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Title: Data Requirements for Digital Twins in Additive Manufacturing

Authors: Shaw C. Feng[1], Albert T. Jones, and Guodong Shao, Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899

ABSTRACT

The number and types of sensors used to monitor additive manufacturing (AM) processes and parts in real time are growing. The emerging digital twins (DTs) associated with the data collected by those sensors and the functions that use that data as inputs are becoming increasingly important research topics. There are fast growing demands across several industry sectors to develop software tools that can create, fuse, and measure both AM DTs and digital threads across the entire AM part lifecycle. While some tools are available, they are not well correlated to part-qualification functions in that lifecycle. The accuracy of the DT tools, the fidelity of their inputs, and the ability to create digital threads are still open research questions. The goal of this paper is to identify the data requirements and technical barriers that are limiting the ability to qualify real AM parts using DTs and digital threads. The data requirements can be used as a guide for AM users to create both. This paper uses laser-based powder bed fusion AM for metals as a case study to help identify those requirements and create those digital twins and threads.

1. INTRODUCTION

Digital Twins (DTs) are recently being used to house and integrate digital representations of humans, objects, and processes in the real world. Common technologies include a combination of the augmented reality (AR), virtual reality (VR), and mixed reality (MR) [1]. These technologies allow humans to remotely monitor, interact, and control objects and processes in the physical manufacturing world in a timely manner, resulting in manufacturing DTs. Early benefits show that DTs can provide manufacturers with better collaboration, realistic virtual measurement, concurrent design and process planning, remote monitoring, and remote product qualification [2].

Additive Manufacturing (AM) is a recently popular fabrication process, which builds parts from the "ground up", is beginning to use these technologies. Unlike traditional manufacturing technologies, which start with a stock material and creates part by machining, forming, and assembly, laser-based metal AM starts with powders and creates parts using a layer-by-layer material, usually metal, fusion process. While the physical fabrication process is well understood, controlling that process, and qualifying the resulting, and sometimes complex microstructural and geometrical, parts are still open research questions. Answering those questions, today, is based on (1) using digital twins of the powders, the processes, and the parts and (2) creating digital threads by integrating those different types of digital twins.

DTs and digital threads can be used to control physical AM processes and qualify fabricated parts. There can be DTs of the input powder, the physical process, the fabricated part, the inspected part, and the manufacturing environment. As defined

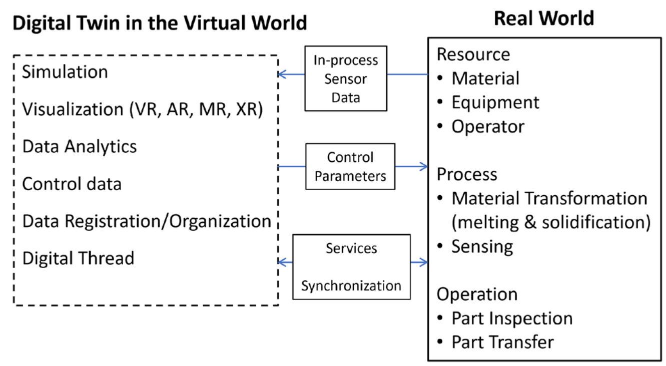

Figure 1 Diagram of Digital Twin in Manufacturing

in ISO 23247 [3], a DT is a "fit-for-purpose digital representation of an observable manufacturing element (OME) with synchronization between the OME and its digital representation," see Figure 1. OMEs include personnel, equipment, materials, processes, facilities, environment, products.

