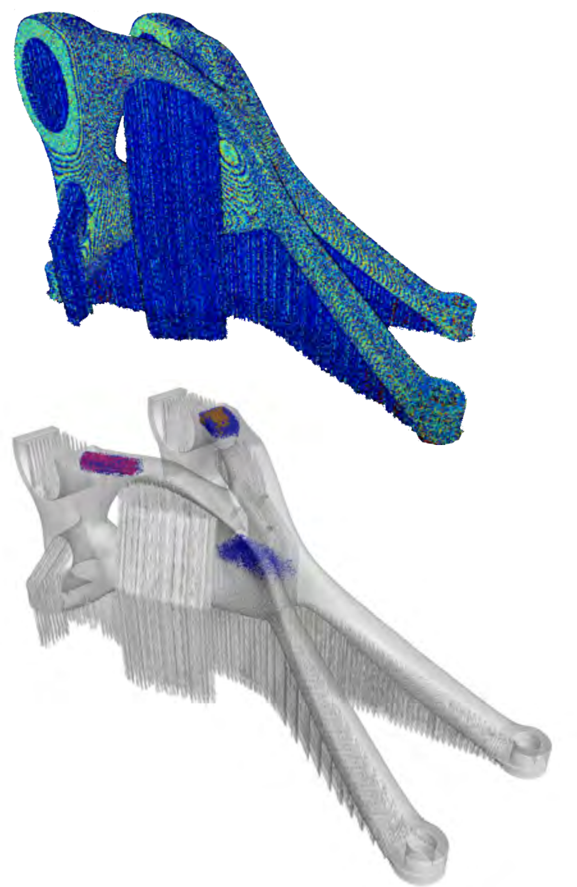
CT Technology in the AM Process Chain

One of the main advantages of additive manufacturing is that it allows designers the freedom to create more than they have historically imagined. However, that freedom can come with a compromise since the more intricate and complex the structure is the more difficult it can be to inspect. This can create quite a challenge for busy manufacturing plants to remain productive. That is where the power of CT scanning comes in.

CT is the best and most accurate NDT method to authenticate the actual build quality of the part. The enhanced capabilities that CT provides result in versatility and product information that you won't find anywhere else. CT virtually eliminates evaluation error and gives you a visual understanding of your product that you may have never seen before.

CT has been widely adopted by AM plants as a tool for non-destructive testing, but there are many other areas of the production process chain where CT can provide valuable information. Think of your Industrial CT scanner as a versatile tool box with many capabilities to assist you throughout the production process. You can perform non-destructive testing of parts and prototypes as well as research and development. Using the acquired CT data in simulations can help validate the engineering design and performance to ensure that the part is fit for purpose as well as provide proof that the concept will work as it is intended to.

Furthermore, CT's advanced data allows analysis and programming with speed and efficiency. Design engineers always operate in an environment where time is of the essence, where fast, accurate data is crucial. Using CT scanning, most inspection reports are complete the same day that the items are received. The reason is the part can be programmed ahead of time using a CAD model and 2D drawing before it is scanned.



