

The Development of a Non-Destructive Quality Tool for Additively Produced Components

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ABSTRACT

Additive manufacturing, often referred to as "3-D printing," is the process of building three-dimensional objects, layer by layer. It uses specialized equipment and leverages data to add each layer in the appropriate geometric shape. This non-traditional approach to production has the power to transform manufacturing by allowing users to avoid removing materials through machining, carving, shaping, or milling. In addition to simplifying production, [additive manufacturing](#) also allows companies to create high-performing parts that cost less while reducing production times and increasing customization options.¹

The additive manufacturing market is projected to grow at a rate of 26.75% between 2021 and 2028.² Technological advancements continue to drive growth, and additive manufacturing itself continues to drive development. While additive manufacturing may well be the future of the manufacturing industry, the need for effective ultrasonic non-destructive testing (UNDT) remains. Testing is essential to determine the reliability of the additively produced part; however, additive manufacturing testing methods must improve to allow for more widespread adoption of this technology.

While additive manufacturing exhibits exciting potential, it has yet to be embraced by the mainstream. It has the potential to revolutionize the manufacturing process, but a reliable non-destructive tool (NDT) for additively manufactured parts has not yet been produced. Developing reliable additive manufacturing testing methods to catch defects in additive manufacturing is critical for sustainable growth.

This paper examines the potential for using a combination of Holographic Non-Destructive Testing and Vibration Testing. Together, this tool would create Modal Assurance Criterion that can be verified and used to calculate defect probability. As a result, this UNDT additive manufacturing tool would provide cost savings and the ability to grow a database of defects for a deeper understanding of part quality, elements that are critical for catching defects faster, and facilitating successful outcomes.

¹ McKinsey Research. "The Mainstreaming of Additive Manufacturing." <https://www.mckinsey.com/business-functions/operations/our-insights/the-mainstreaming-of-additive-manufacturing> Accessed March 14, 2022.

² Data Bridge Market Research. "Market Analysis and Insights: Global Additive Manufacturing Market." <https://www.databridgemarketresearch.com/reports/global-additive-manufacturing-market> Accessed March 14, 2022.

INTRODUCTION

Current additive manufacturing testing methods include tensile testing, creep and stress rupture testing, fatigue testing, as well as crack and fracture testing. [Tensile testing](#), or tension testing, applies force to the material to measure its strength and its capability for elongation to measure elasticity, yield strength, strain, and the point of failure. [Creep testing](#) puts parts and materials into elevated temperatures and exposes them to static mechanical stress to measure deformation and test for failure. Stress rupture testing places a material sample under specific conditions for load level and temperature for a pre-determined length of time. [Fatigue testing](#) uses specialized machines to apply cyclic loads that simulate real-world challenges that additively produced parts and materials may encounter to gauge the safety of the structure, the life expectancy of the materials, and the behavior of the part in real-world situations. [Crack and fracture testing](#) measures crack growth rates and the ability of crack materials to resist fracturing to better understand how materials behave under stressful conditions to prevent cracks and fractures and to determine how long materials are likely to remain useful under a variety of conditions.

Although these testing methods provide valuable insight, a reliable non-destructive tool for evaluating additively produced parts has yet to be produced by the additive community. The ability to evaluate and predict a part's performance is invaluable to the success of additive manufacturing. The tool must work accurately and quickly, but although there have been several tools developed to guide the printing process, post printed part evaluation remains unfruitful.

Limited exploration has been conducted using traditional tools such as Computed Tomography (CT), Radiography (RT), NDE Metrology, Dye Penetrant (PT), and Eddy Current (ET). The aforementioned tests have demonstrated limitations.

CT has supplied a great deal of insight, but successfully locating defects and potential failures is both time consuming and extremely expensive. Once a company has successfully navigated the setup and installation of a CT system, highly specialized staff must run and maintain the systems. Therefore, the cost is not limited to just to the price of acquisition. The resources and management of a CT system are an expensive proposition. Although the information and data from CT scans are invaluable, the acquisition is not trivial.

UNDT for additive manufacturing has shown some promise as a potentially cost-effective method to evaluate defects in additively manufactured parts. However, UNDT resolution is dependent upon material density, distance (or size) of an object, and relative defect size. This methodology is suitable for very small, simple parts. This limitation detracts from large-scale use in the additive industry.