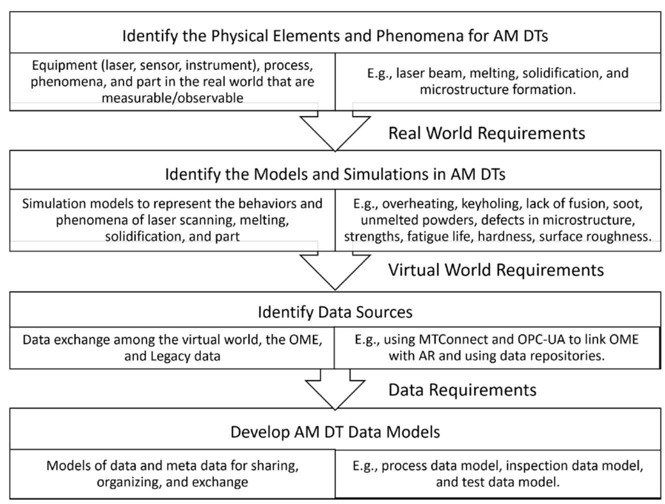

Figure 2 Identification of Data Requirements in AM

To use the term defined in that standard, an AM DT must include the (1) different spatial and temporal scales and resolutions of multi-modal data elements, sources, and flows, (2) software functions that use them as fused inputs to model AM processes and create AM products, and (3) the past, the current, and the future states of both the layer-by-layer, processes, and products. A digital twin implementation architecture for wire +

[1] Lead Author: shaw.feng@nist.gov

arc additive manufacturing based on ISO 23247 has been introduced in [53].

Specifically, AM DTs include the following characteristics:

- Geometric models to describe the designed, fabricated part, and final product
- Physics-based models to simulate the transformation from the powders to the part
- Lifecycle stages from the design, the process, the inspection, and the product
- Data elements needed to generate Virtual Reality (VR) or Augmented Reality (AR) models
- Sensor data and the associated meta data
- Communication and data links to sensors, models, and controllers

In this paper, we use the laser-based, powder bed fusion for metals (PBF/LB-M) [4] process as a case study. We include the acquisition and analysis of real-time data and the results of that analysis to monitor and control that process. More specifically, we focus on (1) correlating DTs of the material, design, process, property, and microstructure data and (2) correlating and combining those DTs to create digital threads that can be used for AM part qualification.

For industry to successfully use digital twins and threads, it needs new knowledge to structure, configure, and build both. To create that knowledge, industry must understand its associated, lifecycle, functional requirements and synchronize them, in real-time, with their physical counterparts. Moreover, industry needs to use that knowledge to better control AM processes, improve the qualify AM parts, measure the uncertainties of each DT, and propagate those uncertainties across the digital threads whenever they are fused and integrated across AM part lifecycle.

The methodology used in this paper starts with an identification of required data types on AM based on the DT standard and qualification standards, to be described next. Then, it is followed by a specific use case, e.g., AM qualification. Applications of data requirements should be identified to complete the method. Figure 2 shows the high-level view of that methodology. The specific example and application of AM qualification is shown in Figure 3. The qualification has three levels. Level 1 is the current practice that uses mechanical property tests, such as fatigue and strength. Level 2 requires microstructural analysis that can explain the mechanical properties. Level 3 includes process data that can show the formation of microstructure and its defects.

To connect the real and virtual worlds, MTConnect[2] and OPC-UA[3] standards can be used to model and transmit in-process data and control data with predefined structures and contextual information.

This paper focuses on the data requirements needed for part qualification. It (1) proposes a definition of, and an approach to creating, AM DTs, (2) reviews standards related to AM DT requirements and AM part qualification, (3) describes the required process, microstructure, and property DTs, (4) identifies technical barriers in creating digital threads that fuse and integrate digital twins, and (5) discovers new technical directions to apply DTs and digital threads in AM qualification. DT-enabled AM qualification is based on existing standards for qualifying aeronautic and astronautic parts including the components and assemblies of structures and engines. These standards have been published by the American Institute of Aeronautics and Astronautics (AIAA) [5] and The National Aeronautics and Space Administration (NASA) [6].

The main contributions of this paper include (1) required DT data objects and information flows for AM part qualification, (2) data formats to enable digital thread using DTs for PBF-LB/M in part qualification, (3) understanding the sensor-based data fusion requirements, (4) using those requirements as inputs to various

