ASM Handbook, Volume 24A, *Additive Manufacturing Design and Applications*
M. Seifi, D. Bourell, W. Frazier, H. Kuhn, editors
https://doi.org/10.31399/asm.hb.v24A.a0006981

Additive Manufacturing Data and Metadata Acquisition—General Practice

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INCREASINGLY, A WIDE VARIETY of additive manufacturing (AM) data is generated through AM development life cycles. The amount, type, and speed of the collected data is unprecedented. Additive manufacturing data are created and used for material development, process improvement, machine calibration, product quality control and qualification, and so on. In the details of these activities, an extensive range of overlapping data needs to exist that may benefit from the sharing of the data. Design data, machine data, as well as measurements from materials characterization, process monitoring, part inspection, and testing are commonly used across many AM activities. The data can be stored and exchanged in various formats, for example, Microsoft Excel spreadsheets, computer-aided design (CAD) models, images, PDF documents, and so on. Engineering decisions often rely on a broad spectrum of data beyond the individual data-generation capability of individual stakeholders.

To enhance the usability and reusability of AM data, metadata, which can be described as a description of data, must be collected and accessible by users. Among the metadata elements, the information about data acquisition is critical for data interpretation and downstream analysis. This article surveys common AM data-acquisition methods, covering preprocess materials characterization in the lab, machine calibration in the field, in-process monitoring during a build, and postprocess part inspections and tests. The focus is to identify acquisition-related metadata for AM data sets to improve data usability and reusability. Also included are exemplar metadata definitions for a data set acquired from light-scattering-based particle size analysis.

Figure 1 illustrates various data collected along the AM part development life cycle (in blue) and from the material and machine

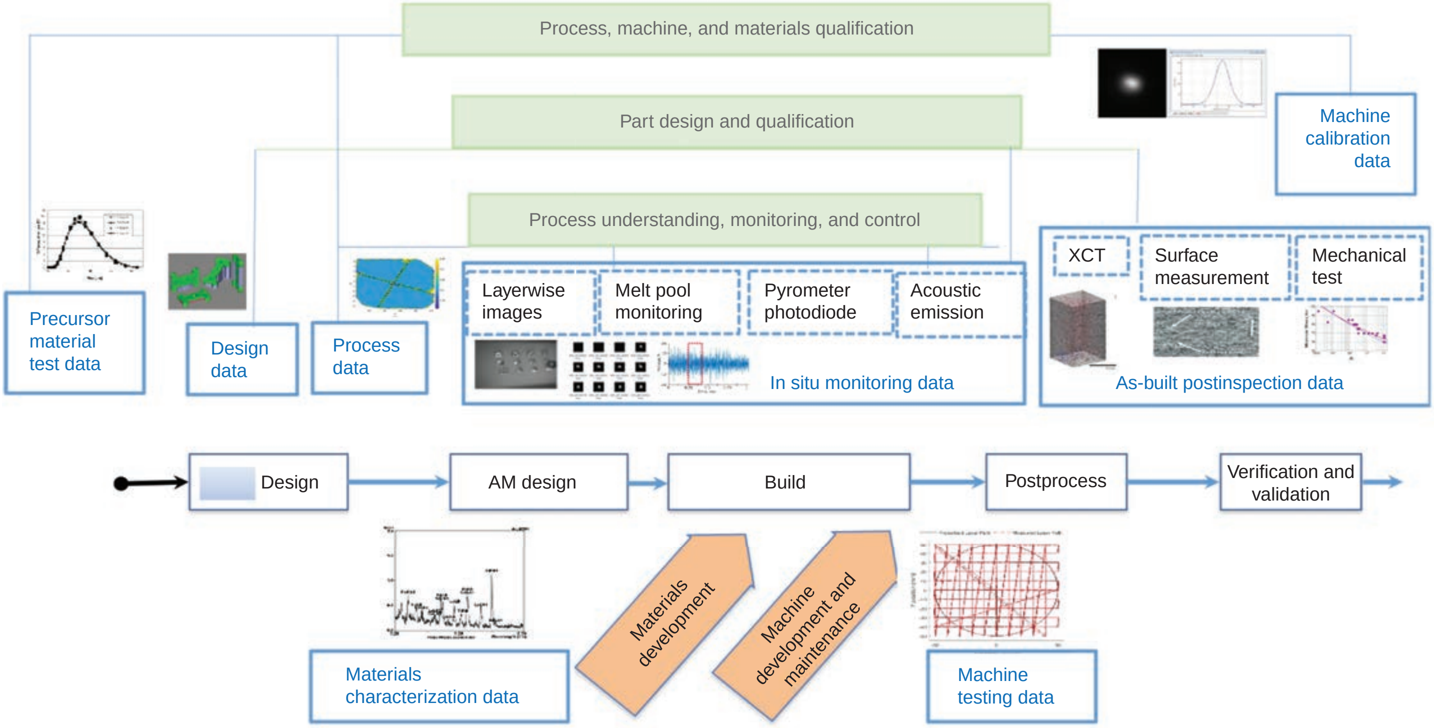

Fig. 1 Additive manufacturing (AM) data-collection landscape. XCT, x-ray computed tomography. Adapted from Ref 1

