SAND2024-01563J

Scientific Foundations and Approaches for Qualification of Additively Manufactured Structural Components

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Abstract

Additive manufacturing (AM) maintains a wide process window that enables complex designs otherwise unattainable via conventional production technologies. However, the lack of confidence in qualifying AM parts that leverage AM process-structure-property-performance (PSPP) relationships stymies design optimization and adoption of AM. While continuing efforts to map fundamental PSPP relationships that cover the potential design space, we first need pragmatic and then long-term solutions that overcome challenges associated with qualifying AM-designed parts. Two pragmatic solutions include: 1) AM material specifications to substantiate process reproducibility and 2) component risk categorization to associate system risk relative to part performance and required part quality. A novel qualification paradigm under development involves efficient prediction of part performance over wide-ranging PSPP relationships through targeted testing and computational simulation. This paper describes projects at Sandia National Laboratories on PSPP relationship discovery, these pragmatic approaches, and the novel qualification approach.

Keywords: additive manufacturing, material specifications, inspection

1 Introduction

Additive manufacturing (AM) of metals enables quickly fabricated, tailored metal structures by faster realization of parts with reduced design and qualification time, smaller manufacturing facilities for small-lot parts that have a variety of parts, and novel designs and architectures and new functionalities not available in subtractive manufacturing. Wide adoption of AM-metal structures has been stymied by lack of materials understanding that is needed to design and qualify such parts. The path to such structures requires both near-term pragmatic approaches to remove barriers to AM and long-term approaches, founded in scientific discovery of AM-metal material and structural behavior, to design and qualify AM-metal structures.

Sandia National Laboratories is exploring use of AM-metal structures by employing such near-term and long-term approaches. This article describes two near-term pragmatic approaches, development of AM-material specifications and an accelerated build health inspection approach, and a long-term research investment of foundational science of AM variables affecting performance to develop process-structure-property-performance (PSPP) relationships that could unleash the potential for AM metal in high-consequence applications.

2 Development of AM-material specifications

Conventional approaches to engineering qualification rely upon a progression of demonstrated capability and repeatability across increasingly complex combinations of materials and design. This is commonly achieved through a building block approach [1] elevating from coupon-level characterization through incremental demonstrations of complexity to arrive at components made of the represented material. Traditional material forms, such as bar stock and plate, lack details prior to the sourcing for material properties characterized at the coupon level. Coupons in this example serve as a screening mechanism for incoming stock used in the subtractive manufacturing of parts. The properties for many applications built from this stock are implicit and controlled by specification, public and private. And the engineering burden to fabricate this material to the desired, specified characteristics remains with material producers and suppliers. However, with the development of additive manufacturing tools, the burden to produce a part, its underlying material and desired properties, has become the combined responsibility of the equipment's operator. Each AM installation is now both part fabricator and material producer simultaneously. The engineering scope to qualify a part for service has expanded into spaces historically managed by contractual exchanges; controlled and documented by material and process specifications, protected by rigorous process control, and checked by destructive coupon testing. This engineering effort relieved part designers, fabricators, and integrators of the burden to build their own supply chains at the commodity level. The financial and infrastructure barrier to installing an AM machine is not too dissimilar to traditional machining equipment (subtractive capabilities). Many machine shops ambitiously install these tools without appreciating the additional engineering burden now a part of fabrication. Other process intensive material technologies, powdered metallurgical processes and casting, also have material and part-making responsibilities, but are typically a specialization of a single service provider, one who is able to navigate the engineering requirements to deliver on form, fit, and function. Until the introduction of AM, reliance on material certificates of conformance in traditional machining may be the historic limit of materials engineering for most subtractive manufacturing operations. The progression from coupon to component qualification should rightly expand for additive manufacturing to include additional levels upstream, earlier in the process. Elements before the coupon that describe the necessary engineering controls to arrive at a verifiably consistent material form that can be called a "coupon" are needed before designing elements, details, sub-components, to ultimately conclude with a component or system able to meet its requirements.

