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Toward a Digital Thread and Data Package for Metals-Additive Manufacturing

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Abstract

Additive manufacturing (AM) has been envisioned by many as a driving factor of the next industrial revolution. Potential benefits of AM adoption include the production of low-volume, customized, complicated parts/products, supply chain efficiencies, shortened time-to-market, and environmental sustainability. Work remains, however, for AM to reach the status of a full production-ready technology. Whereas the ability to create unique 3D geometries has been generally proven, production challenges remain, including lack of (1) data manageability through information management systems, (2) traceability to promote product producibility, process repeatability, and part-to-part reproducibility, and (3) accountability through mature certification and qualification methodologies. To address these challenges in part, this paper discusses the building of data models to support the development of validation and conformance methodologies in AM. We present an AM information map that leverages informatics to facilitate part producibility, process repeatability, and part-to-part reproducibility in an AM process. We present three separate case studies to demonstrate the importance of establishing baseline data structures and part provenance through an AM digital thread.

Keywords

additive manufacturing; digital thread; repeatability; reproducibility; validation; conformance

Introduction

Additive manufacturing (AM), a manufacturing process that directly creates parts layer-by-layer from 3D models, has been recognized as one of the key enablers for a U.S. economic renaissance in the near future [1]. It shows great potential for fabricating geometrically complicated, value-added, and customer-oriented products [2]. In addition, it provides multiple advantages, e.g., less assembly required and fewer waste byproducts, over traditional manufacturing processes [3]. Many researchers, practitioners, and policy makers anticipate that AM will significantly change the manufacturing landscape in the near future [4].

Though the technology has rapidly matured, barriers remain before AM can be realized as a viable production alternative across various domains (e.g., aerospace, automotive, and biomedical applications). Based on analyses from roadmaps [3,4] and review papers [5–8], we classify these barriers into six categories: standards and guidelines [3,4,6]; AM design, modeling, and simulation tools [3–7]; material availability [3,4,6,7]; control systems [3–8]; qualification and certification [3–6,9,10]; and process repeatability and part-to-part reproducibility [3–6]. This paper aims to address the last category, process repeatability and part-to-part reproducibility, while sharing objectives with the other five categories though the common underpinnings of data management and informatics.

Maintaining consistency across AM builds has proven to be a challenge, as subtle variations in process, material, or geometry can affect final part characteristics both locally and globally. Given the various sources of uncertainty, it is important to constrain process, design, and geometry variations from part to part as much as possible. By adopting structured concepts of digital provenance [11] and digital thread [12–15], variability can be more effectively constrained and managed across the life cycle of an AM part. Consistent, well-defined structure of these fundamental concepts is necessary to develop a baseline criterion on which part validation and conformance can be established.

In manufacturing literature [4,16], the terms "process repeatability" and the "part-to-part reproducibility" have been defined, respectively, as the capabilities (1) to repeat the same process (e.g., build-to-build, machine-to-machine, and operator-to-operator) [4], and (2) to reproduce the first part up to the *n*th one that should meet design specifications [4,16]. These definitions will be adopted and extended to AM in this paper, specifically to address the design validation and conformance requirements of additively manufactured parts. Our adopted definitions are further scoped with the following informatics considerations: (1) repeatability incorporates the required information to implement the same procedure over and over with minimal process variation, and (2) reproducibility incorporates the required information to achieve similar results with minimal part variation. Identification and communication of the minimum information for repeatability and reproducibility is essential for industry stakeholders to consistently produce AM parts.

Based on the concept of digital provenance, our prior work has resulted in identification of an AM digital thread [12–15], which covers design information, material, process, and ultimately test information. Research efforts have also led to a general conceptual AM data model and methods for adaptive AM information management. In this paper, we establish baseline data models that will support the manageability and traceability of digital data sets through information identification, structure, and analysis [with a focus on the powder bed fusion (PBF) process]. We present an AM information map consisting of four tiers: AM digital spectrum, key attributes, data package, and reproducibility tiers. We discuss data flow in each AM step of a powder bed fusion system and then develop data models for producibility, process repeatability, and part-to-part reproducibility. We present three representative case studies that demonstrate the producibility, repeatability, and reproducibility concepts in an applied environment. These case studies highlight the need for part-to-part consistency and the communication challenges that are often faced. The outline for this discussion is as follows: the next section provides the background of this paper and after that we identify the key attributes of each AM step in terms of producibility, repeatability, and reproducibility. The section following this describes data models, three case scenarios are presented in the next section, and the last section is the conclusion.

Background

In a recent report [15], NIST researchers describe a decomposition of the AM product-realization process into eight phases and a digital spectrum that links these phases. The AM digital spectrum, from which a digital thread can be established, refers to the generation, storage, and flow of the information needed to implement those phases. The eight phases were later evolved into a six-activity model [17]: (A1) generate AM design, (A2) plan independent, (A3) plan process–machine dependent, (A4) build part, (A5) post-process part, and (A6) qualify part (see Fig. 1). These activities are explained as follows.

- (A1) Generate AM design: this activity generates a 3D tessellated model from conceptual design with considerations for geometric dimensioning and tolerancing (GD&T). This phase represents the "geometric form" of the part, as well as any available design rationale. A geometric model is modified with respect to some criteria, such as topological optimization, internal lattice structure, tolerance for assembly, and thickening/hollowing. The output of this activity is a tessellated 3D model with water tightness.
- (A2) Plan process–machine independent: this activity determines the machine-independent process plans, such as part orientation and support structure. These plans may consider surface qualities, material properties, build times, and need for support structures. The output is an optimally oriented 3D model, including the topologically designed support structure.
- (A3) Plan process–machine dependent: this activity determines the machine-dependent process plans, e.g., slicing, power, scan speed, hatch distance, and scan-path strategy. Because of the trade-off between quality (e.g., surface roughness) and process performance (e.g., manufacturing time and cost), only a near-optimal process plan can be determined by taking advantage of optimization techniques. The output is a machine code for the build.
- (A4) Build part: in this activity, a part is fabricated with respect to the determined process plans. The powder layer is spread with a layer thickness and scanned to selectively melt it. The process is repeated until the whole part is completely fabricated. During the fabrication, it is possible to monitor the melt-pool features (e.g., size and shape) for controlling the microstructure and detecting the defects (e.g., balls). The output is the as-built part.
- (A5) Post-process part: this activity is often needed to finish a part for satisfying design requirements. It may include support-structure removal, property enhancement using thermal techniques [e.g., annealing and hot isostatic pressing

(HIP)], accuracy enhancement (e.g., machining), and surface texture improvement (e.g., shot peening and grinding). The output is the post-processed part.

- (A6) Qualify part: this activity addresses the "final product." It may include any mechanical testing or non-destructive evaluation (NDE) on the fabricated part. In this activity, results from testing can be added to part provenance information, establishing a reference for any future part quality inquiries.