supply chain (in orange). It also shows three major use scenarios of AM data for process understanding, monitoring, and control; for part design and qualification; and for process, machine, and materials development and qualification, respectively (Ref 1). Generally, AM activities can be separated into three phases: preprocess, in-process, and postprocess. (Note: *Process* in this context is the AM process, e.g., the build activity in Fig. 1.) In the following sections, for each phase, representative data-acquisition techniques are described, including general activity type and procedure, instrument and software information, data-collection method, data format, as well as what type of metadata or pedigree information should be recorded for data analysis, and so on.

Preprocess Data Acquisition

Major preprocess AM activities include part design, materials characterization, and machine calibration. The CAD models, process plans, feedstock material acceptance and testing data, and machine calibration data are generated, collected, and analyzed before a build proceeds. Data-acquisition methods vary for individual data types and sources.

Part Design and Process Planning Data

The AM part design and process planning includes multiple steps: concept design, CAD design, AM design, process planning, and build job creation (Fig. 2). In addition, simulations help iterate the design activities and evaluate each design decision. Each step takes information as an input and generates data as an output. In addition, intermediate part design results, as well as the so-called how-to (or pedigree) information, are critical to part quality traceability and should be captured.

Concept Design

During the conceptual design stage, market needs and customer requirements are converted to part sketches and design specifications that define geometry, dimensions, and tolerances. Design specifications also identify the right type of AM process and even the specific machine model required for the fabrication. Material datasheets and machine capability data are also needed for this activity.

A concept design can be also reverse engineered from an existing part. In this case, point clouds are acquired by laser scanning hardware and software in OBJ, XYZ, PTZ, or ASC formats. These formats usually include some metadata that are directly exported from the measurement instrument. The data used and generated at the concept design stage are mainly unstructured data, such as text, images, and point cloud files. Data acquisition relies heavily on software exporting functions and manual data ingestion.

Detailed Design

Three-dimensional (3D) CAD models are the data set that contains 3D geometric elements representing the object/part to be manufactured (Ref 2). The CAD models can be generated by commercial CAD solid modeling software such as SolidWorks, NX, Creo, and AutoCAD. Three-dimensional design is typically an iterative process that involves many iterations of refinements in the shape and dimension of the initial model. It outputs an optimized model according to given objectives and boundary conditions to meet design requirements. Designers are more frequently using simulations during this process to evaluate performance improvement.

The CAD models can be exported from the CAD software in many formats. Some of the file formats are native to the specific program but include more information and features. Some file formats are neutral, enhancing interoperability among different CAD software. Design contents, design rules, and various versions of the CAD models and the pedigree information should be collected and managed. The data and metadata curation is a manual process; in the end, a design document is recommended to record the descriptions of the CAD models and the design process. The Dublin Core Metadata Initiative (Ref 3) specifies some general metadata elements applicable to CAD model description, such as model identifier, creator name, date of the creation, format of the content, and so on. The CAD software can annotate the models with these metadata.

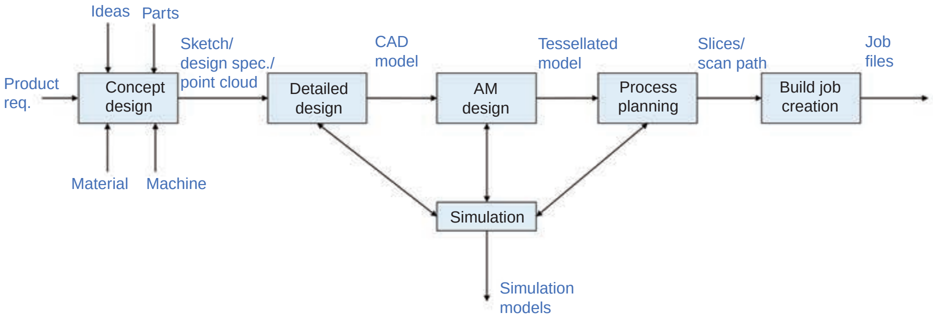

Fig. 2 Additive manufacturing (AM) part design workflow and related data. CAD, computer-aided design

Additive Manufacturing Design

As of this writing, tessellated models are used for many 3D printing processes. A tessellated model is a file that describes the external closed surfaces of the original CAD model using simple geometric shapes or complicated (and imaginative) shapes. A tessellated model forms the basis for a calculation of the slices.

Standard tessellation language (STL) is a file format for tessellated models using triangles to describe the surface shape. The STL file format is the most commonly used format for 3D printing and is supported by many CAD software packages. An STL file contains information only about a surface mesh and has no provisions for representing color, texture, material, substructure, and other properties of the fabricated target object.

