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REVIEW ARTICLE

A comprehensive review: metrology in additive manufacturing and 3D printing technology

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Abstract

Additive manufacturing (AM) is making a big leap in the manufacturing technology world primarily due to its unique capability to produce parts in a layer-by-layer fashion from the digital 3D model with immense versatility in terms of design complexity. In addition, AM does not require any additional tooling and can produce parts with minimal to no material loss. Despite these technological advantages, AM is not making inroads to its potential, mainly due to a lack of fundamental understanding of all the AM processes and cohesive efforts in standardization, metrology (the science of measurement), qualification and certification. As a result, AM produces parts with higher complexity and features yet lacking dimensional accuracy, precision, the required level of tolerances and intended material properties. Particularly, the process-specific standardized metrology and inspection methods for the parts made by AM play a major role in imparting the desired quality and subsequently facilitate the process of certification of the AM part. Considering this, the present article provides (1) a comprehensive review of generic metrology and in-situ, real-time inspection methods that are currently utilized for the parts produced from conventional manufacturing processes in use, as well as (2) a comprehensive review of metrology and in-situ, real-time inspection methods currently and/or may be utilized for the parts produced from AM processes. In addition to these, the appropriate metrology and inspection methods are recommended here for various AM processes. NSWC Corona, the leading agency for the U.S. Navy's Metrology and Calibration (METCAL) program, is playing an important role towards addressing these AM metrology challenges.

Keywords Additive manufacturing · 3D printing · Metrology · Inspection methods · Standardization · Qualification

1 Introduction: additive manufacturing

Additive manufacturing (AM) has been developing rapidly in recent years and is perceived as an emerging industrial revolution [1]. Various sectors have made a substantial investment in the AM industry, with automotive and aerospace companies, and military sector showing special interests [2]. AM technologies demonstrate huge promise and may revolutionize design, manufacturing, logistics, maintenance and acquisition in the U.S. Department of Defense (DoD)/U.S. Navy. AM products and services grew by \$1 billion to a total of \$5.1 billion in 2015 [3] to over \$7 billion in 2018 [4], but market penetration was still only 8%. This is suggestive of the immense potential for growth in the AM sector.

AM is known by many names including additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, three-dimensional (3D) printing and freeform fabrication. All AM processes digitally slice 3D models into cross sections, then use those sections to guide layer-upon-layer ("additive") fabrication of parts [5–16]. This unique approach can manufacture complex parts that are difficult or impossible to produce through conventional "subtractive" manufacturing. Other benefits of AM include reduced material wastage, reduced

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energy consumption and rapid-prototyping capabilities. The design possibilities enabled by AM are remarkable [2]. AM machines can potentially make replacement parts on board the Navy ship or at any port, which allows for design improvements on the fly. This will help eliminate problems associated with obsolescence, allow the Navy Fleet to store fewer parts in inventory and shorten repair times. These useful features of AM will certainly enhance the U.S. Navy's readiness and allow for quick capability upgrades.

The Joint International Organization for Standardization (ISO) and American Society for Testing and Materials (ASTM) International ISO/TC 261—ASTM F42 committee has classified AM processes into seven distinct categories: material extrusion, powder bed fusion, vat photopolymerization, material jetting, binder jetting, sheet lamination and directed energy deposition [17, 18]. Table 1 describes the various categories of AM in more detail.

Even with the wide-spread popularity of AM, the extensive implementation of AM is currently being inhibited by a lack of universal guidelines for metrology, inspection and standardization [19]. Impressive capabilities of AM would remain intangible until the finished parts could be certified as satisfactory and acceptable [20, 21]. This is one of the the primary hurdles to overcome before AM becomes an effective component in the industrial and military toolset. Several roadmap studies have emphasized part-specific metrology and the role of geometric dimensioning and tolerancing (GD&T), but few standards exist specifically for AM [10, 22–30]. Because of this, AM machines can be temperamental, and parts sometimes fail to meet the requirements for mechanical properties, surface roughness or dimensional tolerances [6]. For AM to produce parts with predictable properties and accurate dimensions, new measurement techniques must be developed to complement existing methods [31, 32]. In this regard, metrology will be a critical tool for the characterization and optimization of AM capabilities [2]. The current literature on AM clearly calls for the need of metrology for various AM technologies, but very limited solutions and guidance are currently available [20–30, 33–39]. The Fig. 1a illustrates the process flow steps of additive manufacturing starting from a new idea/concept or from redesigning the existing part (reverse engineering), all the way to obtaining a 3D printed part/model. Fig. 1b shows the evolution of common AM defects inherent to the AM process. The metrology for additive manufacturing is, therefore, very important in first identifying and then applying mitigation strategies to obtain dimensionally accurate parts that have the required surface finish and materials properties.