The material specification has renewed importance with the furtherance of AM modalities and tailored materials. Legacy material chemistries are no longer represented by historical specifications when the process-intensive nature of most AM machines allows for the deliberate tailoring of outcomes [2]. Altogether new material characterization campaigns built atop a "qualified metallurgical process" as defined in NASA-STD-6030 [3], will enable the furtherance of progressive qualification. A repeatable and controlled set of outcomes, published as statically bounded properties, further modifiable by influence factors for service conditions, arrives at guidance for design applications. Developing these new material specifications for AM processes is however limited in their level of precision. Because of the thermal history dependence of material properties in melt-based AM methods (LB-PBF, EB-PBF, LB-DED, EB-DED), coupons do not represent the material in a part, but only the coupon itself. The aforementioned influence factors can attempt to accommodate for features of size (e.g., cross-sectional thickness), but that is further impaired by surrounding geometry. Instead, material specifications are effective guard bands for process repeatability.

Rather than attempt to associate direct relationships between coupon-level testing and its acceptance criteria within a material specification towards describing the material properties within a part, coupons become surrogates for process consistency. Carefully selecting the right property, its associated geometry and test may instead give insight to when a process impacts features of importance or concern. Designing to a global set of properties established by a single set of poorly matched coupons and part geometries results in uncertain levels of design margin because of inconsistent material microstructure. It may be more efficient to detect process abnormalities or drift via coupons than it is to assert product acceptance by a proxy artifact with excessive factors of safety applied uniformly.

3 Accelerated build-health inspection approach

The advancement of additive manufacturing has been accompanied by a rising need for accelerated quality assurance methods capable of providing machine health verification within hours of a completed build. One recent method that has been explored is utilizing torsion coupons to rapidly provide max torque and max angle of twist at break and inform process health. The method as described in ASTM F3626 Accelerated Build Quality Assurance for Laser Beam Powder Bed Fusion (LB-PBF) [4] leverages strategically placed torsion coupons within a given build envelope to rapidly generate strength and ductility measures, i.e. max torque and max angle of twist at failure. These coupons, shown in Figure 1a, are designed to be easily removed using a box wrench and can be tested in the as-built condition immediately after cooling and prior to any post-processing. Testing is then conducted using a torque wrench and fixturing built from off the shelf parts as depicted in Fig. 1b. The objective of this accelerated test method is to interrupt the manufacturing process to avoid costly and time-consuming post-processing of parts with undetected material quality issues.

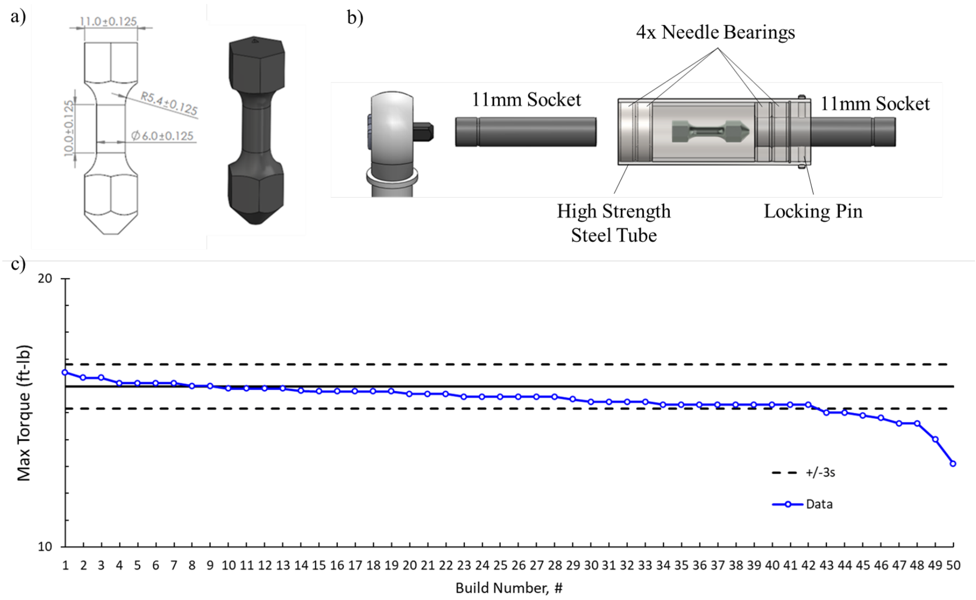

Fig. 1 a) Torque coupon, b) torque fixture for hand driven test method, and c) example of torque coupon based quality assurance.