Additive manufacturing file (AMF) format, an international ASTM International/International Organization for Standardization (ISO) standard format, extends the STL format to use curved triangles for better accuracy and includes additional information, such as dimensions, color, material, and other features. Regardless of STL or AMF, the tessellation step is crucial in AM data preparation, because it defines the maximum quality of the CAD model. Several parameters are used to control the tessellation. For example, the term *max sag* defines how fine the mesh is; *max angle* represents the maximum angle allowed between the norms of two adjacent polygons; and *max length* represents the maximum length of a polygon (edge). These parameters should be recorded for and attached to a tessellation model.

There are issues associated with the tessellation process that leave the surfaces of the tessellation model open. This initial tessellation model could lead to voids and cracks and should be repaired before slicing. Both the initial tessellation model and the watertight repaired tessellation model are the components of part design data. The repairing process can be documented as well.

Process Planning

The process planning phase begins with lattice and support structure generation. A lattice is an interlaced structure with metal-crossed patterns, such as a honeycomb structure or an open-cellular structure. Different lattice structures are designed for different purposes and applications. For example, a lattice structure can be used for noise cancellation, weight reduction, and so on. Additive manufacturing enables lightweight structures while maintaining strength by providing the flexibility to create complex geometries of parts that are impossible or difficult to build using traditional manufacturing methods. Using high-strength materials, AM can produce parts with designs comprised of internal cavities and lattice structures that have reduced part weight without compromising their mechanical performance. Support structures are elements needed for certain types of AM processes with downward-facing surfaces. They are made to properly support a part during the printing process to ensure a stable and successful print; without them, builds are subject to failure. There is AM-specific software developed for lattice and support generation. The surface of the STL model with lattice and support must be closed and watertight as well.

After lattice and support are generated, the watertight tessellated models can be sent to software tools for slicing and scan path generation. Additive manufacturing software vendors such as Materialise and Autodesk provide stand-alone software for the slicing and scan strategy generation, and the results are exported in proprietary file formats. Most AM machines can interpret the file formats and execute the build. Some AM machine builders also utilize their software—or use open-source tools—for slicing and scan strategy generation and exporting build job files that can be downloaded to the machines. Currently, no standardized neutral build job file format has been established yet. Thus, the build jobs created for machines from one vendor are not interoperable with machines belonging to other vendors.

Overall, there is a long list of AM design and process planning data to be collected. The pedigree information about how these models are generated should also be recorded, most likely in an unstructured format. The metadata acquisitions for AM part design are mainly manual processes, which are error prone.

Feedstock Materials Characterization Data Acquisition

Before the printing process, feedstock material must be characterized at the vendor site and the facility of the manufacturer. ASTM F3049-14, "Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes," identifies the characterization techniques that may be useful for powder-based AM. The standard also refers to more than 30 ASTM International/ISO standards for those characterization techniques, each of which describes how the test should be conducted and how results should be reported. While standard methods exist, the format and explicit metadata content for that method are usually lacking or nonexistent. Some data sets and metadata can be acquired from the instrument software directly; most test results and metadata are recorded manually. The following subsections introduce exemplar data-acquisition methods for powder particle materials characterization.

Sieve-Based Particle Size Analysis

The size distribution of a powder used in manufacturing could affect the mechanical properties of the final AM product. Sieve-based powder size analysis generates powder size distribution functions by mechanically separating a powdered metal sample using a sieve shaker and mesh sieves with known opening sizes. ASTM B214 provides a method of dry powder analysis that is precise and reproducible. The measurement process includes three manual steps: stacking sieves and loading samples, shaking for a specified amount of time, and sieved powder collections and weighing. The raw data are recorded by hand and processed for mass percentage or cumulative mass percentage. Both the raw data and the processed data can be saved in Microsoft Excel spreadsheets. The metadata about the powder sample, sieves and shaker, and test are required and can be captured in the spreadsheet as well.

Light-Scattering-Based Particle Size Analysis

This method uses a light-scattering instrument to measure the particle size distribution. ASTM F3049 specifies using the test method described in ASTM B822 to measure particle size distribution for metal powders for AM. Procedures to be followed for light-scattering-based powder size analysis are, to a great extent, specific to the instrument being used and are usually well defined by the manufacturer. The general procedure includes three steps: sample preparation, instrument preparation, and analysis and reporting (Ref 4). The results collected from light-scattering-based powder size analysis are relatively easy compared to the sieve-based results. A particle size analyzer can export particle size distributions as both cumulative and fraction distribution tables or graphs as a function of the observed particle size. However, more metadata are needed to capture complete information about the sample preparation and instrument preparation and configuration, both of which are critical for measurement-error analysis. The extensive list of the metadata is provided in Table 1.

Machine Testing, Maintenance, and Calibration Data Acquisition

The performance of AM machines is critical for the successful fabrications of complex products. The goal of AM machine testing, maintenance, and calibration (all process type-, purpose-, and vendor-specific) is to make sure that a machine or process will function as expected. ISO/ASTM 52941 specifies a minimum of the requirements for qualification testing of laser beam machines for metal powder-bed fusion (PBF) AM. However, there are no details on what type of data should be collected and reported. Based on ISO/ASTM 52930, for installation qualification, tests are conducted to provide objective evidence that all key aspects of the process equipment and ancillary system installation adhere to the manufacturer-approved specification and that supplier recommendations of the equipment are suitably considered. The standard also states that "instruments shall be calibrated periodically, and the calibration records maintained." ISO/IEC 17025 is referred to as a standard for calibration.