Key Attributes for Producibility, Repeatability, and Reproducibility

Fig. 2 shows the AM information map, which consists of four tiers: NIST-AM digital spectrum tier (conceptual model) [15], attribute tier (technical model), data package tier (data model), and reproducibility tier. As the data are mapped vertically from the digital spectrum tier to the reproducibility tier, the information matures. Meanwhile, as information flows horizontally from the "generate AM design (A1)" to "qualify part (A6)," the communication of part-to-part reproducibility increases. Holistically, this data structure provides the foundation for establishiing digital provenance, and ultimately a digital thread.

In the NIST-AM digital spectrum tier, producibility is related to the first activity (A1), because it requires only a few fundamental key attributes to produce a part, e.g., geometric shape and material type. Repeatability is related to the first four activities in the NIST-AM digital spectrum tier (A1 to A4), because it is closely related to the AM process. The key attributes for repeatability are mainly related to the process planning and the actual building. Reproducibility is related to the synthesis of the NIST-digital spectrum (from A1 to A6), which means it is about the AM design, process, as well as the part properties derived from testing. The data package for reproducibility includes data necessary to support producibility, repeatability (process verification), and part qualification. Part qualification occurs when an additively fabricated part satisfies its desired specifications, e.g., surface roughness and tensile strength.

In traversing the NIST-AM digital spectrum tier, data is created during AM processes (A1–A6). The data encompasses all of the information used, created, and exchanged in/between each process. For example, the information involved in "generate AM design (A1)" includes data related to six sub-activities (A11–A16): (A11) generate CAD model, (A12) optimize shape, (A13) tessellate model, (A14) repair tessellated model, (A15) modify tessellated model, and (A16) generate lattice. Each sub-activity generates its own data, such as information about input (e.g., conceptual design), output (e.g., tessellated model with lattices), control (e.g., design specification), and mechanism (e.g., optimization software). Desired structure for producibility, repeatability, and reproducibility is extracted from the digital spectrum tier and further refined by each step in the attribute tier.

The identified key attributes for each step in the AM process are captured in the data package tier. In progressing from the attribute tier to the data package tier, data structure is formatted as the data packages for producibility, repeatability, and reproducibility. From the data package tier to the reproducibility tier, the data packages are continuously verified and validated in terms of producibility, repeatability, and reproducibility. Finally, each data package for product producibility, process repeatability, and part-to-part reproducibility can be given to different stakeholders for their specific purposes. To demonstrate these concepts, three simple case scenarios will be performed in the case study section below.

In the following sub-sections, the key attributes for producibility, repeatability, and reproducibility with respect to the six activity models are identified. We discuss the overarching concept and provide several examples from each step in terms of producibility, repeatability, and reproducibility, laying the foundation of an AM digital thread. We use terminology from the previously published NIST technical report about the six activity diagrams [17]. In the section on conceptual data models for producibility, repeatability, and reproducibility, models are presented that map information from the attribute tier to the data package tier.

KEY ATTRIBUTES IN THE FIRST ACTIVITY MODEL (A1)

Table 1 shows the key attributes for product producibility, process repeatability, and part-to-part reproducibility in relation to A1. The key attributes can be divided into three sub-categories: design, 3D tessellated model, and machine specification. The first sub-category, design, contains several key attributes needed for producibility, repeatability, and reproducibility. The other two sub-categories identify key attributes necessary for only repeatability and reproducibility.

3D model and material type (e.g., Ti6Al4V and IN625) are identified as key attributes for producibility, repeatability, and reproducibility. To generate a tessellated 3D model, there are two ways: a solid model from CAD software using boundary representation (B-rep) is tessellated; and point clouds from a coordinate measuring machine (CMM) or a laser scanner are triangularized using reverse-engineering (RE) technology [18,19]. The design requirements are fundamental to creating an AM part.

Identifying key attributes beyond producibility places a focus on repeatability and reproducibility. Here, key attributes, including a plan for 3D model generation, XYZ coordinates and its connectivity between nodes, surface resolution of a 3D model, and facet types (e.g., triangular or rectangular), are the key attributes. For example, surface resolution of a 3D model should be established, as this attribute is related to the chordal error [20]. The chordal error is the deviation between the actual surface and the triangular facets. Geometrical errors can significantly degrade the quality of a 3D model and generate corresponding errors in process plan activities, especially in the slicing step. Consequently, this deteriorates the repeatability and reproducibility.

Within the data elements of a machine specification, building capacity, accuracy, and feature manufacturability are all key attributes for repeatability and reproducibility. The ability to create a part in a certain machine will be influenced by machine features [e.g., building capacity (mm ×mm × mm), accuracy (mm), multi-material capacity, and building speed]. Manufacturable minimum/maximum feature sizes and angles should be held consistent, including thickness, edge, gap height/width/length, overhanging length, and undercut [21,22].

KEY ATTRIBUTES IN THE SECOND ACTIVITY MODEL (A2)

After A1, the core attributes necessary to establish digital provenance solely focus on repeatability and reproducibility, as the fundamentals for producibility have been established. Table 2 shows the key attributes in A2. The key attributes are divided into two sub-categories: part orientation and support structure. These two sub-categories are a coupled problem, because part orientation will determine support-structure locations.

The orientation of a part is determined by considering time for build, its material properties, surface qualities, and need for support structures. For example, orientation of a part can significantly affect part surfaces through the called “stair-stepping effect.” In this case, the stair-stepping effect can be reduced by adaptively slicing the layer thickness and by orienting the part appropriately. Because of the anisotropic nature of the PBF process, orientation affects material properties as well. For example, Wauthle et al. [23] concluded that orientation of internal lattice structures also affects the material properties, such as yield strength, maximum strength, stiffness, and strain at fracture.

When characterizing the generation of support structures [24], complex geometric features of the model, such as overhangs, undercut, and assembly part with moving components, should be recognized. Key attributes that characterize support structures include: number of support structures, contact points between part and structures, contact points between structure and plate, material of support structure, types of support structure (e.g., block, point, and web), infill density of support structure, and height between build platform and part.

KEY ATTRIBUTES IN THE THIRD ACTIVITY MODEL (A3)

Table 3 shows the key attributes related repeatability and reproducibility in A3. The key attributes are divided into three sub-categories: slicing, process setup plan, and process parameter determination.

After establishing orientation and support structures, the tessellated 3D model [e.g., stereo-lithography (STL) or additive manufacturing file (AMF)] [25] is discretized into sets of 2D slice contours [e.g., common layer interface (CLI)]. These contours provide the reference geometry used to specify process plans (e.g., tool path with process parameters) that guide the operation of AM machines. Thus, individual layers containing XY coordinates and piecewise linear connectivity become key attributes. In addition, if necessary, this should be identified when a layer may contain the multi-features, such as multi-material or functionally graded materials.

The process setup plan can be characterized with the following attributes: machine specification, powder characteristics, and setup plans. AM machine parameters may be specified such as heat source characteristics (e.g., type, mode, and power) and air control specifications. Powder parameters [26] are also key attributes, such as thermal conductivity, absorptivity, specific heat capacity, thermal expansion coefficient, and powder density. Setup plans attributes include part location, base elevation, cooling time after build, and initial bed temperature.