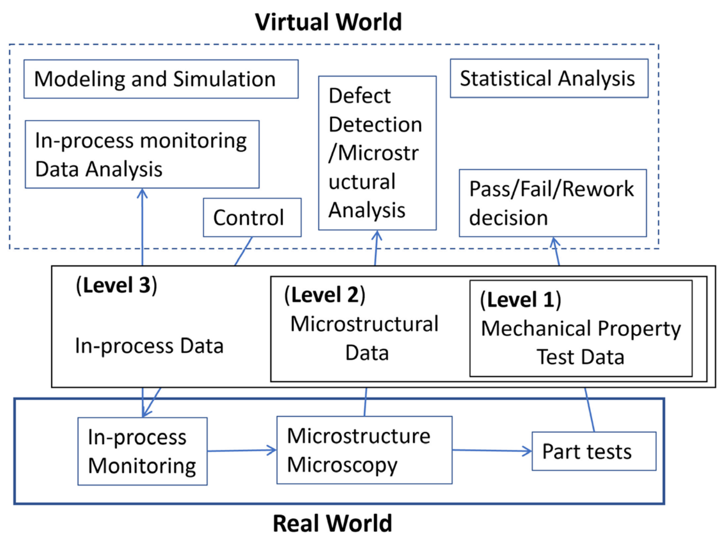

Figure 3 Data Sharing Between Virtual and Real Worlds for AM

mathematical models, and (5) mirroring those mathematical models with observations of their counterparts in the real world.

The paper has five additional sections. Section 2 reviews currently available research results that relate to DTs for manufacturing. Section 3 describes data representation requirements for DT in AM part qualification. Section 4 provides examples of an integration of DT packages applied for AM qualification. Section 6 concludes the paper and identifies the future work on the AM DTs data standardization.

2. REVIEW OF DIGITAL TWINS AND THREADS FOR MANUFACTURING

The DTs and digital threads utilize a variety of emerging technologies [8] as listed below.

- AR, VR, MR, and Extended Reality (XR): AR is where virtual objects and environments are mixed with the real world. The user views the real-world environment along with computer-generated perceptual information. AR enhances the real-world experience with digital details, adding a new layer of

[2] mtconnect.org

[3] https://opcfoundation.org/developer-tools/specifications-unified-architecture#:~:text=OPC%20Unified%20Architecture

perception, and supplementing the user's reality or environment by keeping the real world central. VR is a computer-simulated experience that replaces the user's perception completely from the real world with a similar or different virtual world. VR tricks the user's senses into thinking they are in a different environment. Using a VR headset, the user experiences a computer-generated world of imagery and sounds in which one can manipulate objects and move around using haptic controllers while tethered to a console or PC. MR describes the merging of a real-world environment and a virtual world created by computers. Physical and virtual objects may co-exist and interact in MR environments and in real-time. XR refers to all real and virtual environments combined together, where the interaction between human and computers occurs through interactions generated by computer software and hardware. XR technologies consist of VR, AR, and MR [9].

- Digital twin: digital twins provide the infrastructure for the AM, which can be linked to physical manufacturing. DTs must be linked to the objects, the processes, and the humans in the physical world. As discussed in the previous section, AR, VR, MR, and XR serves as a visualization and immersive component of a digital twin. It requires synchronization with the digital twin [10].
- Artificial Intelligence (AI): Due to the complexities in AM, there are no complete, accurate, AM process DTs. AI, including machine learning, helps enable every process, from business strategy planning to decision making in DTs. Both real-time data and historical data can be analyzed by AI. AI also helps create more realistic looking and accurate avatars by analyzing 2D and 3D images.
- Reconstruction: 3D reconstruction technologies can help create an environment that is realistic representation of the real physical world. The data collected using 3D cameras and 4K photography are used to create life-like simulations that can be used in DTs.

2.1 Related Standards

Standards can help eliminate the current confusions and duplicated efforts about the definitions of AM DTs. Standard can support various technical capabilities such as (1) data collection, modeling, communication, and visualization and (2) architectural frameworks, systems integration, simulation modeling, and measurement methods. Standards also enable the composability and reusability of models and technologies to make the development of DTs more effective and more economical [11].

IEEE P2048 Working Group has made efforts to develop twelve standards for VR and AR with participants from device manufacturers, content providers, service providers, technology developers, government agencies and other parties relevant to VR/AR. These projects focus on different areas such as taxonomy and definitions of devices, immersive video/audio taxonomy and quality metrics, immersive video/audio file and stream formats, person identity, environment safety, user interface, mapping between the virtual object and its counterpart in the real world, interoperability between the virtual objects and its real-world counterpart, in-vehicle AR, and content ratings and descriptors [12].