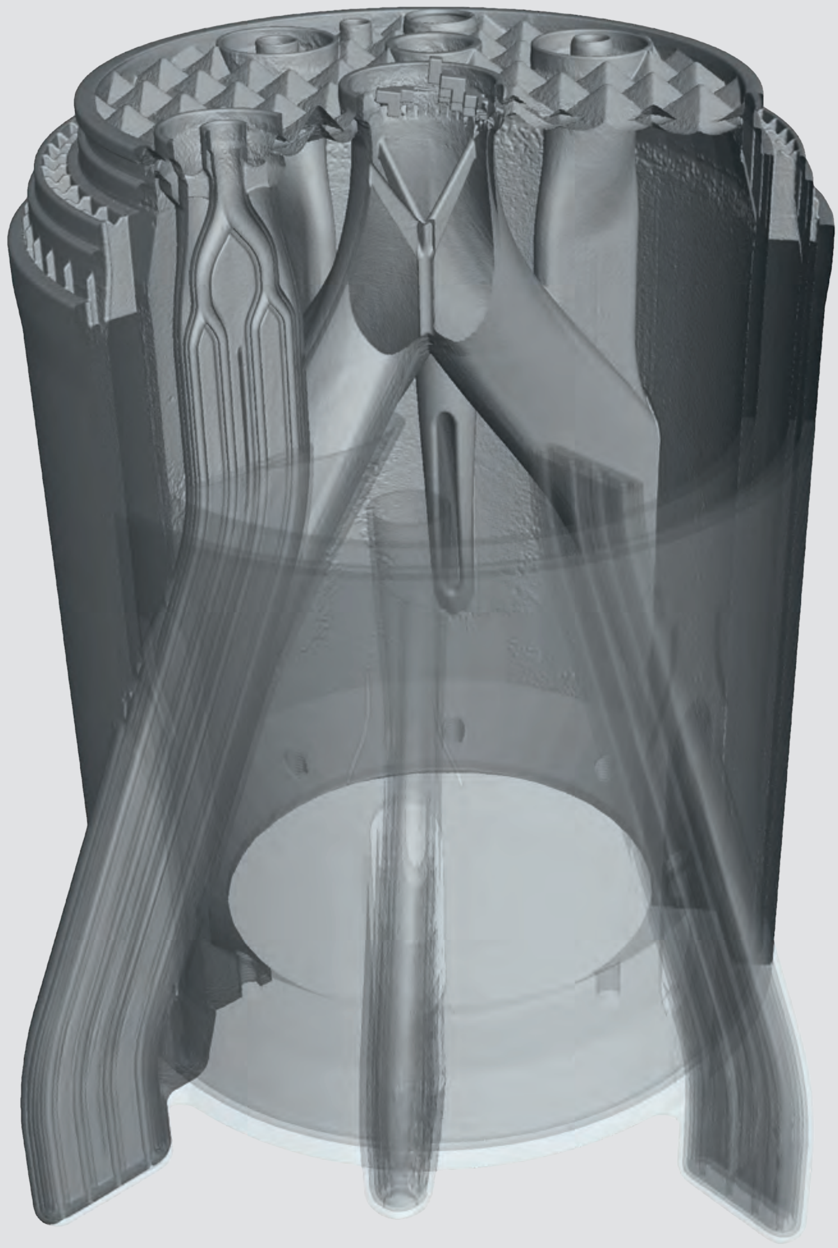
Comparison between online-monitoring data and a CT scan of a 3D-printed bracket. CT helped to correlate monitoring data with actual part quality parameters.

Benefits of CT as a Quality Assurance Tool

CT scanning can help ensure quality in testing results with new innovations to solve the most challenging NDT problems faced by additive manufacturers. Some of the typical flaws that come from the powder bed fusion process such as porosity, lack of fusion, balling (which comes from surface tension of the liquid metal), excessive surface roughness and micro-structural issues can all be detected easily by CT. The CT scan data makes it fast and easy to identify these issues sooner, thus reducing time and increasing productivity. For additive manufacturing, the ability to see inside an object is critical since internal structures can be seen in their functioning position. Also, devices can be analyzed without disassembly. Software programs for industrial CT scanning allow for measurements to be taken from the CT dataset volume rendering. These measurements are useful for determining the clearances between assembled parts or simply a dimension of an individual feature. CT has even become advanced enough for you to conduct precise measurements of internal structures which is especially critical to quality assurance in additive manufacturing.

Other challenges including density variation, embedded features, organic part design, dissimilar metals or materials and surface finishes are all easily detected by CT better than any other NDT technique. With CT you can scan it and resolve all these issues in a very finite amount of time.