Key attributes related to process parameters include: laser power, spot size, wavelength, and mode of a laser, scan speed, hatch distance, layer thickness, scan pattern, and scan layering strategy, as they all significantly affect the part properties [27]. Among these, some process parameters (e.g., power, scan speed, hatch distance, and layer thickness) can be differentiated again with respect to four exposure types: pre-contour, core, skin, and post-contour. The skin can be further characterized as up-skin, down-skin, and side-skin.

KEY ATTRIBUTES IN THE FOURTH ACTIVITY MODEL (A4)

Table 4 lists key attributes related to activity A4, the build of a part. The key attributes are divided into two sub-categories: preparation for a build and build (a part).

Preparation for a Build—The key attributes in this sub-category can be divided into two areas: (1) machine setup, and (2) powder preparation. Parameters used in machine setup are important to establishing digital provenance, such as initial bed temperature, inert gas/air ratio, laser focal point, build plate level and location, recoating blade wear, type/flatness/surface roughness/thickness of build platform, and platform parallelism with a recoater. These parameters are not a complete set, but begin to provide a basis to characterizing the build setup.

Accurate characteristics of a powder material can give the corresponding melt-pool features (e.g., maximum temperature and shape) or thermal properties. Thus, the characteristics of powder material are key attributes, such as powder size, distribution, morphology (e.g., dimensional, spherical, roundness, and perimeter), chemical composition, density (e.g., apparent density, tap density, and skeletal density), and thermal properties (e.g., conductivity and diffusivity) of powder. In addition, the number of times a powder material has been recycled is important.

Build (a Part)—This stage is associated with attributes that will influence process stability. To achieve consistency during part builds, the process environments should be characterized to support stability. This stage can be divided into two areas: (1) process consistency, and (2) motion/position accuracy. Key attributes for characterizing process consistency include the laser beam power/wavelength/mode, inert gas/air rate and ratio, pressure and air temperature of a chamber, humidity control, and layer thickness. Motion/position of recoating arm/blade/laser spot/*z*-axis are key attributes in determining positioning, and all can influence the geometric shape of a part.

KEY ATTRIBUTES IN THE FIFTH ACTIVITY MODEL (A5)

Table 5 lists key attributes identified in A5, all associated with reproducibility, as at this stage the part geometry has been formed and is now being finished. Key attributes can be divided into four sub-categories: support removal, property enhancement using thermal techniques, accuracy enhancement, and surface texture improvement.

The order and process used for support removals should be consistent when finishing a part. Often a part is heat treated with support structures before any support removal process to relieve residual stresses. The cooling time and conditions should be monitored to consistently dissipate any residual heat. Methods of support removal [e.g., wire-electrical discharge machining (EDM) and bandsaw] and removal plans (e.g., machining type: wire-EDM, water type: de-ionized, diameter of wire, process parameter, and fixture/position setup) are also identified as key attributes.

Property enhancement using thermal techniques [e.g., hot isostatic pressing (HIP) or annealing] are also available to help improve part properties, including residual stress reduction, porosity reduction, and microstructure uniformity and ductility increases. For example, for a Ti-6Al-4V metal alloy, the HIP and annealing processes are often implemented at 926°C at 100 MPa and 913°C for 2–4 h and then furnace cooled below 427°C [5]. The part microstructure (e.g., grain sizes, morphology, and distribution of the phases) is a function of maximum temperature, processing time, and cooling rate. Mechanical properties are significantly dependent on the maximum temperatures. Thus, methods of heat treatment and the details (e.g., maximum temperature, pressure, processing time, and cooling rate) become key attributes for supporting reproducibility.

The geometric accuracy of as-processed AM metal parts is generally poorer than that of traditional machining processes, and dimensional day-to-day variability is also common [27]. Methods of machining process for finishing AM part (e.g., adaptive raster milling, sharp edge contour machining, and drilling) and its process plans (e.g., process parameters, fixture/position setup, and tool path) become key to reducing this variability.

Poor surface roughness may be induced from stair-stepping effects or instability of an AM process (e.g., instability in melt-pool formation). Methods of surface texture improvement (e.g., shot peening, painting, and hardening) and implementation details, therefore, become key attributes for reproducibility. For example, in the case of a shot peening process, the size of metal spherical balls and air pressure are important to a consistent finish.

KEY ATTRIBUTES IN THE SIXTH ACTIVITY MODEL (A6)

Table 6 shows the key attributes related to activity A6, the testing and qualification process of a part, essential for measuring reproducibility. The key attributes are divided into five sub-categories: geometric dimensioning and tolerancing (GD&T), defects, microstructure, surface roughness, and part properties.

Test methods for GD&T [e.g., industrial computed tomography (CT) scanner, 3D optical scanner, and CMM] and inspection plans (e.g., coordinate of number of testing points or areas) for flatness, roundness, straightness, parallelism, perpendicularity, and concentricity are all parts of reproducibility. For example, specific settings of CT scanners, such as a setting of 155 kV for an X-ray source operating at 10 W of power at 3000 angles [28], will influence whether images are comparable.

During the AM process, defects (e.g., cracks, porosity, and delamination) can occur [29,30], which is why inspections are so important. Non-destructive evaluation (NDE) is one type of test that is often associated with AM, as more traditional inspection methods can be destructive and therefore expensive [31]. NDE methods include remote visual inspection, industrial CT scanning, dye penetrant inspection, magnetic-particle inspection, ultrasonic inspection, eddy-current inspection, acoustic emission inspection, thermographic inspection, and stereomicroscope inspection methods. Inspection plans for defects (e.g., cracks and porosity) and the subsequent details become important attributes in establishing digital provenance. For example, details of a density test may include the use of distilled water for minimizing the presence of air bubbles, and a temperature of 22°C [32].

As with NDE, other inspection methods for microstructure [e.g., optical microscopy and scanning electron microscopy (SEM)] and the results (e.g., grain size, morphology, and growth direction) are also important attributes. For example, information, such as coordinates and number of testing areas, cutting method, and polishing method, should be identified when a sample specimen is prepared and tested.

Inspection plans for surface roughness become the key attributes, such as measurement devices, coordinates and number of measuring points, and surface roughness metrics. For example, surface roughness metrics, such as average roughness (R_a) and maximum roughness height (R_t), should be identified for reproducibility.

The testing of part properties can be categorized into four areas: mechanical properties [33], electrical properties, chemical properties, and thermal properties. Mechanical testing [34] can be divided into (1) deformation properties (where the tests attempt to quantify how a material will yield or deform), and (2) failure properties (where the tests attempt to quantify the potential for the component to rupture or fail). Deformation property tests may include tension, compression, bearing, modulus, and hardness tests, whereas failure property tests include fatigue, fracture toughness, and crack growth tests. In some cases, such as with uniaxial tensile testing, the testing sample type (e.g., dog-bone specimen) should be identified. Whereas the tests used may vary, it is important to maintain consistent metrics so that data can be interpreted and compared.