Hence, efforts were made in this review paper to provide the past, present, and future of metrology of AM and 3D printing technologies. This review paper gives an overview of measurement and inspection methods available for AM technologies. Section 2 covers general inspection methods for mechanical features, surface roughness and dimensional measurements. Section 3 proposes new inspection methods for AM and discusses how general methods could be applied with little to no modification. The final section includes a strategic plan for qualifying and standardizing AM through inspection and measurement. This section also briefly describes the vital role that NSWC Corona, the leading agency for the U.S. Navy's Metrology and Calibration (METCAL) program, is playing towards addressing these AM metrology challenges.

2 Background—metrology: measurement and inspection methods

Metrology is much more familiar than one might think; almost everyone unknowingly practices it in everyday life [40, 41]. It includes any determination that is quantified with numbers and expressed in units. Metrology also involves establishing units, developing measurement protocols, producing artifacts that act as measurement standards to allow traceability of measurements, and analysis of measurement uncertainties and accuracies [41]. This contrasts with inspection, which uses standards to evaluate the fitness of parts without measuring physical dimensions. Inspection is widely used with mass production because making quantitative measurements is often more time consuming and expensive.

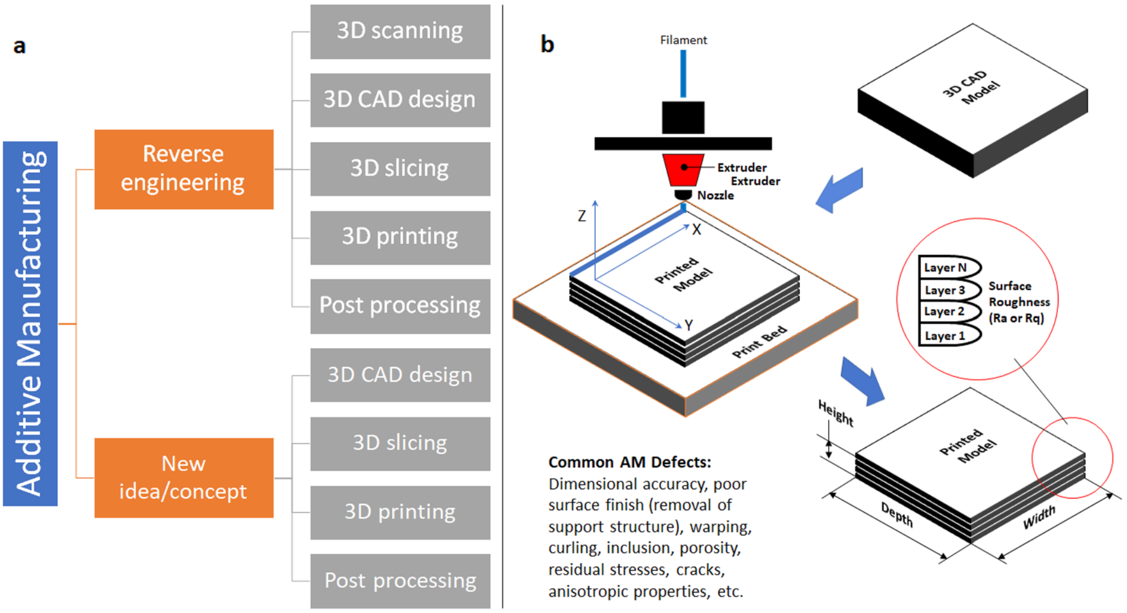
Metrology and inspection are vital and inexpensive means for enhancing the quality of AM. Some of their applications are (1) confirming whether the parts are within the required tolerances, (2) characterizing different AM processes and, (3) establishing standard methods that help minimize inspection costs and maximize measurement accuracy. For AM capabilities to continue growing, testing will need to incorporate both emerging and existing techniques [31].