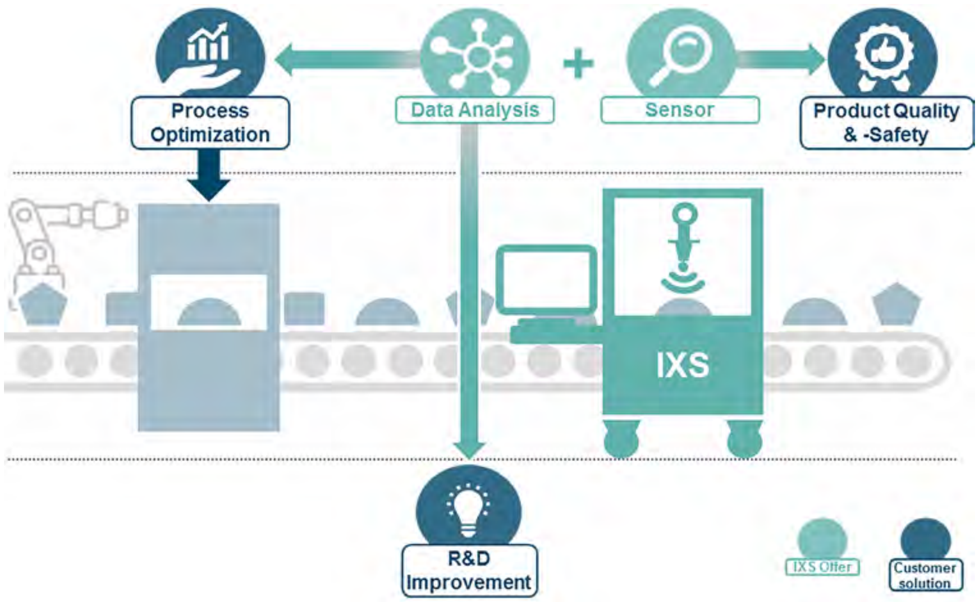
Adoption of this technology has enabled users to visualize internal structures in ways that were not possible before without sacrificing the part. Industrial CT has become a particularly popular choice for NDT because of the advantage it offers over any traditional 2D method by enabling visualization of the internal construction from every angle.



Additively manufactured measuring probe for a rocket engine test stand

© RSC Engineering GmbH

Bionic design of a helicopter bell crank.



The Power of CT as an Informational Tool for Research & Development

As CT becomes an increasingly popular choice for NDT in additive manufacturing, the role of CT is beginning to expand from a quality inspection tool in the production phase to an informational tool in the research and development stage. In order to gain future information about how a design will perform in production, we must start at the very beginning. One of the biggest challenges that design engineers face in the development process is making sure that the final part has good properties. From a material science perspective, that is probably the biggest challenge of additive manufacturing. How do you reduce the number of defects that could form? If powders don't completely sinter together, it forms defects that may lead to failure. Residual stress can develop based on how the metal is processed which can cause internal strain on the material and lead to cracks in the part.

Due to the relative newness of additive manufacturing, researchers are still trying to understand the many different aspects of it, how the materials work together, and how to decrease the likelihood of defects in final parts. By using industrial CT as an informational tool, you can test the materials and conduct materials simulations beforehand which will solve many of these issues and optimize the manufacturing process. Information gained from the CT data can effectively be transferred to plant production lines, reducing the cost, risk and time in manufacturing.

For instance, the helicopter bell crank was designed to reduce the mass of the original part while increasing torsional and bending stiffness. The organic shape is a great indicator of what is possible in metal printing and the tremendous opportunities that new additive manufacturing techniques can bring to the industry. The intricate design made it impossible to detect and measure the quality of the internal structures with 2D x-ray alone. CT was used to ensure that the integrity of the design was not compromised during the prototyping process.

> **Using CT systems for our research on additive manufacturing processes and 3D printed parts increases cost- and time-efficiency of our development cycles. This is why CT is an integral part of our daily business.**
>
> Elena LOPEZ, Dr.-Ing.
> Division Manager Additive Manufacturing
> Fraunhofer Institute for Material and Beam Technology (IWS)

Knowledge is Power

Utilizing CT as an informational tool in the design phase can lead to a smoother production process by identifying the following information:

Proof of Concept
CT simulation can help to verify that the design will be able to function properly and achieve the desired goal when fully developed and produced with the final printing parameters.