Development of Conceptual Data Models

From the identified key attributes, we develop conceptual data models to support the establishment of digital provenance through a digital thread. Fig. 3 presents a high level data package in terms of a product, process, and resources (PPR) model [35]. Reproducibility is the most inclusive and, thus, includes the entire data sets from the six processes. In contrast, repeatability includes the data sets from A1 to A4. Producibility concerns information, such as the 3D model and material type, relying on minimal design specification. Here, we examine the relationship between the data package as a product and its relationship to producibility, repeatability, and reproducibility.

In using the PPR model, address the development of a part from design, to manufacture, to qualification. Where previously we looked at the information that is incorporated across life cycle stages, the PPR model generalizes this information at an additional level of abstraction. The resources domain can be categorized into four sub-domains: equipment, software, human, and material. The equipment subdomain can include general equipment information (e.g., manufacturer’s name, maintenance history, manufacturing capability, and machine specification). The software sub-domain can include general information such as vendor, version, and license and the human sub-domain can include personnel information (e.g., name, affiliation, and title) and skill level. The human domain also can be categorized into designer, operator, controller, and tester with respect to their different roles. Finally, the material sub-domain can include vendor information (e.g., vendor name and fabricated date) and powder characteristics (e.g., powder size and distribution, morphology, chemical composition, and thermal properties), for example. These additional levels of abstraction are important as they can be used to help normalize data across heterogeneous platforms.

Traditionally, an additively fabricated part is a single physical artifact, but passes through multiple stages of "realization." We expand on this concept, and consider the dataset from each phase as contributors to a digital artifact called a "data package." To this point, we refer back to the phases of the AM digital spectrum. Following the transition from a digital model to a physical artifact, a product domain can be categorized into seven sub-domains: DataSet I-1, DataSet I-2, and DataSet II through DataSet VI.

Each of these data packages provides key information from service requesters (e.g., customer) to service providers (e.g., manufacturer) about the design and manufacture of the product, in terms of producibility, repeatability, and reproducibility. DataSet I-1, including 3D model_info and material_type, contains information that is relevant to producibility, repeatability, and reproducibility, but only fully contains the data necessary for producibility. By extending from DataSet I to DataSet IV, the data sets now fully support part producibility and processing repeatability. Integrating DataSet V and DataSet VI with DataSet I–IV completes the data package for reproducing AM parts, proving information related to part design, manufacture, and finally qualification. Fig. 3 outlines these concepts, and whereas the information identified is not inclusive, it is representative of establishing digital provenance through data packages in metals AM.

A Case Study

In this section, three simple case studies demonstrate establishing digital provenance through the concepts of producibility, repeatability, and reproducibility. Each case study is used to validate the feasibility of the proposed data package concept between service requesters (e.g., customer) and service providers (e.g., manufacturer). The producibility scenario is illustrated by earlier NIST studies on test artifacts [27] and the circle–diamond–square artifact [36–38]. For repeatability and reproducibility, we use a round-robin test case that required builds of circle–diamond–square artifacts. To demonstrate the data packages, XML (extensible markup language) files for the information exchange for producibility, repeatability, and reproducibility are represented, respectively.

DATA PACKAGE FOR PRODUCIBILITY (DATASET I)

In this case study, we use the NIST test artifact (100 × 100 × 17 mm^3 and 101,000 mm^3) and the circle–diamond–square artifact. Fig. 4 shows a use case scenario for the NIST artifact in terms of producibility. The case scenario is as follows: (1) a service requester designed the 3D model and specified the material type for the test artifacts; (2) the requester stored the data package into XML schema; (3) the requester distributed the data package to two service providers; (4) each service provider fabricated the part based on the data package by using their own manufacturing resources, and; (5) the parts generated were given to the service requester.

Fig. 5 shows the XML file of data package of the NIST test artifact, which is related to the conceptual data model for producibility in Fig. 3. It contains the 3D model (STL file) and the material type information. Each service provider has different resources, as: (1) service provider I has an electron beam melting (EBM) system with Ti-6Al-4V, and (2) service provider II has a direct metal laser sintering (DMLS) system with Ti-6Al-4V. Fig. 6 shows the photographs of the test artifacts built by two providers. It is shown that the features of the artifacts were not produced consistently by the service providers, as they use different manufacturing processes with different machine capabilities. Fig. 7 shows the bottom side of the circle–diamond–square artifact. Each artifact shows different support-structure patterns. Because the process job file is not given to the service provider, they fabricated the artifact with their own process plans, resulting in different processes, and ultimately different parts.

DATA PACKAGE FOR PRODUCIBILITY AND REPEATABILITY (DATASET I–IV)

This case scenario uses the same artifacts as case study 1, except that service requester also provided DataSet II–IV to the service providers. Each service provider fabricated the circle–diamond–square test artifacts with the 3D models and consistent process information. In this case scenario, the part is the circle–diamond–square test artifact and the specified powder is titanium alloy (Ti6Al4V). EBM processes were used to fabricate the artifact.

Fig. 8 shows the use case scenario. The case scenario is as follows: (1) a service requester identifies the 3D model, material type, and AM process data (DataSet I–IV); (2) the requester stores the data package into XML schema; (3) the requester distributes the data package to three different service providers; (4) each service provider fabricates the artifact with the data package; (5) the fabricated parts are sent to the service requester, and (6) the parts are machined by the wire electrical discharge machining (EDM).

Fig. 9 shows the XML file for the additional data package, which is related to the conceptual data model for repeatability in Fig. 3. The extended data package contains the 3D model (STL file), material type, and process files. The support structures for the test artifacts are added to the data package. The slice file (SLI file) of the supported artifact is also added to the data package. These datasets, as well as machine specific information when available, combine to run the AM machine. For example, process parameters with preheating are acceleration voltage 150 kV, beam current 30 mA, scan speed 15 m/s, initial substrate temperature 600°C, and initial powder temperature 200°C [39]. Additional process parameters are maximum current 30 mA, line offset 100 μm, focus offset 10 mA, and speed function index 60 [40].

The XML file containing DataSet I–IV is distributed to the three different service providers. Fig. 10 shows the photographs of the test artifacts built by three service providers. Unlike what was seen in case study 1, the three artifacts are of similar appearance in shape, color, and texture. However, if studied closely, it can be seen that noticeable variations remain between the parts.

DATA PACKAGE FOR REPRODUCIBILITY (DATASET I–VI)

The case scenario of data package for reproducibility extends beyond that of repeatability. Whereas the information to create the part remains the same, this data package also includes post-process information, test plans, and additional design requirements to the service providers. In this scenario, design requirements included are the average surface roughness (R_a: 40 μm) and maximum roughness height (R_t: 100 μm). Each service provider fabricates the circle–diamond–square artifact and performs the post-processes and tests necessary to meet and qualify against the requirements. A laser PBF process and stainless steel powder are used to fabricate the artifact.