Maintenance is based on the original equipment manufacturer guidance to schedule system/subsystem checks. The content and format of maintenance records is usually proprietary. The data from AM machine tests, maintenance activities, and instrument calibration are typically unstructured and are usually manually collected with the help of templates from the machine vendor; the format of the documents is typically PDF.

In-Process Data Acquisition

In situ data acquisition in AM is important. Unlike the conventional machining/subtractive manufacturing process, there are very limited autorecovery mechanisms in the AM process. Most defects in the build process will be buried inside the final parts forever. Therefore, in situ data acquisition is needed to capture all the process abnormalities and predict the build qualities. However, the AM process is dynamic by nature. It involves a fast heating/cooling rate and usually a fast-moving heating source, such as laser or electronic beam in the PBF system; this imposes several challenges to the in situ data-acquisition process. This section investigates the requirements and methods commonly used for in situ data-acquisition in AM. Laser powder-bed fusion (L-PBF) is the system used in the example; however, it can be applied to other AM processes as well.

In Situ Data Types

The data in the L-PBF process can be categorized into two types: process parameters and process variables. The process parameters are the inputs to the AM process, such as laser power/speed/position, laminar gas flow speed, build plate temperature, powder layer thickness, and so on. For an ideal system, the process parameters should be identical to their commanded value. Process variables are the measurable outputs from the AM process, such as the intensities of the electromagnetic wave (light) or mechanical wave (sound) emissions, temperature changes, surface roughness (R_a) before and after the build/powder spreading, and so on. These are the measurements of the physical quantities generated from the AM process. Process variables are often measured using third-party instruments, often with their own data formats and metadata.

Table 1 Metadata elements for light-scattering-based particle size analysis data set

Metadata element category	Metadata element name
General descriptive	Data set identification (ID)
	Data set uniform resource identifier
	Test, inspection, or characterization (TIC) ID
	TIC name
	TIC type
	TIC standard
	TIC procedure
	TIC start time and date
	TIC end time and date
	TIC location
	TIC notes/comments/description
	TIC operator
	TIC point of contact
	TIC vendor/supplier/contractor
	TIC equipment
	Date of last calibration
	Date and time of last alignment
	Equipment temperature
	TIC software
	TIC destructive vs. nondestructive
	TIC temperature
	TIC temperature control method
	TIC location of temperature measurement
	TIC humidity
Activity-type specific descriptive	Instrument analysis run time
	Number of measurement
	Replicate number
	Particle size distribution principle of measurement
	Particle size distribution parameter basis
	Optical obscuration
	Type of light-scattering model applied
	Threshold for acquisition of valid data (if applied)
	Range selected
	Optical arrangement
Sample descriptive	Specimen ID
	Specimen origin ID
	Specimen type
	Specimen mass
	Specimen description
	Specimen sampling/extraction/fabrication method
	Specimen deviations from recommended specimen configuration or preparation
	Real refractive index of the sample material (where applicable)
	Imaginary refractive index of the sample material (where applicable)
	Dry sample description
	Dispersion gas ID
	Dry dosing/feeding device
	Dry dispersion dosing rate (where applicable)
	Dry dispersion pressure
	Wet sample description
	Dispersion liquid ID
	Dispersion liquid volume
	Real refractive index of the dispersing liquid
	Dispersion liquid temperature
	Dispersion liquid pump speed
	Dispersion liquid stirring speed
	Liquid dispersant ID(s)
	Liquid dispersant(s) concentrations
	Sonication equipment
	Wet dispersion sonication frequency (energy)
	Wet dispersion sonication duration
	Wet dispersion sonication pauses before starting measurement
	Wet dispersion optical path length (where applicable)
Data set content	Particle size distribution density function
	Particle size cumulative distribution
	Particle size distribution percentiles
	Particle size distribution mean diameter
	Particle size distribution mode diameter
	Particle size distribution standard deviation
	Particle size distribution range
	TIC pass/fail
Data set administrative	Data right
	Data license
	Distribution list

Process Parameters

The process parameters measurement is crucial, because it ensures the system is performing within the acceptable tolerance and detects faulty equipment early. This can include both static and dynamic performance. For example, Fig. 3 shows a sample laser scan path from a faulty galvo. The laser beam is positioned on the build plane by a pair of mirrors driven by x- and y-galvo motors. In Fig. 3, the x-galvo failed and was detected by the in situ measurement of the galvo positions. Figure 4 shows the results from a galvo frequency-response test. A scan command described by the equation $X = A\sin(w(t) \cdot t)$ is fed into the galvo, where A is amplitude, and t is time. As t increases, the galvo is driven faster. The difference between the commanded and measured positions is the position following error.