Several relevant standards on part qualification requirements have also been published. For example, a qualification standard on structures, structural components, and assemblies for space systems specifies design requirements, special structural items, and documentation requirements for astronautic systems [5]. Types of anomalies, including stress, crack initiation time, material anomalies, manufacturing anomalies, and service-induced, in aircraft structures are listed in a Federal Aviation Administration (FAA) Advisory Circular (AC) 33.70 document, which specifies damage tolerance and fatigue evaluation of aircraft structures [6]. A digital thread for AM qualification by NASA, specifies the qualification of a material process, including the minimum mechanical properties for space flight systems [7]. The mechanical properties, such as static (tensile, stiffness, hardness) and dynamics (fatigue and impact) properties, are used in the paper to develop DT data requirements.

2.2 Related Research

Qualifying AM parts requires performing the following activities: (1) collecting, registering, and fusing multi-modal sensor data, (2) integrating the results as inputs to high-fidelity physics, simulation, Data Analytics (DA), and AI models, and (3) using the model outputs to control the fabrication process, if needed, by changing the process parameters. The data, the inputs, the process, the outputs, and the parameters all exist in the physical world. There are digital twins of everything but the entire physical fabrication process. Currently, the physics and simulation models are digital twins of only parts of the fabrication processes. The DA and AI are digital models, but they are not digital twins of any part of that process. They simply map a specific set of DT inputs to specific, DT set of outputs [13].

Recently, NIST has conducted research that focuses on building a simulation of laser scan with melt-pool size control strategies for higher density parts [32] and using DTs for part acceptance for nuclear applications [54]. This paper extends those research results, as described in Sections 3 and 4.

The earliest research papers associated with DTs began several years ago. Grieves et al. discussed the uncertainties in data, unpredictable outcomes, and undesirable behaviors when developing a complex suite of DTs [14]. Tao et al. reviewed the history of, and the theories associated with, several DTs available at that time [15]. They focused on simulation, verification, validation, fusion, and interactions and they argued that modeling is the key factor to developing DTs. Another paper that focused on modeling design and materials DTs for manufacturing can be found in [16]. A review on the applications of DTs provides case studies on manufacturing, healthcare, smart cities, etc. [17].

More recently, the topic of DTs has become very popular. Some implementations of DT have already been published. Liu et al. provided a review of rich sets of definitions and various conceptual models of DTs of objects and functions in the AM product lifecycle [18]. Selected definitions and models are applied in this paper. Wu et al. focused on the building high-level models of the data flowing between virtual assets and their real-world counterparts throughout some selected lifecycle stages, such as design, production, sale/purchase, and service [19]. Glatt et al. developed simulation-based digital twins for implementing the material flows and the processes in a discrete-part assembly factory [20].

In a similar example, Jiang et al. built DTs to implement the connections between the physical and virtual assets associated with operations, machines, materials, environment, and relationships between logistics and production on the shop floor [21]. In another AM example, Ladj et al. focused on the capabilities of DA to extract knowledge from data collected from sensors that monitor the physical AM operations [22]. Finally, Yavari et al. centered his research correlating in-situ, temperature distribution measurements with the design and heat transfer models and using the associated DTs for defect detection in the fabricated AM part [23].

3 DATA REQUIREMENTS FOR AM PART QUALIFICATION

Data collected from a multi-modal sensor is the key requirement in building DTs of both a physical object and a physical process. During the AM part fabrication process, data is collected in real time from a variety of sensors that monitor the current states of the build process and the built part. Before the process begins, however, the part is designed, and the powdered material is selected. Metadata that is about the data, such as sensor specification, setup, sensor parameter settings, and configuration is then created.

3.1 AM Part Design Data Requirements

In AM, like traditional manufacturing, designing parts is based on the customer's specifications and requirements. The result of designing includes a part model, performance requirements, and the associated powder properties; all of which eventually lead to AM part qualification and several different DT data types [24]. A set of data collected from a sensor represents an aspect of the real asset or phenomenon of the process. Those data types include the

- Shape design: Computer Aided Design (CAD), lattice design, design rules, surface roughness, and design allowables
- Powder production/preparation: modeling of gas atomization of metal (in wire form)
- Optimization of support structure, self-supporting design, lattice structure, setup orientation
- Form data: size, tolerance, and performance specifications
- Mechanical properties: maximum tensile strength, hardness, toughness, bending load, and fatigue life
- Constraints: operating environment, working temperature, maximum weight, size, fatigue cycles, among others

3.2 Powder Material Selection Data Requirements

The quality of the selected powder materials is essential and often determines the final quality of the AM fabricated part. Data requirements, and their associated DTs, on powders are discussed in the following subsections:

3.2.1 Powder properties, including geometries, chemical, and physical properties

Geometric properties of the selected powders include their size distribution and statistical shapes. Chemical properties include chemical components and percentages. Physical properties include thermal properties, mechanical properties, and density. Thermal properties include absorptivity, emissivity, conductivity, liquidus temperature, solidus temperature, and specific heat. Mechanical properties include the friction coefficient and the porosity.