Fig. 11 shows the use case scenario. The case scenario is as follows: (1) a service requester identifies the 3D model, material type, design requirements, AM process information, post-process information, and test information (DataSet I–VI); (2) the requester stores the data package into XML schema; (3) the requester distributes the data package to two service providers; (4) each service provider fabricates the part with the data package; (5) each service provider performs the specified postprocesses such as heat treatment and wire electrical discharge machining (EDM); (6) each service provider measures the surface roughness of the designated top surface of each part by using a stylus profilometer; and (7) the parts and test results are given to the service requester. Fig. 12 shows the XML schema of the data package, which is related to the conceptual data model for reproducibility in Fig. 3 (DataSet I–VI). Fig. 13 shows the photographs of the test artifacts built by two service providers. Notice that these two artifacts show the least variation of the three case studies provided. As additional instructions and requirements were included in the data sets, the service providers were able to better qualify their parts. For instance, the surface roughness of each test artifact satisfies the design requirements.

Conclusion

This paper describes the development of data models to address existing AM production challenges including: (1) data manageability through information management systems, (2) traceability to promote product producibility, process repeatability, and part-to-part reproducibility, and (3) accountability through mature validation and conformance methodologies. We proposed an AM information map consisting of four tiers: NIST-AM digital spectrum (conceptual model), attribute (technical model), data package (data model), and reproducibility (digital thread) tiers. We identified key attributes from different stages of the AM life cycle and presented conceptual data models toward establishing digital provenance with an AM-specific digital thread. These data models feed into data packages with respect to producibility/repeatability. Together, the established data packages and digital thread provide a foundation on which future validation and conformance methodologies can be built.

An operational scenario was included to demonstrate AM production challenges and how different levels of data packages can guide a PBF process. It was shown how data packages built on producibility, repeatability, and reproducibility can be expressed and shared via the XML format. Through the operational scenarios, from producibility (DataSet I) to repeatability (DataSet I–IV) to reproducibility (DataSet I–VI), we demonstrate that as data matures variations in the produced part decrease.

Acknowledgments

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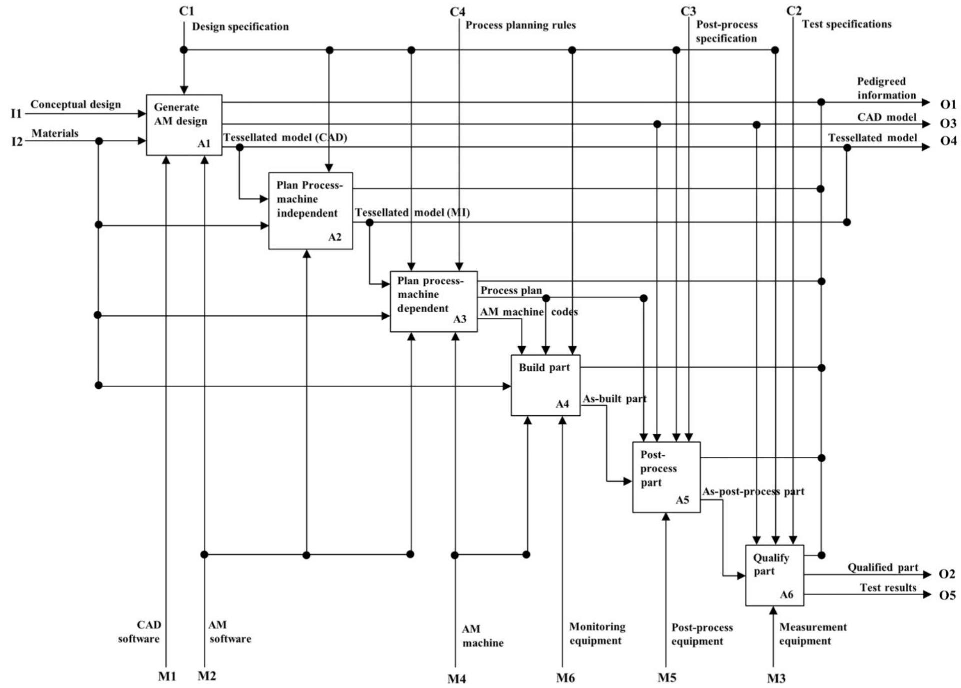

FIG. 1.

IDEF0 functional diagram consisting of six activities to build an AM part [13].

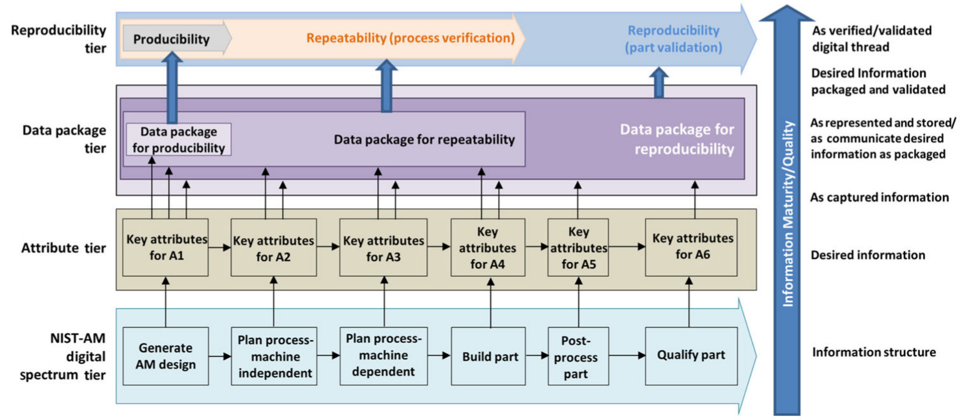

FIG. 2.
AM information map consisting of four tiers.

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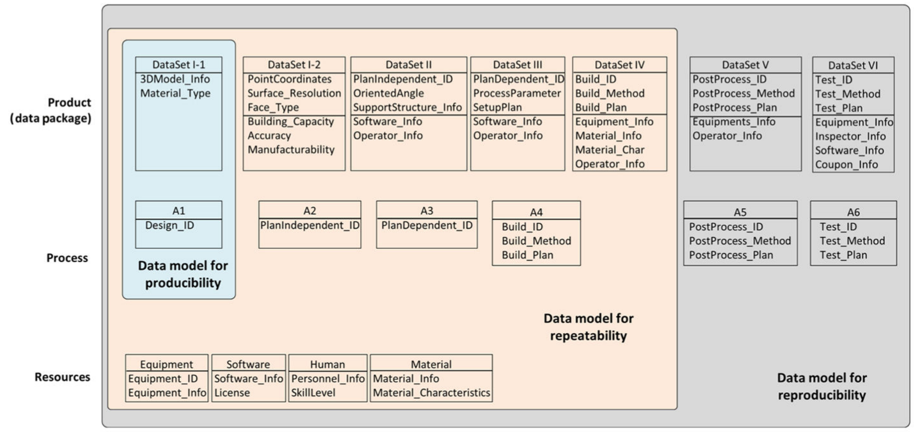

FIG. 3.