Some process variables, such as coaxial melt pool images, will only be meaningful if they are synchronized/registered to the laser position. Such synchronization requires that the process variables and process parameters are recorded simultaneously. This is important if the scan (position) command is not accessible, so the camera can only be synchronized with the measured galvo position. Figure 5 shows an example where the coaxial melt pool images are registered with the laser position/speed, so their behavior can be explained. (The way the coaxial melt pool images are taken is described in the next section.)

Typical process parameters can be in situ measured on an L-PBF system, including:

- *Galvo positions:* These are usually measured by the galvo encoder signals, because the laser is positioned to the build plane by a pair of mirrors driven by galvo motors. Laser position/speed can be derived from the galvo position.
- *Laser power:* Most commercial laser power units provide an analog output proportional to the laser power. Laser power can also be measured using a dichroic mirror to direct a small portion of laser power to a photodiode.
- *Laser spot size:* On systems equipped with active focus control, the position of the laser focal lens can be changed by a linear motor. The laser spot size can be measured indirectly by the position of the linear motor.
- *Gas flow rate:* A laminar flow of inert gas is usually created on top of the build plane to remove spatter and plume. The gas flow rate can be controlled/measured by a flow meter.
- *Build plate temperature:* On systems equipped with heated build plates, the temperature can be controlled/measured by the heating module and thermocouple.

Process Variables

Process variables are the measurements from the physical AM process. A typical process variable can be the melt pool area or the powder temperature. They can be affected by numerous input process parameters. Sometimes the process variables and process parameters can overlap. For example, for a system equipped with a powder temperature control device, the powder temperature could result from the heating effect from the melt pool/laser beam or the temperature control device. In such a case, the preset powder temperature should still be a process parameter, and the measured temperature

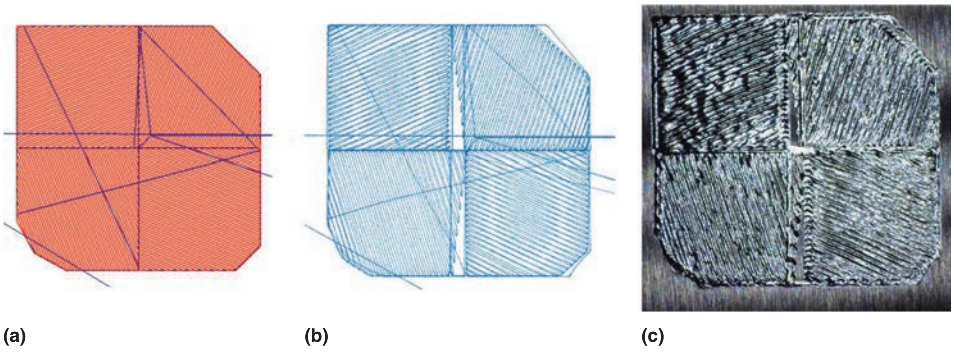

Fig. 3 Galvo motor failure example. (a) Commanded scan path. (b) In situ measured scan path. (c) Scan tracks image

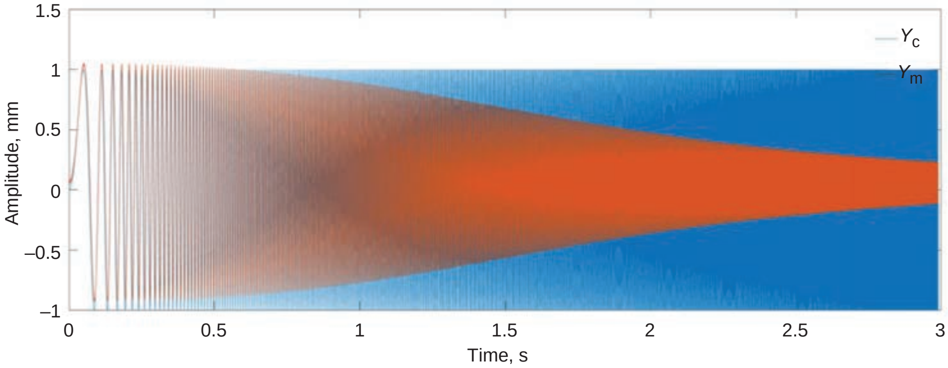

Fig. 4 Frequency response of a galvo motor. Blue (Y_c) is the commanded galvo position; it is a sine wave with increasing frequency. Orange (Y_m) is the measured position. As the frequency increases, the measured position quickly falls behind the commanded position. Adapted from Ref 5