Fit for Purpose
CT can also simulate and determine the effectiveness of the design to fit its intended purpose, under anticipated or specified operational conditions.

Measurement
One of the most exciting advances in CT scanning is the ability for the latest systems to combine CT scanning WITH metrology measurements all in a single scan, as part of a single step. This is important in the research and development stage as the advantage of saving time in a simpler single process is significant.

Comparison to CAD
A CT scan can be compared to a CAD model or two CT scans can be compared to each other. This happens after the two data sets are registered with any of the common methods. This helps to ensure production accuracy.

Mechanical Simulation with CT Data

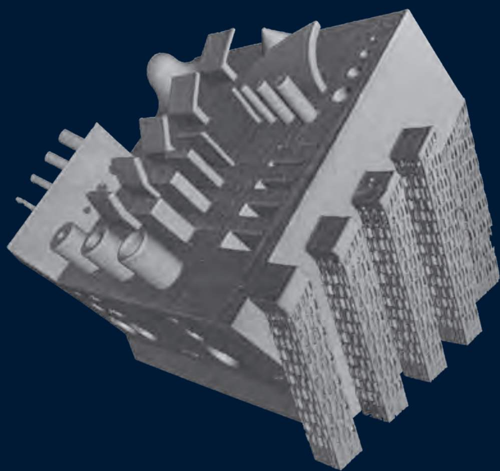
CT simulation can help to predict if the raw materials being used will react the way that they are intended for the part design. Mechanical simulation (FEM simulation) can be performed either enriching the CAD with the CT data provided by the system or using the CT data only. This allows engineers to simulate failures or defects with REAL flaws which is important in the R & D phase. If a part is going to fail it is better to discover that in the early phase of design and move on, rather than waste time and money in the long run. The more inconsistencies that can be discovered early in the process can eliminate issues later.

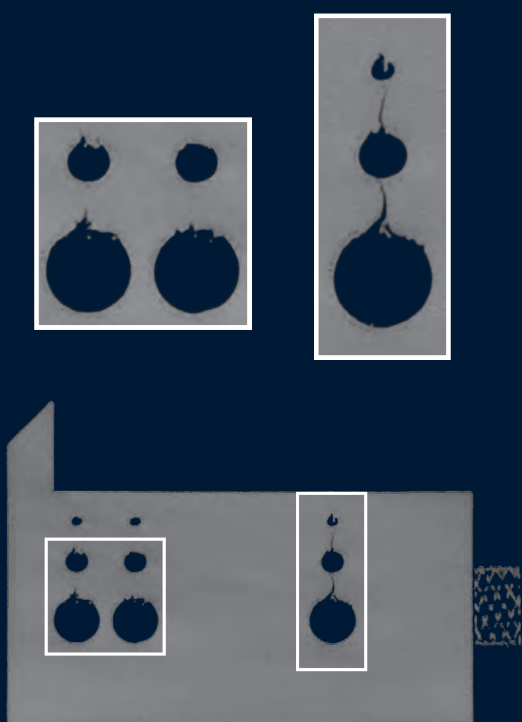
Dissimilar materials

Dissimilarities in the raw materials can lead to a decrease in the quality of the final product. Powder with dissimilar grain sizes can cause defects such as delamination while pores/gas inclusions within the grains (deflagration/mini explosions) can produce voids or defects in the finished part.

Surface Finish

CT can address many of the challenges that additive manufacturing design engineers face by enabling them to see the roughness of the part's inner surface so that you can make assumptions on the quality of the finishing.





2D slice

AM-demonstrator. Residual stresses inside the part lead to cracks.

Residual Stresses

In some additive manufacturing process, the part goes under repeated expansion and contraction from the heating and cooling of the build process. This repeated heating and cooling can lead to residual stress, a result that shows up as cracks, warpage and other forms of deformation. CT analysis in the development stage can provide helpful information into the materials used in the finished design and what to avoid using or doing.

