Predicting Failure in Additively Manufactured Parts—"The Effects of Defects"

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ABSTRACT

While the use of metal additive manufacturing (AM) has grown immensely over the past decade, there still exists a gap in understanding of process defects in AM, which often inhibit its use in critical applications such as flight hardware. The Johns Hopkins University Applied Physics Laboratory (APL) is developing novel techniques to replicate authentic surrogate defects in AM parts and characterize their effect on mechanical response. Advanced data processing methods, such as machine learning, are being leveraged to develop predictive failure models, which will help enhance our understanding of the effects of defects.

The effects of defects and ultimate prediction of when defects become critical failure points is an ongoing challenge in the selection and qualification of emerging materials. The rapid growth of metal additive manufacturing (AM) processes in recent years has led to a renewed interest in modeling and understanding of defect networks. However, analytical approaches to predictive failure caused by embedded defect networks were originally developed for legacy manufacturing methods such as casting and forging and are not representative of real-world AM defect structures. In addition, experimental capabilities to create surrogate defects and validate crack

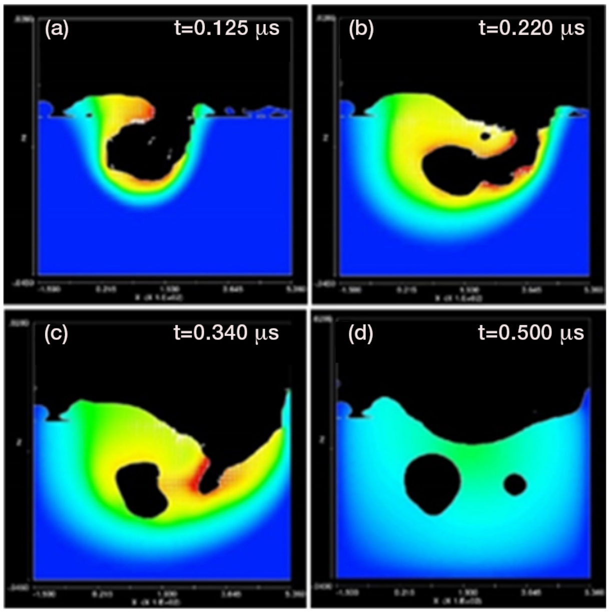

Figure 1. CFD modeling of defect (keyhole porosity) formation over time in Ti-6Al-4V during laser powder bed fusion. Complex fluid flow results from a combination of surface tension gradients (Marangoni effect) and laser surface depression (recoil vapor pressure), resulting in small pores that become trapped in the material during solidification.

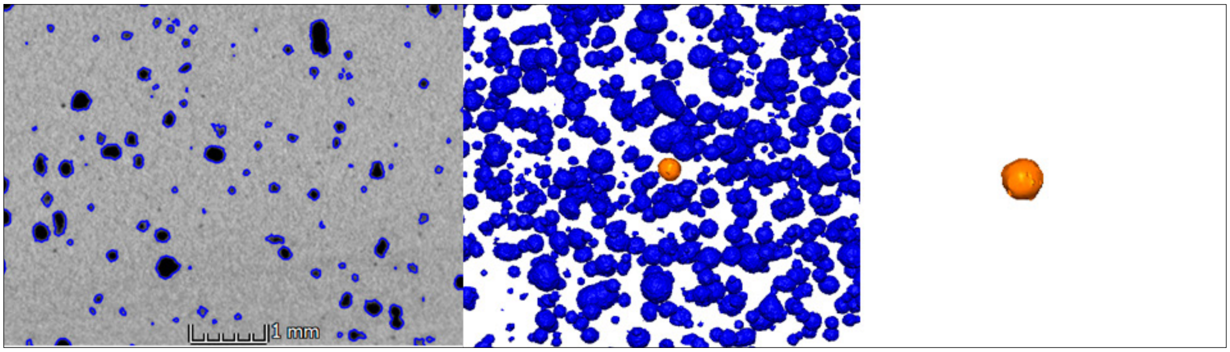

Figure 2. XRCT data processing techniques for identification of porosity in an $AlSi_{10}Mg$ AM specimen. The defect structure is seen in the 2-D slice (left) and can be segmented in 3-D (middle) and uniquely quantified (right).

nucleation and growth processes have proven difficult to implement and control. The underlying goal of this research is to produce a predictive failure modeling technique that leverages large amounts of real-world empirical data to better inform qualification standards in AM.