3.2.2 Powder material selection constraints, based on the described properties

Geometric, chemical, physical, mechanical properties limits, corresponding to the properties described in the above paragraph.

3.3 AM Build Data Requirements

There are five types of DT part-data requirements for AM qualification: mechanical property data, microstructure data, in-situ and ex-situ measurement data, surface roughness data, and scanning data.

3.3.1 Mechanical Property Data

Mechanical property data are used to prove that the part can meet the performance requirements. The data requirements are as follows. Mechanical tests, used to generate mechanical property data, can be categorized as static and dynamic tests, as mentioned in Section 2. Static tests include tensile strength, yield stress, ultimate stress, elongation, stiffness, buckling strength, corrosion resistance, and hardness. Dynamic tests include fatigue (life), impact (fracture toughness), and dimensional stability. Meta data is about the tests (setup, operations, and settings) and machines (eddy current, radiography, ultrasound, X-ray computed tomography, etc.)

3.3.2 Microstructure Data

Microstructure data are used to show that AM part microstructures can support the mechanical property tests. There are two major types of microstructure data. The first type includes data from the analysis of microstructural images, such as grain sizes, grain orientations, grain phases, precipitates, twins, crevice locations, and results from statistical analyses. The second type includes sample-related data such as location, orientation, and dimensions relative to the build platform coordinate system.

3.3.3 In-situ Measurement Data

In-situ measurement data can be used to support microstructural analysis and to show that the melted and solidified tracks are closely related to microstructural formation. Data for DTs are (1) spread, powder-layer, measurement data, (2) scanned-layer, measurement data including boundary dimensions, edge roughness, discontinuity, balling, and lack of fusion, and (3) melt-pool, measurement data and analysis, such as sizes, shapes, locations, spatters, and plumes.

3.3.4 Ex-situ Measurement Data

Once the part has been fabricated, a final inspection takes place. This inspection uses several different types of ex-situ, sophisticated measuring instruments. Examples of such equipment include X-ray Computed Tomography (XCT), ultrasound sensors, eddy current sensors, and coordinate measuring machines. The data collected using those instruments include

- Porosity data include pore sizes, locations, and orientations.
- Crack, including dimension, location, size, and shape/notch
- Unmelted (trapped) powder including dimensions and locations
- Feature measurements for dimensions, locations, orientation, and profile based on geometric tolerance specifications [25]

3.3.5 Surface Roughness Data

The second component of the first level requirements is surface roughness requirements. They are as follows:

- Surface roughness measurement contextual (meta) data (on post-processed part)
- Measurement results, for example, R_a for surface roughness in a line (1D) and S_a for surface roughness in an area (2D)

3.4 Scanning Data

The fourth level is scanning data that contains laser control commands as follows:

- Scanning paths including the X, Y, Z location of the laser spot relative to the build plate coordinate system
- Process parameters, such as laser power, laser spot dimension(s) and shape, and scanning speed
- Imaging sensor, including sensor type, specification, settings, and configuration [26]

4. AM DT Examples

Some examples of how to organize the data needed to create DTs are described in this section, following the data requirements in Section 3. These examples are based on the traditional, object-oriented approaches including the parent-child, abstract-instance, and data-functions relationships. These examples are closely related to data requirements described in the previous sections.

4.1 Additive Manufacturing Digital Twin (AMDT) package

To improve AM part qualification, we propose an Additive Manufacturing Digital Twin (AMDT) package, which is an abstract programming entity based on an object-oriented approach. AMDT includes data types, data links, service types, function types, and synchronizations among them. Implementing each type requires meta data including the data's purpose, date, time, and its use for qualification. Data links focus on the data's relationships to in-situ monitoring sensors, microscopy, and ex-situ inspection instruments. Function types include DA, AI, physics-based models, and simulation. Service types include qualification reporting, physical phenomena (melting, solidification, grain growth, cracking, etc.), process (AM operation, material handling, etc.) simulation. Synchronization, which is based on the collected sensor data, specifies the relationship between DTs and their physical counterparts including physical objects and physical processes.