Microstructure non-uniformity and anisotropy

Additive manufacturing processes offer the ability to create metallic parts with complex shapes without the expense and time commitment required with traditional approaches. However, the complex, non-uniform temperature histories of these processes result in materials with complex, anisotropic microstructures.

Density variation

One of the parameters to measure the quality of an additively manufactured part is the density, as it affects e.g. the mechanical strength of the product. Where other methods can surely give accurate information about the density of the tested part, CT allows engineers to get deeper into analyzing where the density variations within an AM part predominate. This helps to understand and adjust the production process and allows revealing potential weak points within the final product.
Besides the issues that can come up with the materials used in AM, the shape and complexity of the design can also cause problems if not properly inspected.

Geometric Limiting Factors:

Complexity
CT, combined with the latest software technology, provides the perfect tool for the efficient analysis of complex geometries using CAD to assist in the selection of critical feature -based data. The ability to select data, specific for the analysis of critical features, is key in providing information which can help improve and validate new processes for the manufacturing of complex parts.

Embedded features
Beyond inspection and quality control, CT scanning can aid in reverse engineering. Engineers can literally get an inside look at a part without having to disassemble it. Using CT scans, internal geometries and material densities are easily visible. The data gathered from these CT scans makes it far simpler to understand how a particular part functions or if it meets necessary specifications.

Organic/Agile part design
When it comes to designing new parts, the opportunities are endless. Engineers now have the freedom to design concepts that were not possible before and to change that design very quickly to try again. Instead of designing for manufacturing, they can manufacture to the design. CT is especially crucial for organic part design as it allows for pre-testing and validation of the CAD.

Hip cup implants. Additive manufacturing offers new levels of individualization and complexity.

Misconceptions about CT in Additive Manufacturing

There are many misconceptions about using CT in additive manufacturing. It's a relatively new technique for additive, so many are still learning about how it can be used. First, there's the common perception that CT is too slow, but advances in CT scanner design and technology during the past few years have eliminated this problem. Today's scanners have come a long way to improve speed and efficacy, more than doubling their production value. What used to take days or weeks to produce can now be done in a few minutes or hours. Also, stringent design and production standards have resulted in system durability that withstands the rigors of high-volume use.

CT scanning resolution has also improved significantly, resulting in crystal clear images that can detect even the most minute flaws. Many scanners can provide resolutions in the single digit microns range. This is quite a big step forward compared to past designs. Today's CT software has also gotten easier to use, with improved workflow design and advanced protocols to make reconstruction faster and better. While in the past CT's software and overall system complexity used to require staff with PhD-level education, today's CT systems can be operated by technicians in the lab or plant floor, making it a far more economical tool in practical use. Since both CT professionals and AM professional think in terms of slices, part orientations and 3D space, they have quite a bit in common. That's because great minds think alike.

Another common misconception is that you can't perform metrology using CT. That may have been true in the past but recently CT has become advanced enough for design engineers to conduct precise measurements in addition to just looking for defects. CT professionals are also now very familiar with metrology, so they can speak the correct language. Now we can do both – NDT and metrology – in the same machine.

And finally, there's the misconception that CT scanners are too costly, but the truth of the matter is you can buy a scanner for more competitive prices than you think. CT scanners have dramatically lowered in price during the last several years. CT inspection systems come in many different configurations, so you are sure to find the right choice for both your production needs and your budget. If you don't have enough volume to purchase your own unit, you can still get the benefit of rapid CT scan information through an outsourced service bureau or YXLONs Inspection Services. Don't forget the value CT adds to your process chain – saving you a great amount of money in quality related costs later.

The Shape of Things to Come

In the future, AM will provide even more alternatives to "conventional" manufacturing technologies in many situations. It will deeply impact the way products are manufactured, delivered and maintained.