Conceptual data model of producibility, repeatability, and reproducibility with respect to product, process, and resources.

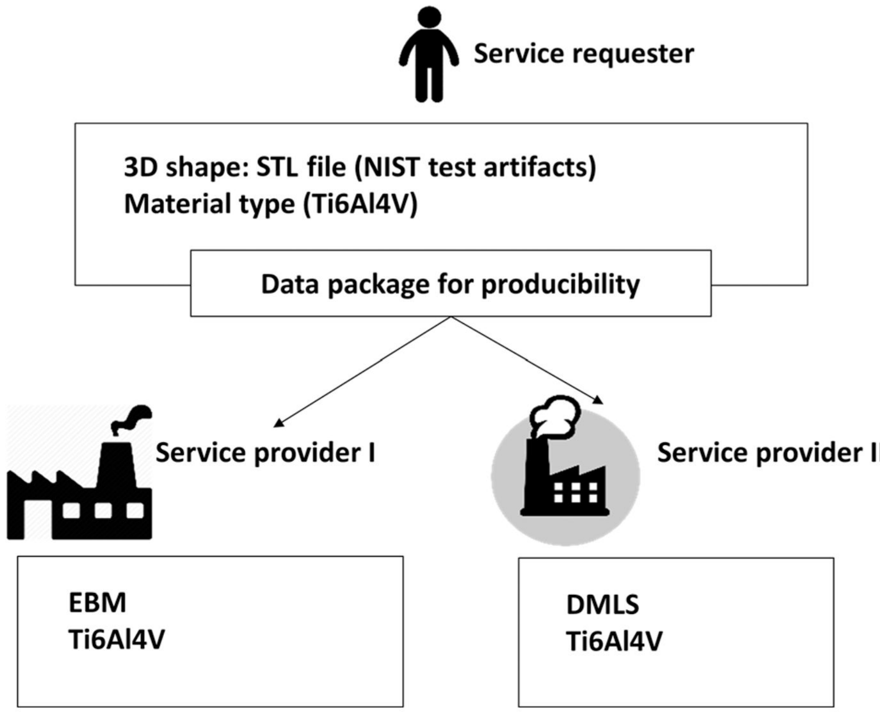

FIG. 4.
Use case scenario for NIST artifact in terms of producibility.

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```xml
<amProducts>
    <Product>
        <Header>
            <ProductType>MODEL</ProductType>
            <Name>NIST TEST Artifact Build STL File</Name>
            <Application>Siemens NX 9.0</Application>
            <Author>Peter Johnson</Author>
            <Description>STL file of NIST test artifact</Description>
            <LastModified>2014-05-04</LastModified>
        </Header>
        <Design>
            <Part id="001">
                <DigitalModel id="NIST_EL_SID_001">
                    <Name>NIST Test Artifact STL Model</Name>
                    <File>NISTTestArtifact.stl</File>
                </DigitalModel>
            </Part>
        </Design>
    </Product>
    <Product> [14 lines]
    <Product> [196 lines]
</amProducts>
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    <Equipment> [20 lines]
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        <RatedMaterialProperties> [30 lines]
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        <InertGasAtomization>false</InertGasAtomization>
        <LotID>ANY</LotID>
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</Resources>
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FIG. 5.

XML schema of data package for producibility.

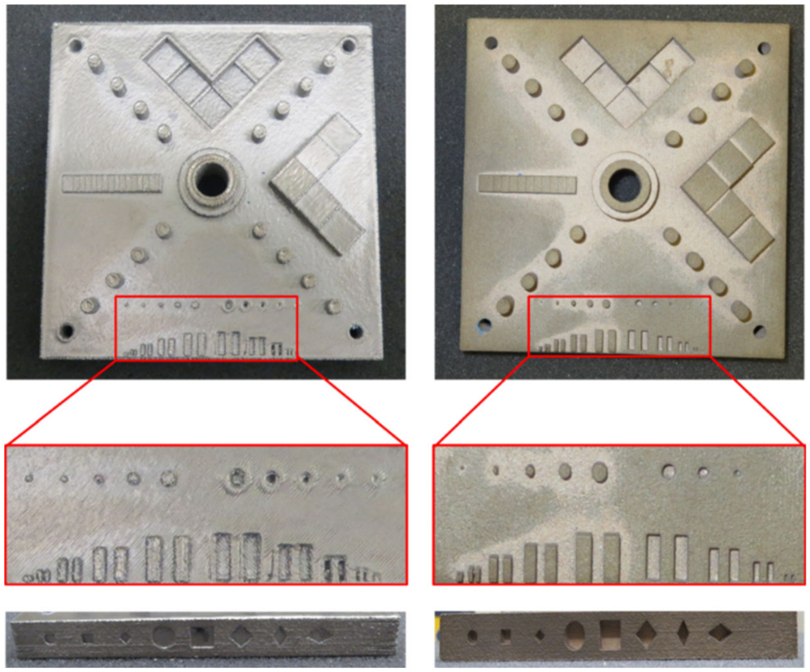

FIG. 6.
Photographs of the test artifacts built by two service providers. Left to right: Provider I (EBM/Ti6Al4V) and Provider II (DMLS/Ti6Al4V).

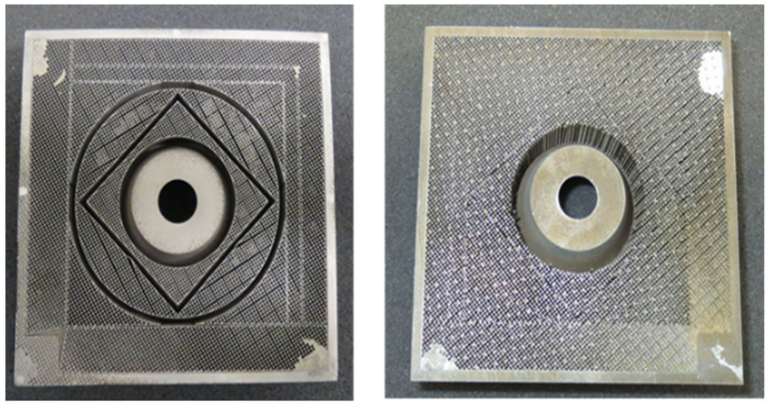

FIG. 7.
Photographs of the test artifacts built by different process plans (e.g., different support-structure pattern).