4.2 Additive Manufacturing Qualification package

We are also proposing an Additive Manufacturing Qualification (AMQ) package, which is a subtype of AMDT package. The AMQ provides common data types, meta data types, data link types, service types, function types, and the required synchronizations. Again, each file has its meta data that includes qualification date and time, part design information, fabricated part information/serial number, and qualification procedure,

The common data includes Qualification ID and Qualification description. The data links are the AM Machine Simulation and Powder Material simulation. The AMQ consists of seven packages. They are described in the following sub-sections.

4.2.1 Product Design DT package

The Product Design DT (PDDT) package is a component of the AMQ package. The PDDT package provides qualification-needed, product-design information including a model of the designed product. The PDDT package is primarily for modeling and displaying the design. Based on AM part design data requirements described in Section 3.1, the focus is on files that provide design geometry as well as design rules [26]. Those design files require meta data including the design ID, a description, and the date and time the design was created. Each file includes a required Additive Manufacturing Format in amf format [27]; for example, the associated Standard for the Exchange of Product Model Data (STEP) file is the in the stp format [28], and the stereolithography file is in the stl format. (Note there are many other commercial design file formats available.) The data link types include the actual CAD model and design rules. Function types include design analysis function [29] and the design requirement selection [30].

4.2.2 AM Build DT package

The Additive Manufacturing Build Digital Twin (AMBDT) package is a part of the AMQ package. It provides common data types, data links, service types, functions, services, and synchronization for an AM build process that fabricates a part with laser beam(s). Based on AM build data requirements described in Section 3.3, the following elements are in this package. The meta data includes the build ID, build description, the date, and the time. The common data types comprise (1) the information associated with the machine including its manufacturer, model, size, and the number of laser beams; (2) the powder material including its chemical composition, powder size distribution, shape description, vendor-provided name, and manufacturer; (3) recoater data including its type, rake angle if it is a blade, and powder feeder size; and (4) laser data including its power, beam diameter, scan speed, scanning paths, hatch spacing, contour speed, contour powder, infill speed, infill power, up-surface speed, up-surface power, down-surface speed, down-surface power, and the build-plate coordinate system. Other data includes layer thickness, inert gas type and Oxygen level. The data link types are coaxial images, layer-wise images, thermal images, and photo diode data. Function types are fluid flow simulation, microstructure transformation simulation. Figure 4 shows a diagram of the digital twin in AM build.

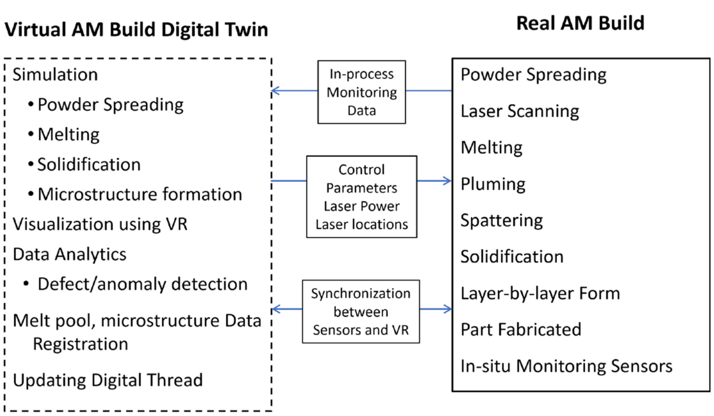

Figure 4 Diagram of Digital Twin in AM Build

The package includes Setup DT package, Scan DT package, Melting and solidification DT package (phenomenological DT), Microstructure DT package, and Mechanical Property DT package. They are described below.

4.2.3 Setup DT package

The Setup DT (SUDT) package provides common data types, data links, service types, functions, services, and synchronization for an AM Setup in fabricating a part with laser beam(s). The following elements are in this package. The meta data includes setup ID, CAD file type, part reference frame, and the build-plate, coordinate system. The common data types include the Part file (CAD file), layer thickness, and part location and orientation relative to the build plate coordinate system. Function types are part setup function including part slicing function [31] and laser scan simulation functions [32].