The first problem to solve is how to create authentic surrogate defects in AM parts on demand using laser powder bed fusion. APL has developed novel techniques to introduce real defects via direct manipulation of the laser processing parameters.[1] While this may sound trivial, it requires an immense amount of knowledge about the manufacturing process, and specifically the complex physics of molten metals and rapid solidification. To solve this first problem, robust computational fluid dynamics (CFD) models had to be generated and refined to accurately determine the processing conditions required to form a defect. An example is presented in Figure 1.

Once the defects are successfully embedded in the AM materials, nondestructive imaging methods are needed to effectively validate and characterize the resulting defect structure. X-ray computed tomography (XRCT) has been a go-to technique for visualizing defects in many applications. However, quantification of defects is often reduced to a single parameter, such as percentage porosity or average pore size. To understand the mechanical response in relation to defects, size and morphological data are required. Using adaptive image segmentation and automated defect recognition, the defects can be identified and separated from the volume (Figure 2), allowing for numerical characterization. These data can be combined with other microstructural and crystallography analyses to paint a more complete picture.

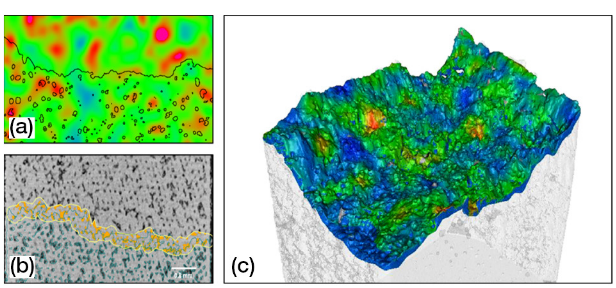

Figure 3. Characterization using XRCT to quantify defects and correlate directly to mechanical test results. The global porosity distribution is seen in a 2-D slice, with posttest fracture surface in black (a). Local porosity can be isolated to just the failure region (along the fracture surface) and independently quantified (b). This local porosity can be summarized and overlaid onto the resulting fracture surface (c), providing insights into how defects ultimately affect and influence failure.

By focusing the integration of XRCT into dynamic experiments, the defect structure can be directly correlated with the mechanical response. One approach developed by APL includes registration of XRCT data from a specimen with embedded defects, both before and after tensile testing to failure. This allows for a unique quantification of the defect structure at the failure location, along the fracture plane. Use of this technique showed that for Ti-6Al-4V AM samples with embedded porosity, the pretest porosity within the region where the fracture occurred was significantly higher than the bulk porosity.[2] An example from these results is shown in Figure 3. This supports the hypothesis that defect networks influence mechanical failure. These data can also be complemented with digital image correlation (which provides strain on the surface of the sample), as well as digital volume correlation (which uses the defect shape and motion to estimate internal strain fields).

The methods and techniques being developed in the work described here can be applied to virtually all materials, given that there are feasible manufacturing and characterization methods available. One of the main challenges the team faced in this work was the vast amount of raw data generated and the resultant data reduction required. The largest leap in progress is being realized through implementation of advanced machine learning and artificial intelligence approaches. These data-hungry techniques are able to overcome the challenges and uncover hidden linkages and relationships not previously seen. Ongoing efforts in implementing deep learning techniques are yielding promising results that will ultimately influence new models for predictive failure and will change the way we go about design, manufacturing, and qualification of AM parts.

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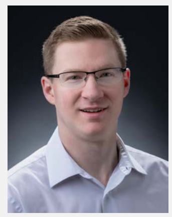

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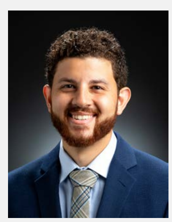

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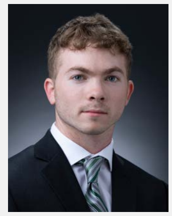

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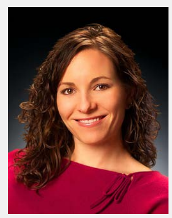

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