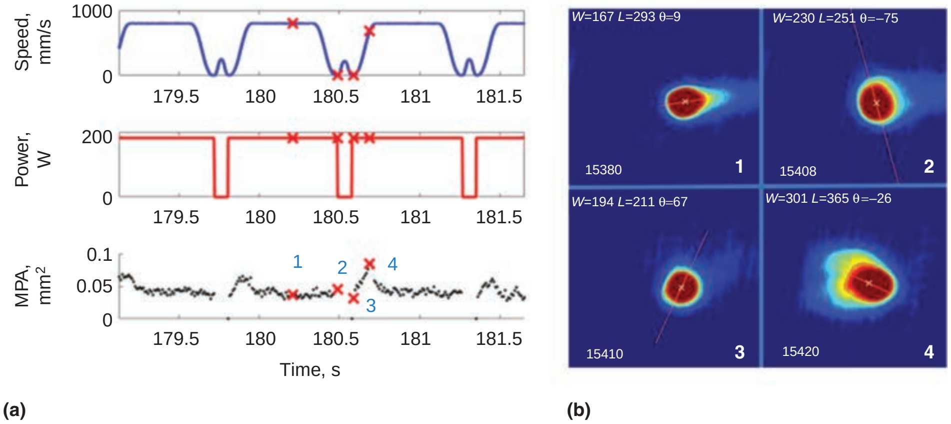

Fig. 5 (a) Melt pool area (MPA) extracted from melt pool images plotted together with laser speed and power. (b) Melt pool images (pseudo color) at locations marked by "x's" in (a). Image 1 is at a steady state, 2 is at the end, and 3 and 4 are at the beginning of a scan. Adapted from Ref 6.

should be the process variable. Some common measurements of AM process variables include:

- *Measurement from coaxial melt pool image:* Melt pool image is unarguably the most important process signature of the AM process. Figure 6 shows how the coaxial melt pool image is captured, where the camera field of view (FOV) moves with the heating laser. The melt pool monitoring camera can be near-infrared or infrared. Process variables that can be extracted from the coaxial images include but are not limited to melt pool area, width, length, cooling rate, contrast, and so on.
- *Measurement from staring image:* Opposite to the coaxial image, the staring image has a fixed/stationary FOV and usually covers a large build area. Multiple staring cameras can be installed at different view angles, and the image can be taken with strobe lighting as well.
- *Acoustic signal:* The mechanical wave emitted during the AM process can be detected by an acoustic sensor.
- *Photodiode signal:* The photodiode can be installed coaxially or inside the build chamber to measure the melt pool emittance. The advantage of a photodiode over a camera is its high speed and low cost, but it can only measure the average intensity of its FOV.
- *Surface roughness measurement:* The surface roughness before and after powder spreading can be measured with a laser profiler or stereo vision system.
- *Other environmental variables:* This includes such variables as build chamber temperature, pressure, oxygen level, and so on.

Acquisition Methods

There are two types of acquisition methods: synchronized and unsynchronized. For an L-PBF additive manufacturing process, the synchronization is usually with the laser scan position. Figure 6 provides an example of synchronized coaxial melt pool imaging. The images are taken by a high-speed camera optically aligned with the heating laser. Therefore, the camera FOV moves with the laser scan position. There are two ways to synchronize the image to the position:

- The camera can be triggered by the laser position. This can be the measured position, as shown by the dotted line in Fig. 6, or by the commanded position if an interface is provided. This is referred to as active synchronization.
- The laser position can be recorded/marked when an image is taken. This can be done either by triggering the data acquisition whenever an image is taken (as shown by the blue dotted line in Fig. 6) or by putting a time stamp on both signals that need to be synchronized based on a common clock. In the unsynchronized case, the camera is running independently, and the scan position is either unknown or cannot be mapped with certainty. Synchronized data acquisition provides more information but usually is also more difficult to implement. For some process variables, such as staring images, there is no need for synchronization.

One advantage of active synchronization is that the region (points) of interest (ROI) can be defined, which can significantly improve the data-acquisition efficiency, such as creating a so-called smart data-acquisition strategy. The state-of-the-art digital cameras of today (2023) can easily take 100,000 images per second, with 8-bit image depth and 120 by 120 pixels image size. However (as of this

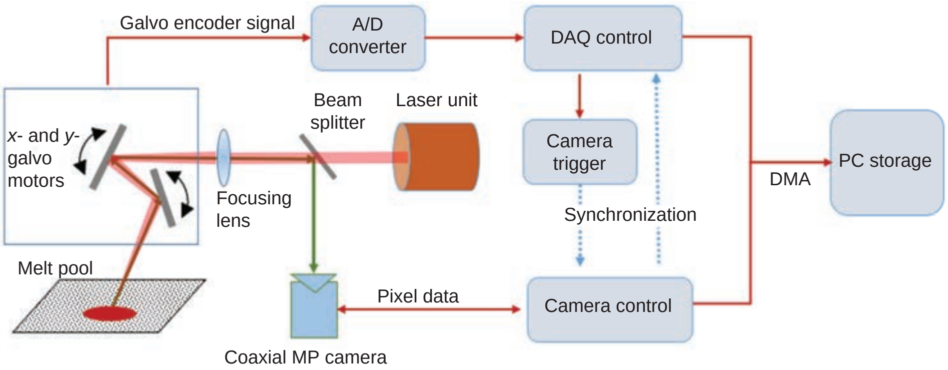

Fig. 6 Schematic of synchronized coaxial melt pool (MP) imaging. A/D, analog/digital; DAQ, data acquisition; DMA, direct memory access; PC, personal computer

writing), no current camera communication protocol standards can stream image data at this rate. The compromises include lowering the imaging rate to match the streaming speed and storing the images temporally on the onboard memory of the camera and streaming later. Because some cameras support imaging and streaming at the same time, a carefully planned imaging strategy can use the onboard memory as a buffer and trigger the camera at a higher rate, but only when laser power is on and in the ROI.