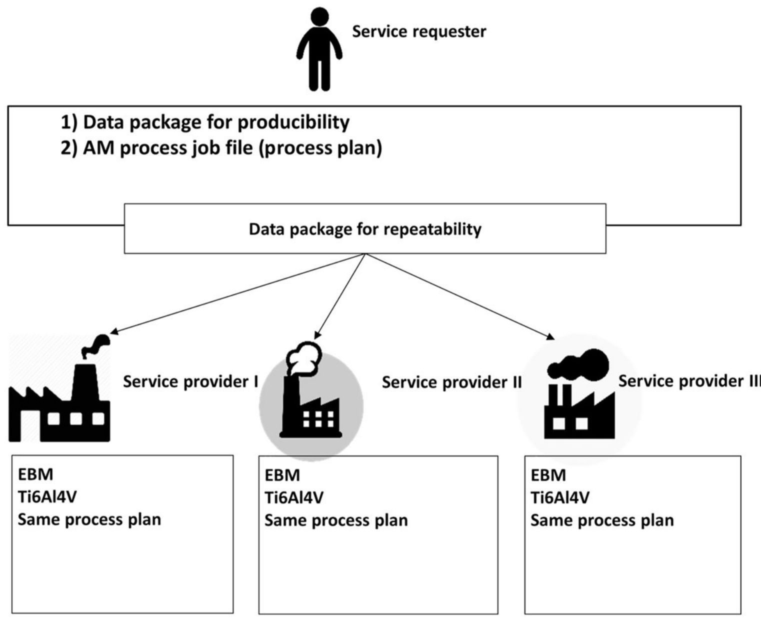

FIG. 8.
Use case scenario for circle–diamond–square test artifact in terms of repeatability.

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```
        <Product>
            <Header>
                <ProductType>PROCESSPLAN</ProductType>
                <Name>NISTCircleDiamondSquareTestArtifact0001buildID0 Process Plan</Name>
                <Application>Magics 20</Application>
                <Author>William Smith</Author>
                <Description>process plan for M270</Description>
                <LastModified>2014-05-04</LastModified>
            </Header>
            <ProcessPlan>
                <BuildSetting> [12 lines]
                <RecoatingSetting> [8 lines]
                <Atmosphere> [5 lines]
                <Platform> [5 lines]
                <MaterialSpecificSetting> [146 lines]
                <BuildFile id="NIST_EL_SID_002"> [3 lines]
            </ProcessPlan>
        </Product>
    </amProducts>
    <Resources>
        <Equipment>
            <Manufacturer>Arcam</Manufacturer>
            <ModelName>Arcam S400</ModelName>
            <ManufacturingDate>2012-01-01</ManufacturingDate>
            <Description>Arcam EBM Technology</Description>
            <MaintainanceHistory> [6 lines]
            <CalibrationHistory> [7 lines]
        </Equipment>
        <VendorMaterial> [38 lines]
```


FIG. 9.

XML schema of data package for repeatability.

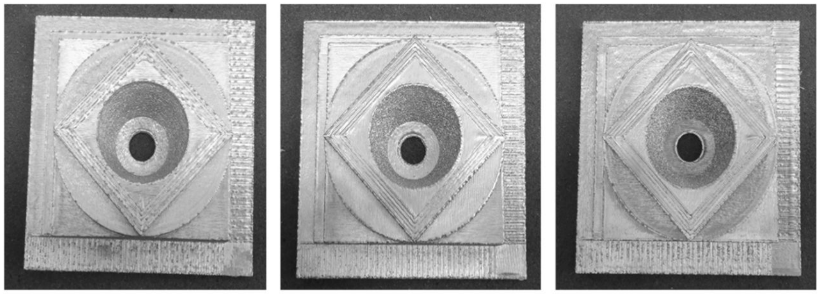

FIG. 10.
Photographs of the test artifacts built by three service providers. Left to right: Provider I, Provider II, and Provider III.

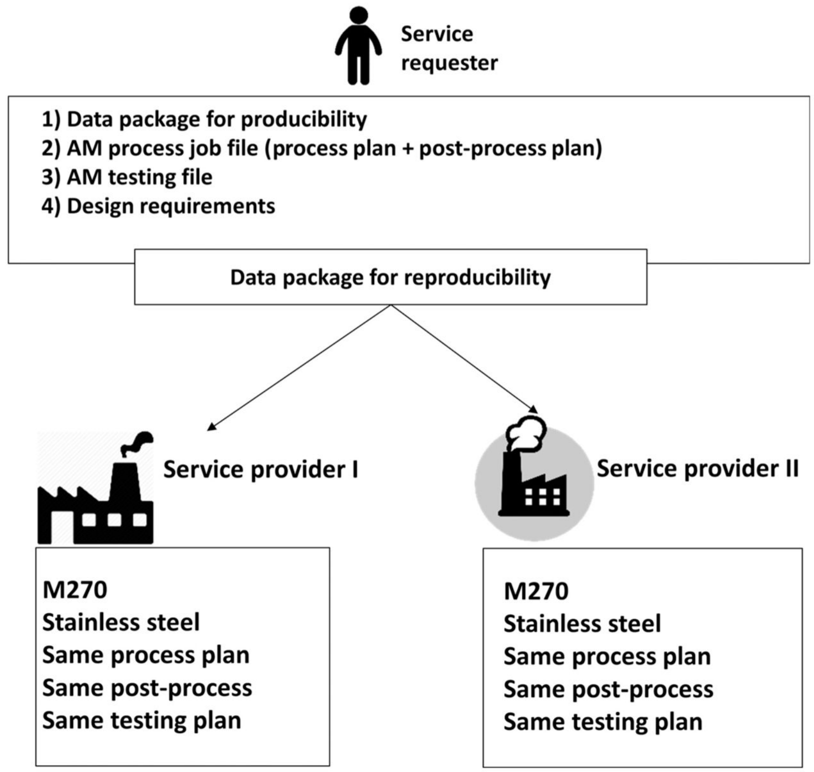

FIG. 11.

Use case scenario for circle–diamond–square test artifact in terms of reproducibility.

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        <Name>NIST TEST Artifact Build Spec</Name>
        <Application>Adobe PDF</Application>
        <Author>Peter Johnson</Author>
        <Description>Build specification for NIST Diamond shape Test Artifact</Description>
        <Units>um</Units>
        <LastModified>2006-05-04</LastModified>
    </Header>
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        <SurfaceMax>50</SurfaceMax>
        <SurfaceAve>10</SurfaceAve>
    </Spec>
</Product>
<Product> [196 lines]
<Product>
    <Header>
        <ProductType>TESTREPORT</ProductType>
        <Name>NISTDiamonShapeArtifactTestReport</Name>
        <Application>Adobe</Application>
        <Author>Michael Edmondson</Author>
        <Description>NIST Diamond Shape Artifact Surface Roughness test</Description>
        <LastModified>2015-07-30</LastModified>
    </Header>
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        <TestData>
            <SurfaceMax>37.5</SurfaceMax>
            <SurfaceAve>8.6</SurfaceAve>
        </TestData>
        <File>NISTSRT.pdf</File>
    </TestReport>
</Product>
```


FIG. 12.

XML schema of data package for reproducibility.