Standardized units allow values recorded anywhere to be compared on the same scale. Measurements are also the only way to collect ample data about a process and its results to develop process control systems. Types of measurement include direct (comparing to a primary or secondary standard; e.g., a tape measure), indirect (direct measurements are used to calculate an end result; e.g., a calculating area), fundamental (absolute method), comparative (comparing to a known value of the same quantity) and substitution (direct comparison methods of known value with same quantity) [41]. There are other ways to classify measurement and inspection methods based on the nature of the method and/or practice such as destructive/non-destructive, contact/contactless, real-time/off-time, and in-situ/ex-situ.

All these methods have certain specific advantages and disadvantages; therefore, thorough investigation is required before adopting these methods for AM. However, the

Table 1 Classification of AM processes, reproduced from [17]

Categories	Technologies	Materials	Power source	Merits/demerits
Material extrusion	Fused deposition modeling (FDM) Contour crafting (CC) Atomic diffusion additive manufacturing (ADAM) or Bound metal deposition (BMD)	Thermoplastics, ceramic slurries, metal pastes Bound metal filaments with metal powder held together by a wax and polymer binder. Materials: 17-3 PH stainless steel, D2, A2, and H13 tool steels, Inconel 625, Titanium Ti-6Al-4V, 316L Stainless Steel, and Copper	Thermal energy	*Merits*: Inexpensive extrusion machine Multi-material printing *Demerits*: Limited part resolution Poor surface finish
Powder bed fusion	Selective laser sintering (SLS) Direct metal laser sintering (DMLS) Selective laser melting (SLM) Electron beam melting (EBM)	Polyamides/polymer Atomized metal powder (17-4 PH stainless steel, cobalt chromium, titanium Ti-6Al-4V), ceramic powder	High-power laser beam Electron beam	*Merits*: High accuracy and details Fully dense parts High specific strength and stiffness *Demerits*: Powder handling and recycling Support and anchor structure
Vat photo-polymerization	Stereo-lithography (SLA)	Photopolymer, ceramics (alumina, zirconia, PZT)	Ultraviolet laser	*Merits*: High building speed Good part resolution *Demerits*: Over-curing, scanned line shape High costs for supplies and materials
Material jetting	Polyjet/inkjet printing	Photopolymer, wax	Thermal energy/photo-curing	*Merits*: Multi-material printing High surface finish *Demerits*: Low-strength material
Binder jetting	Indirect inkjet printing (Binder 3DP)	Polymer powder (plaster, resin), ceramic powder, metal powder	Thermal energy	*Merits*: Full-color objects printing *Demerits*: Require infiltration during post-processing Wide material selection High porosities on finished parts
Sheet lamination	Laminated object manufacturing (LOM)	Plastic film, metallic sheet, ceramic tape	Laser beam	*Merits*: High surface finish *Demerits*: Low material, machine, process cost Decubing issues
Directed energy deposition	Laser engineered net shaping (LENS) Electron beam welding (EBW)	Molten metal powder	Laser beam	*Merits*: Repair of damaged/ worn parts Functionally graded material printing *Demerits*: Require post-processing machine



Common AM Defects:
Dimensional accuracy, poor surface finish (removal of support structure), warping, curling, inclusion, porosity, residual stresses, cracks, anisotropic properties, etc.

Figure 1 Process flow of additive manufacturing showing the importance of metrology: **a** common AM steps and **b** evolution of common AM defects

non-destructive, contactless, real-time, in-situ measurements along with accurate and less-time and cost-consuming methods that are consistent and facilitate process control are more favorable for AM. The following sections discuss various state-of-the-art metrology and inspection methods.

2.1 Dimensional metrology

Dimensional metrology is concerned with geometric features, particularly in the measurement of size, distance, angle, form or coordinates. Dimensional metrology is especially critical in monitoring and controlling manufacturing processes where contacts between mechanical components create drifts in geometry. Physical measurement capabilities can vary from a scale or ruler to sophisticated optical measurement and interferometry instruments [42].

2.1.1 Linear measurement

Linear measurement is carried out with various measuring instruments that are designed to cater to industrial needs. Most linear measurement instruments are a higher-order version of a simple ruler/scale. They are either non-precision or precision and graduated or non-graduated based on the measurement requirements. However, they are selected or utilized based on the objective of accuracy, the precision of measurements, quickness, ease of use, and reduced wear and tear. Some of the common linear measurement instruments are listed in Table 2. Among these, calipers, Vernier and micrometer instruments are a few very popular linear measurement instruments.