PT, ET, and RT all share a common shortcoming in their primary use as UNDT additive manufacturing tools. They are designed as surface metrology tools. This creates the inability to accurately determine the internal structure of parts, an issue that becomes more prevalent as parts become larger and more complex.

Another common issue that prevails in all these methodologies is sample mounting, particularly the lack of a generic, easy-to-work-with fixture or method of supporting the part. There is a wide variety of additively produced parts manufactured, and these parts come in a nearly infinite assortment of shapes and sizes. The need to evaluate virtually anything from a simple block to a complex gas turbine blade is

just as critical as the effectiveness of the tool. As an example, a CT allows for nearly any size and shape part to be loaded into a machine, which enables the widespread use of this diagnostic tool for nearly any component. A universal tool for testing needs to supply a simple, highly flexible part mounting capability, or there will be no seamless way to use it. To be successful, a testing methodology must lend itself to a flexible mounting or sample support system.

The most promising test for evaluating additively produced parts is Holographic Non-Destructive Testing (HNDT). HNDT is widely used as a quality NDT to locate defects in composite materials, cracks, and voids; residual stress in metals; and interior irregularities and can be used on a wide variety of parts in many shapes and sizes. Coupled with a high-energy vibration technique, HNDT has the potential to become a far more powerful and effective tool in the investigation of defects in additive manufacturing and composite materials. The combined techniques have been used successfully to search for delamination, voids, and other structural defects in composite components. This is a direct parallel to the type of analysis that is needed for 3D printed components.

Documented studies on testing utilizing HNDT with laser ultrasonic testing (LUT) to detect internal defects such as holes in structures show some promise. During testing, the energy level required remained below the threshold for thermal ablation of the surface of the material. While promising, the results are limited due to the energy requirement to excite large, dense structures, as well as complex geometry. Additionally, complex shapes will require higher resolution capability. Commercially acoustic ultrasonic NDT systems, which rely on modal analysis to determine defects, are available. However, the lack of widespread use and adoption among the additive community are representative of the gaps in analysis. They are limited in resolution, and extraordinarily complex geometries limit the accuracy of the results.

VIBRATION / HOLOGRAPHY AS A TOOL

The aerospace industry relies on mechanical [vibration testing](#) to develop S-N curves and determine the fatigue level of components. This method focuses on the relationship between stress and the number of cycles to failure at a given stress level. Stress fractures or defects are detected by the shift in vibration frequency at a given energy level, coupled with a change in the requirement for more driving energy. Therefore, defects absorb energy. This testing methodology provides the ability to impart a large amount of vibrational energy into test specimens. Typically, it is used as a destructive tool, but it can also be married to modal analysis.

Coupling holography with high-energy vibration allows a part's unique modal signature to be determined and the structure evaluated at those modes. A typical use leveraging modal vibration analysis would be Modal Assurance Criterion (MAC). Part-to-part variation is determined by using MAC. The closer two identical parts are, the higher the MAC value of the parts. Therefore, a MAC of 100% indicates all mode shapes are identical. This type of analysis is commonly used in aerospace vibration testing of blades. However, it can also be applied to an object or manufactured part. Using an impact hammer and a holography system, an object's modes can be mapped, and the structure's identity can be resolved. Once a few parts are mapped, the data can be matched for parts to determine if there is a difference in MAC

and energy from part to part. This difference is an indication of variation and defects in parts similar to an energy shift from a crack or fracture initiation.

Conceptually, by using a combination of Holographic Non-Destructive Testing and Vibration Testing, we should be able to generate a "golden" modal model of a "perfect" part. Golden and perfect are used to define a nearly defect-free part that matches the design model as nearly as possible. This modal model will then be used to run a comparison to additively produced parts to generate their respective MACs. This will also allow us to screen for defects and effectively qualify specimens. The defects can then be further explored from this dataset to generate a database of defect types and the corresponding effects on modal data. CT scans would be required to precisely define defect types and validate their locations.