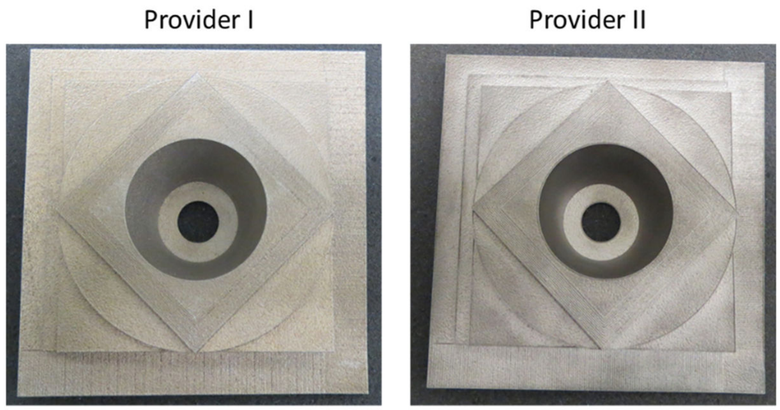

FIG. 13.
Photographs of the test artifacts as built by two service providers.

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TABLE 1

Key attributes of producibility, repeatability, and reproducibility in A1.

	Sub-Categories	Attributes	Producibility	Repeatability	Reproducibility
A1	Design	3D model	×	×	×
		Point clouds: point data set of XYZ coordinates	×	×	×
		B-rep model: data set for boundary representation	×	×	×
		Material type (e.g., Ti6Al4V and IN625)	×	×	×
		Design requirements			×
	3D tessellated model	Plan for 3D model generation		×	×
		XYZ Coordinates and its connectivity between nodes		×	×
		Surface resolution of 3D model		×	×
		Chordal distance		×	×
		Facet type (e.g., triangular, rectangular)		×	×
	Machine specification	Building capacity (build volume)		×	×
		Accuracy (resolution)		×	×
		Feature manufacturability		×	×
		Min/max manufacturable feature size		×	×
		Thickness/undercut		×	×
		Edge/gap/overhang length		×	×

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TABLE 2

Key attributes of repeatability and reproducibility in A2.

	Sub-Categories	Attributes	Producibility	Repeatability	Reproducibility
A2	Part orientation	Part orientation angle		×	×
	Support structure	Characteristics for support structure		×	×
		Number of support structure		×	×
		Contact points between part and structures		×	×
		Contact points between structure and plate		×	×
		Material of support structure		×	×
		Types of support structure (e.g., block, point, and web)		×	×
		Infill density of support structure		×	×
		Height between build platform and part		×	×

TABLE 3

Key attributes of repeatability and reproducibility in A3.

	Sub-Categories	Attributes	Producibility	Repeatability	Reproducibility
A3	Slicing	Individual layers containing XY coordinates and its piecewise linear connectivity		×	×
		Representation of multi-features		×	×
		Multi-material		×	×
		Functional-graded material		×	×
	Process setup plan	Machine specifications		×	×
		Powder characteristics		×	×
		Setup plans		×	×
		Part location		×	×
		Base elevation		×	×
		Cooling time after build		×	×
		Initial bed temperature		×	×
	Process parameter determination	Process parameter		×	×
		Laser power, wavelength, and mode		×	×
		Scan speed		×	×
		Hatch distance		×	×
		Laser spot size		×	×
		Scan pattern		×	×
		Scan layering strategy		×	×
		Four exposure type		×	×
		Pre-contour		×	×
		Core		×	×
		Skin (up-/down-/side-skin)		×	×
		Post-contour		×	×

TABLE 4

Key attributes of repeatability and reproducibility in A4.

	Sub-Categories		Attributes	Producibility Repeatability	Reproducibility
A4	Preparation for a build	Machine setup	Initial bed temperature	×	×
			Inert gas/air ratio	×	×
			Laser focal point	×	×
			Build plate level and location	×	×
			Recoating blade wear	×	×
			Type, flatness, surface roughness, and thickness of build platform	×	×
			Platform parallelism with recoater	×	×
		Powder preparation	Powder characteristics	×	×
			Size/distribution	×	×
			Morphology (e.g., spherical, roundness)	×	×
			Chemical composition	×	×
			Density (e.g., apparent/tap/skeletal density)	×	×
			Thermal properties	×	×
			Recycled time	×	×
	Build (a part)	Process stability	Process consistency	×	×
			Laser beam power, wavelength, and mode	×	×
			Inert gas/air rate and ratio	×	×
			Pressure and air temperature of a chamber	×	×
			Humidity control	×	×
			Layer thickness	×	×
			Motion/position accuracy	×	×
			Recoating arm/blade/laser spot/*z*-axis	×	×

TABLE 5

Key attributes of reproducibility in A5.

	Sub-Categories	Attributes	Producibility	Repeatability	Reproducibility
A5	Support removal	Enough cooling time-lapse for dissipating residual heat		×	
		Method of support removal		×	
		Wire-EDM, bandsaw, brush, compressed air		×	
		Process plans for support removal		×	
		Machining type: wire-EDM		×	
		Water type: de-ionized water or dielectric fluid		×	
		Diameter of wire: 0.254 mm		×	
		Process parameter		×	
		Fixture/position setup		×	
	Property enhancement using thermal techniques	Method of heat treatment		×	
		Hot isostatic pressing, annealing process		×	
		Heat treatment process plans		×	
		Maximum temperature		×	
		Pressure		×	
		Processing time		×	
		Cooling rate		×	
	Accuracy enhancement	Method of machining process for finishing AM part		×	
		Adaptive raster milling and sharp edge contour machining		×	
		Process plans for machining		×	
		Positioning/fixture setup		×	
		Process parameters		×	
		Tool path		×	
	Surface texture improvement	Methods for surface texture improvements		×	
		Shot peening, painting, hardening		×	
		Shot peening plans for surface roughness improvement		×	
		Size of metal spherical balls		×	
		Air pressure		×	

TABLE 6

Key attributes of reproducibility in A6.

	Sub-Categories	Attributes	Producibility	Repeatability	Reproducibility
A6	GD&T	Test methods for GD&T			×
		Industrial CT scanner, 3D optical scanner, CMM			×
		Test plans for GD&T			×
		Testing device (e.g., CMM) and its guidelines			×
		Coordinate of number of testing points or areas			×
		Test plans for external dimensional accuracy			×
		3D optical scanner			×
		Reverse engineering tool			×
		Error metrics: volumetric error, Hausdorff distance			×
		Test plans for external and internal accuracy			×
		Industrial CT scanning			×
	Defects	Testing plans for cracks and porosity			×
		Ultrasonic testing			×
		Archimedes testing			×
		Industrial CT scanning			×
	Microstructure	Testing methods for microstructure			×
		Optical microscopy			×
		Scanning electron microscopy (SEM)			×
		Test plans for microstructure			×
		Device: SEM			×
		Sample preparation			×
		Coordinates and number of testing areas			×
		Cutting method			×
		Polishing method			×
	Surface roughness	Test plans for surface roughness			×
		Device: A stylus profilometer			×
		Coordinates and number of testing points			×
		Metrics for surface roughness			×

Sub-Categories	Attributes	Producibility	Repeatability	Reproducibility
Part properties	Test plans for mechanical properties			×
	Testing type			×
	Preparation of testing sample type			×
	Standard: ASTM E8			×
	Test plans for electrical properties			×
	Test plans for chemical properties			×
	Test plans for thermal properties			×