As a quality assurance method, the results from coupon tests can be compared to historical data generated over several build iterations. An example of this process is demonstrated in Fig. 1b where max torque values are tracked for each build with a 6sigma (+/-3 Sigma) allowable variation. At build 61 the max torque value falls out of this range and triggers an interruption to downstream post-processing as well as production activities until machine health can be verified. It is important to note here that the torsion coupon is not representative of the part itself, as the thermal history is not the same between coupon and part, and instead indicative of process changes or drift that may or may not result in the part not meeting requirements. The impact of unrecognized build corruption can be realized considering a simple serial production strategy in which 5 machines with one production run a day creating 20 parts each. Consider approximate time costs of depowdering taking 1 day, stress relief taking 1-3 days, plate removal taking 1–3 days, additional thermal processing taking 1-10 days, and testing for material property verification taking 10-20 days. This in-series, step-wise process suggests it could take anywhere from 14-37 days to identify a previously unrecognized build corruption through conventional testing programs. Considering the corruption propagates to the continuing production runs with a part cost of \$200.00, the monetary cost of scrapped parts alone would be \$280,000-\$740,000 for those 14-37 days in labor and materials. This example exemplifies the need to for pragmatic quality assurance methods to detect process changes effectively and efficiently.

To validate this approach, the sensitivity to process changes was explored for multiple AM materials, but for brevity only results for 316L stainless steel are presented here. In Figure 2a results for variety of process changes resulting in a range of energy densities show a degradation in max torque for sufficiently low energy densities. Interestingly, the max torque values plateau at energy densities $\geq$ 40 J/mm^3. This is not particularly surprising considering the toughness of 316L stainless steel and associated resilience to defects requiring significant fractions of lack-of-fusion type defects that result from low energy processes, as opposed to gas entrapped and keyhole type pores. Furthermore, considering degradation of the process in AM it is typically more likely that a build encounters a low energy condition that results in the scrapping of parts, e.g., degradation of laser, defocusing, etc. The results in Figure 2a suggest the accelerated test method can capture these low energy events. In fact, experiments have demonstrated that a single corrupted layer in the gage of the torque coupon is detectable, suggesting the approach is capable of identifying single layer anomalies at laser powers 20% below nominal laser power.

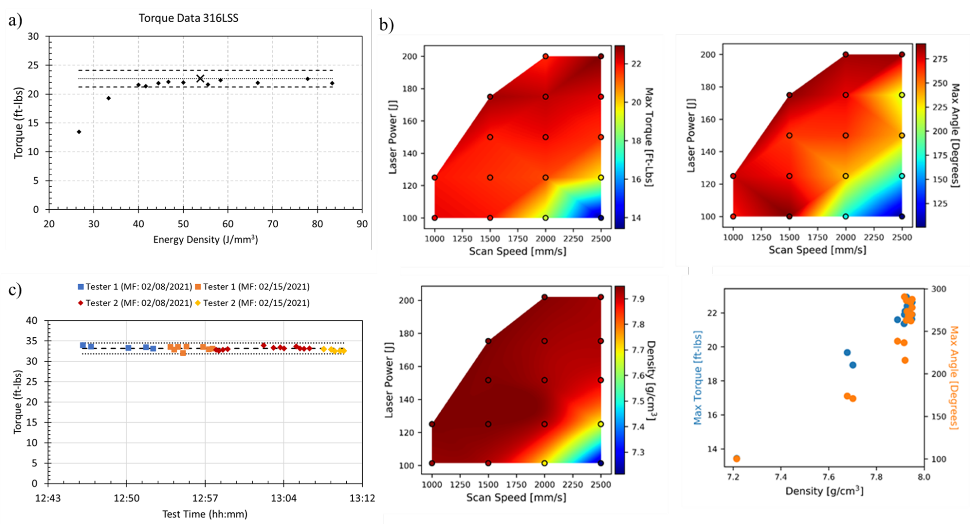

Fig. 2 a) Max torque results with respect to changes in process energy density, b) max torque, angle of twist, density, and combined max torque & density process charts, and c) user and time dependency results.