APPROACH

The suggested approach for this new NDT additive manufacturing tool is to use a combination of Holographic Non-Destructive Testing and Vibration Testing to develop a MAC for an additively produced part. This would then be verified against a computer-generated gold standard from the design file. The MAC would be used as an indication of defect probability. The first outcome would be a simplistic go/no-go tool. Scanned components with a MAC of less than 90% match to standard would be considered a failure. A deeper understanding of the use of this tool as a screening tool to detect defects in additive manufacturing would require a comparison of CT scan data to the holographic results.

Intentionally manufacturing defects into a part would allow for the creation of a database of scan data correlated to those defects. Therefore, we propose a two-fold approach. Initial work will be centered on design and establishment of universal test apparatus. This would be a small, high-energy shaker, ultimately a piezo-based system, a generic clamping system, and a holography setup integrated into the system.

To create the most completely open and versatile system, it is critical that the interface for the shaker apparatus and system be as generic and flexible as possible. There has been some research showing that a three-point mount and nesting system can replace a broach block fixture. This would enable a completely generic mount system that would then be used as a quick go/no-go gauge to determine credibility of this approach. The second phase would involve the manufacture of specific defects into a variety of parts, building a correlation to defect type, and compiling the resulting system data. This would require exploring CT scanning to validate the data produced by the test apparatus.

The ideal path would be to print tensile, creep, and fatigue samples with and without defects. This would create the ability to correlate mechanical properties to defects as well as demonstrate the ability to locate defects. The sequence would be to print test bars, test them using HDT-Vibration, conduct CT to validate the test data, and then generate mechanical properties. This will allow the creation of a database that correlates defects to structural differences as well as determines the effect on a material's properties.

BENEFITS

Additive manufacturing is growing at an incredible rate. The need for an effective NDT additive manufacturing tool to qualify parts quickly is critical. This tool would provide a cost-effective solution to this issue. The ancillary benefit to the development and subsequent use of this tool would be the growing database of defects and the relationship to part quality. Once the database of defects grows and is explored, the relationship between defect causes and effects can be better understood. This will facilitate the development of a knowledgebase of defect prevention and grow the toolset for producing higher-quality additive parts.

A secondary and equally important effect of understanding the defects present in parts is the relationship between defects or imperfections and service performance as well as part life. As manufacturing engineers, we tend to scrap at a higher rate, impacting cost and potentially wasting good serviceable components. Once an understanding and relationship are developed between defects and property effects, a more robust design tolerance criteria can be developed. A deeper understanding of the effects of defects will open the allowances and restrictions on the level of quality for parts additively produced. This would allow an increase in generosity of tolerances. Therefore, an understanding of the relationship between defects and properties will allow cost-savings by allowing more generous tolerances.

CONCLUSION

Although NDT options like HNNT show promise in evaluating defects in additive manufacturing, the current methods also pose limitations, particularly with larger and more complex projects and materials. The need for UNDT additive manufacturing tools has been a driving force for innovation, and our solution poses potential cost savings in addition to presenting the prospect of opening up restrictions and better understanding of quality levels. By using a holistic approach that combines HNNT and Vibration Testing to develop MAC and create a database that would correlate defects to the effects on material properties and structural differences, as well as use CT to validate data, we are able to gain improved knowledge about defects in additive manufacturing.

This NDT additive manufacturing tool has the potential to deliver critical insight into the ways defects affect additively produced parts and provide better understanding of how this impacts quality levels. Ultimately, as an UNDT additive manufacturing tool, it could deliver cost savings in addition to allowing greater tolerances, as we are able to develop more robust design tolerance criteria.

The creation of effective, efficient UNDT additive manufacturing testing methods has been a barrier to the widespread adoption of additive manufacturing to date.³ Combining NDT additive manufacturing approaches can help remove some of the technical barriers in additive manufacturing while enabling users

³ PHM Society Papers. "A PHM Approach to Additive Manufacturing Equipment Health Monitoring, Fault Diagnosis, and Quality Control," Jae Yoon, David He, and Brandon Van Hecke. <http://papers.phmsociety.org/index.php/phmconf/article/download/2338/1315> Accessed March 15, 2022.

to better assess quality using an integrated approach that also facilitates the development of a database that can be used on an ongoing basis to continue making improvements.