4.2.4 Scan DT package

The Scan DT (ScDT) package is a package that is a part of the AMBDT package. It provides meta data types, data types, data links, service types, functions, services, and synchronization for a laser scan to fabricate a part with laser beam(s). Based on scanning data requirements described in Section 3.4, the following elements are in this package: (1) meta data includes scan ID, scan date and time, operator, and description and (2) common data types are scanning parameters including laser power, laser beam dimension, scan locations in the laser coordinate system with time stamps, sensor triggering time stamp (stamps if multiple sensors), and layer number. Data is linked to the laser scanner (galvanometer), and to the staring video camera(s). Function types include CAD model slicing function; scan paths generation function; and machine control commands generation, including time stamps, laser spot locations. Synchronization involves the galvanometer in specified periods of time.

4.2.5 Powder Spreading-Melting-Solidification package

The Powder Spreading-Melting-Solidification DT (PSMSDT) provides meta data types, data types, data links, service types, functions, services, and synchronization for a laser scan to fabricate a part with laser beam(s). Meta data is associated with sensor data, and it includes sensor ID, frame rate, sensor description, and sensor configuration. Types of simulation functions include turnkey simulation software. The types of data linking the real and virtual process are melt pool data, including dimensions (length, width, and depth), area of the melt pool, thermal gradient, laser spot center location, maximum melt pool temperature, solidification velocity, and melt pool condition such as lack-of-fusion, normal, over-heating, or keyholing. A data link connects the scanner and scanning parameters including laser parameters (spot size, power) in real process to the virtual process. Another link connects coaxial camera sensor that images in jpg, png, or tif are generated to the data registration module in the PSMSDT. The other data link connects images in jpg, png, or tif from staring camera sensor(s) in the real AM machine to the data registration module in the virtual world. Functions in the PSMSDT are as follows: a powder spreading modeling method [33, 34], a melt pool model in Computational Fluid Dynamics [35, 36, 37, 38], Finite Element Methods [39, 40, 41, 42], and Solidification using cellular automata methods and Calculation of Phase Diagram (CALPHAD) methods [43, 44]. The synchronization between the virtual and real world takes place by data streaming from a coaxial camera sensor for monitoring the melting process that forms the melt pool and the solidification process that forms the track, video camera on laser scanning the powder bed to form a layer of solidified metal, and the gas flow monitor.

4.2.6 Microstructure DT package

The MicroStructure DT (MSDT) package is part of the AMBDT package. It provides meta data types, data types, data links, service types, functions, services, and synchronization for microstructure formation during metal solidification in the tail of the melt pool. Based on scanning data requirements described in

Section 3.3.2, the following elements are in this package: meta data are the sample condition, etch time, image type, microscopy meta data including types, capability, image size, sample orientation, sample preparation, accelerating voltage on Electron Backscattering Diffraction (EBSD) Scanning Electron Microscope (SEM), accelerating current on EBSD SEM, scan area, step size, and comment. Others like wide-, small-, ultrasmall-angle X-ray spectroscopy, and energy dispersive spectroscopy can be added when needed. Since spectroscopy data, which are very small scale and are only used in detecting defects in high performance parts, their details are out of scope of this paper. Detailed microstructure data is described in Section 3.3.2.

Common data types are microstructural features such as crevices, twins, grain sizes, grain orientations, voids, precipitates, soots, texture, different phases, orientation and misorientation relationships between grains and phases, and fractures. Data Links in this package include EBSD SEM images in tif. Function types include microscopy data analysis functions, phase field simulation of laser powder bed fusion [45, 46], nucleation [47], microstructure evolution simulation [48, 49, 50, 51], and cellular automaton for grain structure simulation [52]. Synchronization involves microstructural data and it associated analysis when available. Figure 5 shows a diagram of the digital twin in AM microstructural formation.