Field-programmable gate array (FPGA) is usually used for high-speed data acquisition and processing. An image stream rate of 20,000 frames per second was demonstrated at the National Institute of Standards and Technology (Ref 7, 8), with dual-camera links and frame grabber implemented by FPGA. The images are 8-bit grayscale and 120 by 120 pixels. The melt pool areas are also computed in the FPGA in real-time and made available to the real-time feedback control algorithm. Cameras with onboard FPGA are also commercially available, which can be programmed for real-time image compressing and analysis.

Analog sensors, such as thermocouples, photodiodes, analog position encoders, and so on, generate analog voltages. They must be converted into digital signals first before they can be stored, which is done by an analog-to-digital converter (ADC). The sampling rate of the ADC decides the temporal resolution of these data. For example, the laser position in Fig. 6 is sampled at 100 kHz.

Often the bottleneck of in situ data acquisition is not the speed of the sensor but the data-transmission bandwidth and the storage. Most data will eventually be stored on a Windows personal computer. A direct memory access approach should be used to avoid delay.

Usages of In Situ Data

The data acquired from the in situ monitoring process can be used to study and optimize the process and to predict the part qualities. Some typical applications include but are not limited to:

- *Physical/statistical model validation:* The data are used to understand the process and to establish links (models) between the process parameter and process variables (input and output of the physical process). In such an application, an in situ data process is not required, but input and output data correlation is important.
- *Part certification:* The in situ data can be used to predict the possible defects in the final part. This can be assisted with machine learning, where a model can be trained first with the labeled in situ data. The in situ data can also be processed. The labeling is based on postmeasurement results, such as x-ray computed tomography (XCT) or surface profiler. The postmeasurement data must be registered with the in situ data first, which can be challenging.
- *Real-time feedback control:* In situ data can be used to adjust the process commands in real-time to achieve a control objective, such as maintaining a constant melt pool area. Different from the previous two types of applications, data synchronization/registration may not be required. Still, the data must be made available to the process control loop as soon as possible.

The in-situ-acquired process parameters can also be used to calibrate the dynamic performance of the system and improve the system design (Ref 9, 10).

Postprocess Data Acquisition

Postprocess AM activities involve a lot of measurements for part inspection and qualification. The data-acquisition methods for XCT-based nondestructive inspection and part surface assessment are illustrated in this section. Other types of postinspection data-acquisition and metadata definitions can be obtained similarly based on the relevant testing standards.

X-Ray Computed Tomography

X-ray computed tomography is a nondestructive, postprocess inspection technique for the detection of internal flaws (e.g., pores and cracks) and dimensional measurements. Details on the background and XCT scan-acquisition processes are discussed in Ref 11 to 13; this section focuses on the aspects of data curation. For an XCT scan, multiple radiographs of the object are acquired following the scan trajectory (e.g., circular scan and helical scan). These two-dimensional (2D) radiographs are combined through a reconstruction algorithm, for example, filtered backprojection or iterative methods (Ref 14) to generate 3D volumetric image data. The reconstructed image intensities are related to material x-ray attenuation coefficients (Ref 15), and the reconstructed values may be rescaled and saved in floating-point values, for example, 32-bit single precision $(\pm 3.4 \cdot 10^{38})$, 16-bit (0 to 65535), or 8-bit (0 to 255). (The numbers in parentheses represent the image-intensity ranges.)

The reconstructed images can be exported in a 3D image format or as a stack of 2D cross-sectional images. Cross-sectional images can be extracted from the 3D data along any of the three orthogonal axes (x, y, and z) as well as any arbitrary orientation after an image-transformation process is implemented. It is recommended to export the data using a file format with lossless compression. Metadata are generally recorded on separate files that describe the XCT acquisition and reconstruction settings, for example, voxel pitch, magnification (geometric and optical), exposure time (or frame rate), number of projections, and reconstruction algorithm (type and parameters), as well as any correction processes implemented (e.g., bad pixel correction and flat-field correction). The exported XCT data can be imported to XCT data analysis software or custom-developed codes for part surface determination and flaw-detection analysis. Registration and alignment with other data sets (e.g., in situ monitoring results or other postprocess measurements) can be carried out in this step.