The high-throughput coupon has also shown some promise at rapidly identifying process windows. The process dependent performance of the torque specimens was explored for 316L stainless steel with laser powers ranging from 100-200 W and at scan speeds of 1000-2500 mm/s. All 48 samples were built on a single plate with three samples being printed for each of the process settings shown in Figure 2b. Data are shown as averages of all three samples except for three settings which only had two successful tests. These samples were all built on a ProX-200 DMP where standard printing parameters were optimized for 113 W and 1400 mm/s. The top two heat maps show the process dependence of the max torque and angle of twist clearly decrease with decreasing laser power and increasing scan speeds, i.e., low-energy conditions. This is very similar to the behavior expected for bulk density obtained from 1cm x 1cm x 4cm bars using the same system, shown in the bottom two charts of Figure 2b.

Finally, the repeatability of the test method in regard to test operator and test date were explored to understand the variability from user-to-user as well as single user. Figure 2c shows the results for max torque of two operators on two distinct test dates. The x-axis is plotted as time series with slight overlap from operator 2 and operator 1 for day 1 and day 2, respectively. The aggregate of data suggest notable consistency between users and dates considering the torque to failure operation was conducted by hand with minimal instruction for rate of twist. This result builds confidence that the rapid hand driven test method can provide critical insights into the process health efficiently and effectively. The applicability of this approach for additional materials is being explored to better understand the material sensitivity.

4 Foundational science of AM variables affecting performance

The previous pragmatic approaches are beginning to break down barriers of perceived risks associated with variability in AM processes and parts. That risk can be further reduced with development of PSPP relationships that help designers take advantage of novel shapes and functionalities while avoiding pitfalls of variability that eat away at safety margins. Many variables were considered to develop PSPP relationships for AM metals including the following: process, microstructure, flaws, part geometry, heat treatment and other post-processing, post-machining, anisotropic mechanical behavior, strain-rate-dependent behavior, mode of deformation and loading, damage, fatigue, and fracture. Such PSPP relationship understanding can be incorporated in design workflows including topology optimization to balance the novel shapes with increased bulk to reduce risk from AM variability. Below highlights two types of studies that demonstrate the foundational understanding being gathered to create these PSPP relationships.

4.1 Fracture and part geometry

The Sandia Fracture Challenge (SFC) is a forum for benchmarking prediction capabilities for fracture. The third SFC [5] problem was an AM 316L stainless steel component with several holes, channels and cavities. Fracture of these 316L stainless steel structures, with a quantified void structure and as-printed surfaces, had only modest variability in their global deformation behavior because the stress concentrations in the structure dominated the overall part deformation and failure. These structures underwent interrupted testing to monitor the evolution of the crack initiation and propagation, where each specimen was scanned via computed tomography (CT) after each interrupted test [5]. These structures experienced local variability in the general vicinity of the dominant stress concentrations: the cracks initiated in slightly different locations due to the interaction of pores, surface roughness, and part geometry. Figure 3 shows two cases where the crack began at the high-stress intersection point of channels and a hole or at a surface defect near the high-stress intersection point. Also, the crack paths deviated due to the internal pores. This research demonstrates that geometry, particularly with high-stress concentration locations, can reduce overall variability in AM-part performance, but the voids and surface roughness can lead to stochastic local behavior. This understanding might lead designers to purposefully locate a stress concentration that leads to predictable part behavior and to not add many different repeated structures like thin strength members where a printing flaw or the surface roughness could lead to any of those thin members to fail in a stochastic manner. The designed stress concentration is not meant to reduce the failure resistance of the AM part overall, but rather to make the failure more predictable and thus enable safe failure modes of the AM part and the assembly it is in, if applicable. The structure can still be designed to meet part requirements with a stress concentration while also having predictable failure, unlike a similar AM part without the stress concentration but with stochastic failure and potentially unsafe failure modes.