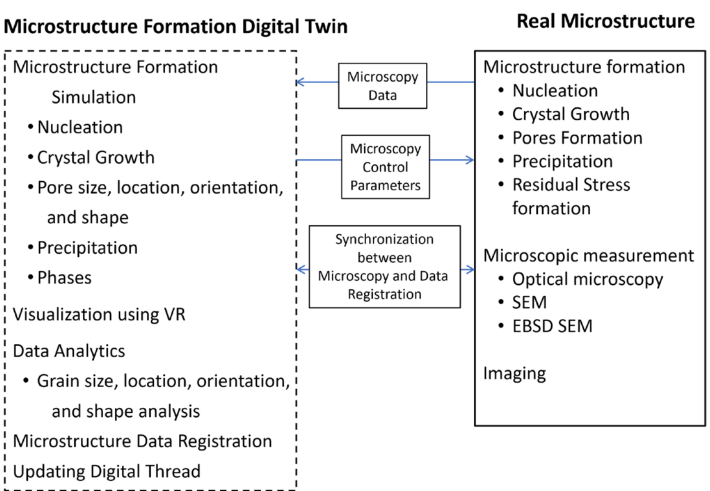

Figure 5 Diagram of Digital Twin in Microstructural Formation

4.2.7 Mechanical Testing DT package

The Mechanical Testing DT (MTDT) package comprises the following test data: tensile, hardness, and fatigue life. Other mechanical testing DTs can be added if needed. Based on scanning data requirements described in Section 3.3.1, the package includes common data types, meta data types, data links, service types, function types, and synchronization. Meta data includes tensile strength, types of hardness, and fatigue-life, test-machine descriptions. The latter comprises the machine model, location, maximum load, coupon dimensions, coupon orientation relative to the machine coordinate system.

Common data types are (1) tensile data including measured yield, ultimate, and elongation; (2) fatigue test data including the number of cycles that the test part broke and measured amplitude of the cyclical stress; and (3) hardness test data including the type of hardness, the measured indentation, and the measured load. Data Links include primarily the mechanical test results. Function types are crack propagation simulation function and indentation simulations. Synchronization requires the testing machines to receive the latest test results. Figure 6 shows a diagram of the digital twin in a mechanical property test for part.

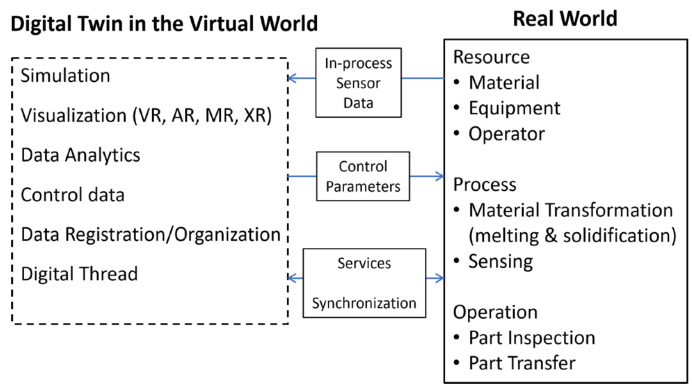

Figure 6 Diagram of Digital Twin in a Mechanical Property Test

5 CONCLUSIONS AND FUTURE WORK

This paper focused on the DT concept and listed the data types that are associated with the digital twins and digital threads to establish the process-(micro)Structure-Property (PSP) relationships. Understanding these relationships is important because they can show root causes of microstructure abnormalities, which, of course affect the mechanical properties of the fabricated AM parts.. Both have been increasingly important research topics needed to qualify AM parts. There are DTs of object and processes in the physical AM world. Examples of AM object DTs include the geometry of the designed part, the scanned sensor data that is used to monitor the part as it is built layer-by-layer, and different sensor data that monitors the environmental conditions during the fabrication process. Since AM processes still involve humans, who uses these DTs to change process parameters when needed, the same DTs can be used to generate virtual or augmented reality the AM process. Moreover, the same DTs can be inputs a variety of physics-based, DA, and AI models that are used to make predictions about the current state of the part. Additionally, there are also DTs, which use the phenomenological laser-track models, to simulate the melting and solidification processes that change the powders to the part. Importantly, since AM is a highly dynamic and real-time process, synchronization with the real (physical) world using data links is essential to continually update the AM DTs.

Future work will be test implement an AMQ package that will include some selected packages, such as design, setup, and build. Parallelly, microstructure and mechanical testing DTs need to be implemented using published microstructural and mechanical property data from sources, such as AMBENCH[4] and open-source software tools. On standardization, the set of AM DT data requirements can be an input to a standard guide development. DT Packages can also be an input for standardization, like the AM technical data package [55]. Additional DTs are required for final qualification. Finally, geometric tolerances and dimensions can be included in the qualification process if there are critical dimensions that need to be inspected and verified in AM parts.

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