The determined part surfaces are used for dimensional measurements by fitting geometric primitives and comparing them with the original CAD file. The determined part surfaces can be exported as a surface mesh file. Binary masks of pores can be found using pore-detection algorithms based on a labeling process (Ref 16). Various properties of the pores (e.g., volume, equivalent spherical diameter, location, and orientation) can be found and exported to a table (Ref 17–20). The pore size and shape analyses provide important information for the investigation of AM processes (Ref 21–23). The binary images and labeled images can be exported and fed to digital twins, and computational modeling such as finite-element simulation can be carried out to understand the effect of flaws (Ref 24–26).

Surface Measurement Data Acquisition

Surface measurements are used to identify the topography (i.e., height variations) on the surface of a part. Traditionally, these measurements have been used to develop correlations to the fabrication process or part performance (Ref 27). The instruments for capturing these data are well described in the American Society of Mechanical Engineers (ASME) and ISO standards (Ref 28–32). Data are captured by optical (e.g., noncontacting) or tactile (e.g., contacting) equipment. In some cases, surface measurement instruments can achieve spatial and height resolutions in the submicrometer range (Ref 1). Surface metrology best-practice documents are available and are useful in understanding the basic principles used by the community (Ref 33–35). However, there are currently no best-practice documents specifically for measuring AM surfaces, although Chapter B-5 of ASME B46.1 (Ref 28) discusses the challenges of measuring AM surfaces. Additionally, as of January 2022, ASTM International had work item WK66682 in subcommittee balloting.

Surface metrology instruments usually capture data in the form of a one-dimensional array of heights (e.g., [*x*,*z*] datapoints) for so-called profile data or a 2D array of heights (e.g., [*x*, *y*, *z*] datapoints) for so-called areal data, with uniform spacing in the *x*- or *x*- and *y*-directions. Often, areal measurements are referred to as two-and-a-half dimensional (2.5D) data because no two height values can occupy the same *x*- and *y*-position. In other words, overhangs and undercuts are not representable in traditional surface measurement data. This poses a challenge when acquiring surface data from XCT, as previously mentioned. With XCT data, the full three dimensions of the part can be seen. Thus, transformation to 2.5D or a different treatment of the data is required.

Measurements are performed in a range of environments, from handheld stylus equipment used in the field to high-precision equipment in labs with highly controlled environments. Depending on the equipment used, measurements are performed manually or automated in a batch. Rarely are measurements performed online or remotely due to the risk of damage to the equipment or surface being measured. These measurements are almost always captured by the equipment, although the transfer to a computer for permanent recording and analysis may require manual intervention in some cases.

Proprietary and nonproprietary formats (e.g., .X3P, .SDF, .XYZ) are used to capture data from the measurements. Each of these formats has its metadata and header information, some of which are directly exported from the measurement instrument. Once data are captured, postprocessing of the data is almost always performed. This typically includes leveling; form removal; filtration of the spatial wavelengths contained in the data; separation of the data into form, waviness, and roughness; and calculation of parameters (Ref 28, 36–38). In some cases, outlier removal and data-fill operations are also performed.

Dozens to hundreds of profiles and areal parameters exist (Ref 28, 36, 39, 40). These parameters can take the form of a single number or graphs (e.g., material ratio curves, amplitude-wavelength analysis, etc.) that are meant to summarize the height distributions in a meaningful way. Additionally, there are methods for segmenting surfaces (e.g., Wolf pruning) and analysis techniques (e.g., fractal methods) available in ISO standards (Ref 38), as well as techniques being developed in research.

Regardless of the situation and techniques, the methods for capturing and processing the data are always relevant to the measurement and reporting of surface data. Different instruments have different metrological characteristics (Ref 41) and limitations in the bandwidths they can capture (Ref 42), which can create discrepancies between measurements of the same surfaces in two different instruments. Additionally, methods used to postprocess data can have significant effects on the calculated parameters. These must all be considered when investigating surface measurement data.

The extent of information that should be recorded depends on the uncertainty calculations required (Ref 33, 43). At the minimum, however, the list of information that should always be reported includes but is not limited to equipment manufacturer, equipment model, specifics of the equipment setup (e.g., objective used, magnification lenses, type of stylus used, etc.), specifics of the measurement (e.g., FOV size, point spacing, number of stitched measurements, location of measurement, evaluation length, sampling length, etc.,), and any operations performed on the data (e.g., leveling, outlier removal, form removal, filters applied, equations for calculating parameters, etc.). These settings are often assumed, because the equipment is described as conforming to ASME and/or ISO standards. However, this does not mean that every measurement performed with the equipment follows the standard. Thus, it is the duty of the user to understand these standards and to ensure the proper handling of the data and equipment and the reporting of the settings and results.

Data Set Metadata

Based on the data-acquisition method description, metadata can be identified to describe the AM activities and the resulting data set. The metadata elements can be grouped into several categories: general descriptive metadata, measurement/activity-specific descriptive, sample descriptive (optional for design data set structural information), and administrative information. Table 1 shows an example of metadata for light-scattering-based particle size measurement (selected from ASTM International WK75158). In this case, TIC represents test, inspection, or characterization. For design data, the prefix of TIC in the metadata element names can be replaced with design.

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