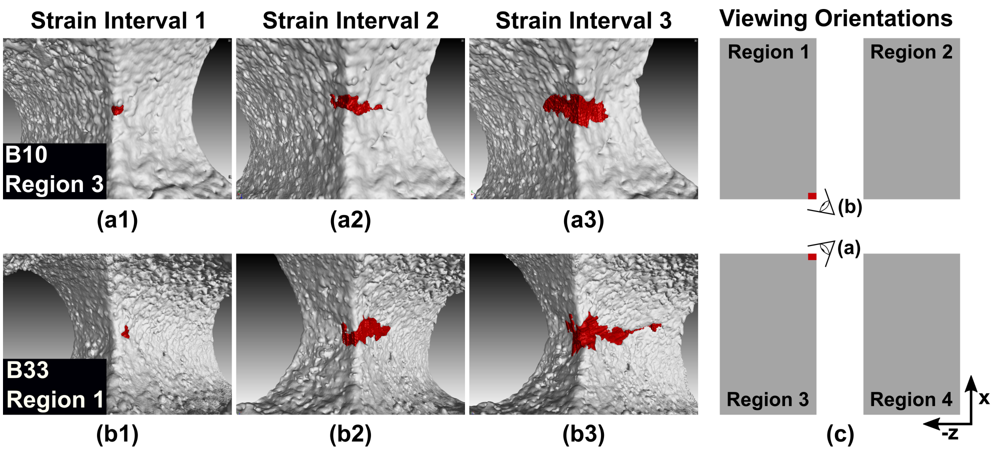

Fig. 3 Evolution of cracks at three different interrupted loading levels for two different specimens as seen from 3D reconstructed CT scans with the voids and crack highlighted in red: in B10 (a1-a3), fracture begins first at a high-stress intersection point, while in B33 (b1-b3), fracture initiates at a location offset from the high-stress intersection point at a surface defect. Reprinted from [5].

4.2 High-rate material characterization and modeling

Sandia is also a leader in the study of the high strain-rate response of AM materials. Sandia has performed numerous studies to understand the thermodynamic, constitutive, and failure response of AM materials at high strain rates [6–10]. Additionally, Sandia has been a pioneer in efforts to understand the phase stability of these, often less studied, AM alloys. X-ray diffraction measurements at third generation light sources, like the Advanced Photon Source at Argonne National Laboratory, under both static and dynamic high-pressure loading conditions have shown unique and interesting behavior in common AM alloys [9, 10]. Sandia is also developing computational capabilities to explore the influences of grain structure and geometry on the dynamic response of AM materials and components. This includes efforts to use kinetic Monte Carlo (KMC) simulations of the AM process to generate representative microstructures and the use of CT scans incorporate as-printed geometries into the simulations [11]. The KMC simulations take in build parameters (i.e. scan speed, layer thickness, hatch spacing, etc) to generate a grain-scale representation of the AM material [12]. One example is shown in Figure 4 on work looking at the dynamic compaction of AM lattices [13]. In this work, phase contrast imaging (PCI) was used to generate radiographs of a lattice unit cell during the compaction. Hydrocode simulations [14, 15] were then run on the as-printed lattice using CT scans. Through careful indexing during the experiment, a direct comparison between the compaction behavior observed experimentally and computationally was obtained. These studies show how Sandia is developing PSPP relationships for high-rate behavior that we have begun to incorporate into computational modeling workflows to better predict the mechanical behavior in structures.