From prototyping and tooling to direct part manufacturing in industrial sectors such as architectural, medical, dental, aerospace, automotive, furniture and jewelry, new and innovative applications are constantly being developed. Other uses of additive manufacturing will continue to present themselves – some companies are already experimenting with additive manufacturing to make everything from houses to food – especially as costs come down and the actual manufacturing speeds up.

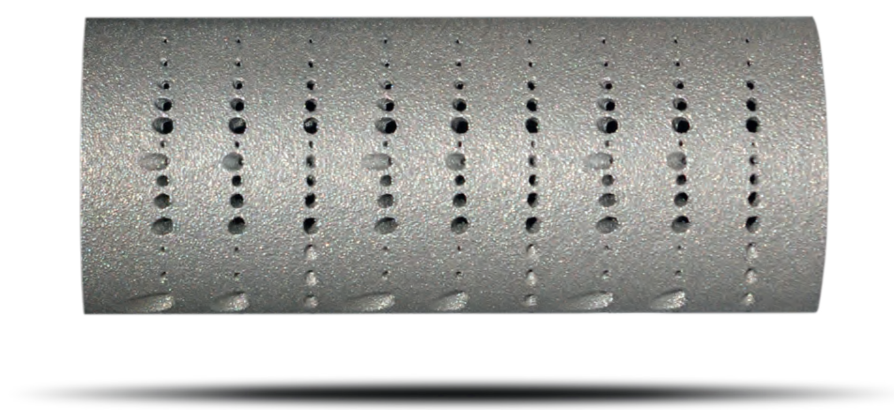
The demand for more complex part designs will increase as engineers discover the limitless abilities of AM to produce the most intricate geometric shapes and sizes.

- As stricter safety standards are employed by markets such as the medical and aerospace industries, the need for more informational tools in the research and development process will increase.

- The onset of technologies like self-driving vehicles, alternatively powered aircraft and the automotive electrification trend will also drive the demand for more intricate designs.

- The demand for decrease in weight will not only affect the aerospace industry but others as well. Medical, dental and automotive applications will demand lighter parts. In fact, the aerospace, automotive, and medical industries are expected to account for 51% of the 3D printing market by 2025.

- 90% of AM in the automotive industry is for prototyping and 10% for production – this will continue to shift.



Conclusion

Computed Tomography (CT) is arguably the most exciting method in the NDT (non-destructive testing) world—and its applications are virtually limitless. It's now time to take its rightful place as an informational tool in the research and development phase. Many design engineers aren't aware of the many benefits CT can provide in the early stages of part design.

The valuable information that CT provides in the discovery stage will empower engineers, designers, researchers, scientists and anyone interested in additive manufacturing part design to leverage CT to see things they have never seen before without damaging the object under inspection. X-ray CT can be used to achieve:

- More precise inspection of parts
- Automated defect recognition
- Accurate metrology inspections
- Reverse engineering datasets for additive manufacturing
- Collaboration with investigators located anywhere in the world
- Prediction of design behaviour
- Analysis of raw materials
- Proof of design concept
- CAD comparison

Imagine going back to the future to the initial product design phase and predict how the design will work after production. Seeing inside your sample, viewing defects, making measurements, and seeing density changes are all possible with the power of industrial CT.

The fast-evolving technology of additive manufacturing technology won't be slowing down anytime soon. The demand for more intricate designs as well as lighter parts will increase substantially. As additive manufacturing becomes a popular choice for more applications in the future, the need for speed to market is crucial. Stricter safety standards will be employed by the medical and aerospace industries creating the need for more informational tools in the research and development process.

Learning how to design for additive manufacturing can pose challenges, which is why using CT as a tool in the research and development stage can save time, money and possibly lives.

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GERMANY – HEADQUARTERS

YXLON International GmbH
a company of the Comet Group
Essener Bogen 15
22419 Hamburg
Germany
T: +49 40 527 29-0
www.yxlon.com

AXT PTY LTD
Authorised Distributor
YXLON
Australia & New Zealand

1/3 Vuko Place
Warriewood
NSW 2102 Australia

+61 (0)2 9450 1359
axt.com.au
info@axt.com.au

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