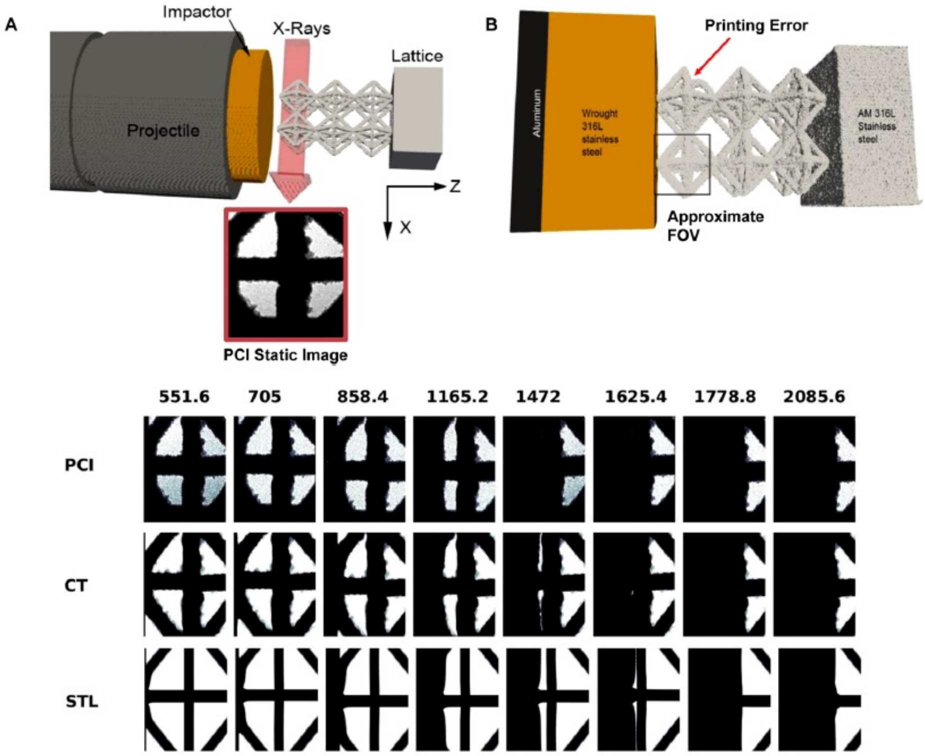

Fig. 4 A schematic of a dynamic compaction experiment coupled with X-ray phase contrast imaging (A) along with the corresponding hydrocode simulations using the as-printed geometry as defined by CT scans (B). This enables a direct comparison of the transient deformation states obtained in the experiment (PCI row), to those predicted by the hydrocode simulations using both the as-printed geometry (CT row) and using the drawing STL files given to the machine (STL row). The numbers above each row correspond to the time of the image relative to impact. Good agreement between the transient deformation states observed and predicted by the hydrocode simulations are obtained using the as-printed geometry in the simulations as opposed to the STL files used for printing the lattice. This figure is reprinted from [13] under the Creative Commons CC-BY-NC-ND license.

5 Conclusion

These examples of pragmatic approaches and foundational research in AM materials demonstrate how we as a community can overcome perceived problems with AM materials that have appeared to stifle innovative uses of AM in challenging applications. Materials specifications for AM materials shift our thinking in that a part's functional shape is usually formed simultaneously with the solid material, unlike traditional processes with the material formation ahead of part formation. Detection of issues with an AM build is best found early in the process as to prevent waste of time and material, and thus approaches that can identify off-nominal builds early like the torsion coupons provide a mechanism for faster and better parts with higher yield. Foundational studies of the interplay of mechanical behavior and microstructure, geometry, and other factors are necessary to improve how we take advantage of the benefits of AM technologies without suffering its current limitations or issues. This foundational work, alongside pragmatic approaches, must continue as processes evolve and address the challenges with AM.

Acknowledgments. The authors would like to thank our colleagues at Sandia National Laboratories that supported the work summarized here, in particular Dr. Paul Specht. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. This written work is authored by an employee of NTESS. The employee, not NTESS, owns the right, title and interest in and to the written work and is responsible for its contents. Any subjective views or opinions that might be expressed in the written work do not necessarily represent the views of the U.S. Government. The publisher acknowledges that the U.S. Government retains a non-exclusive, paid- up, irrevocable, world-wide license to publish or reproduce the published form of this written work or allow others to do so, for U.S. Government purposes. The DOE will provide public access to results of federally sponsored research in accordance with the DOE Public Access Plan.

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