Table 2 Common categories of linear measurement instruments [40]

Common instruments	Vernier instruments	Micrometer instruments
Scale/ruler	Vernier caliper	Outside micrometer
Combination set	Dial caliper	Digital micrometer
Square, protractor, center head	Digital caliper	Inside micrometer caliper
Calipers, floating carriage height and depth gauge	Vernier depth gauge	Inside micrometer
Slip gauges	Vernier height gauge	Depth micrometer
Snap gauge		
Frequency-modulated continuous wave ranging (laser-based method)		

2.1.2 Angular measurement

Angular measurements are specifically needed not only to measure angles, but also to measure flatness, straightness and parallelism for alignment purposes.

Table 3 shows some of the common angular measurement instruments. Among these, a few popular ones are the protractor, Vernier and micrometer instruments.

2.1.3 Comparators

Rather than absolute measurement, comparators work on the relative measurement principles, where the only difference is that the dimensions are evaluated and compared with the known dimensions or standards. They are categorized into four broad categories: mechanical, mechanical-optical, electrical and pneumatic (Table 4). As the name implies, their primary working mechanism is driven by mechanical, optical, electrical, or pneumatic principles. They are described below.

2.2 Surface metrology

Surface variations can be measured using linear or angular measurement and inspection instruments. Surface metrology measures the variation within the surface or the variation between two points on the same surface. Surface characteristics (surface finish, topography, or roughness) are of the utmost importance (sometimes even more than the dimensions) in the manufacturing field. This is because when the parts are assembled together, properties of their mating surfaces has significant impact towards the successful manufacturing of the whole system, in terms of friction, stress, corrosion, aesthetic appearance, reliability, etc. A close look at any surface always reveals some surface irregularities such as waviness and roughness that generally have a distinct relationship with the manufacturing process [40].

Table 3 Common categories of angular measurement instruments [40]

Common instruments	Optical instruments
Protractor	Optical clinometer
Combination set	Autocollimator
Sine bars	Angle dekkor
Sine center	
Angle gauges	
Spirit level	
Laser level	
Clinometer	
Tilt sensor	
Tilt meter	
Theodolite	
Gyroscope	

2.2.1 Surface roughness measurement methods

The common terminologies associated with surface irregularities are roughness, waviness, lay, flaws, surface texture and error of form. It is necessary to carry out some specific analyses to measure these surface irregularities and assign a numerical value to them. Some of the popular representations of surface roughness are 10-point height average (R_z), centerline average (R_a) and root mean square (R_q) value. Table 5 lists some of the common surface roughness measurement techniques (direct or comparison measurement) and the following section describes a few of these methods briefly.

2.3 Coordinate metrology

Coordinate metrology is the most advanced method to measure three-dimensional (3D) coordinate information at its highest level [43]. For 3D measurements, the information about coordinates of the location or position is essential. The current ability to manufacture parts with the highest precision (micro- to nano-level) is only possible due to the coordinate metrology instruments. Advancements in the field of electronics, mechanics, mechatronics,

Table 5 Common surface metrology methods [40]

Contact (tactile)	Contactless (optical)
Stylus and datum	Optical profilometer
Stylus probe	Interferometry
Tomlinson surface meter	Confocal microscope
Taylor-Hobson Talysurf	Focus variation
Stylus profilometer	Structure light scanning
Atomic force microscope (AFM)	Electrical capacitance
	Electron microscopy
	Photogrammetry

Table 4 Classification of comparators [40]

Mechanical	Opto-mechanical	Electrical	Pneumatic
Dial indicator	Zeiss ultra-optimeter	Linear variable differential transformer (LVDT)	Free flow air gauge
Johansson mikrokator	Optical projector	Electronic comparator	Back pressure gauge
Sigma comparator			Solex gauge
Plug gauge, ring gauge			

Table 6 Basis of coordinate measurement techniques [43]

Contact	Redundant	Contactless
Coordinate measuring machines Contact operating in 3D system Optical operating in 2D system Multisensor 2D/3D	Coordinate redundant machines (1) Articulated-arm coordinate measuring machines (AACMMs) (2) Laser tracker systems (LTSs)	(1) Systems using structured light (2) Photogrammetric systems (3) Systems performing laser triangulation (4) Systems based on the measurement of beam returning time (time of flight [TOF]) (5) Computed tomography (CT) systems (6) Magnetic resonance imaging (MRI) systems (7) Machine vision systems

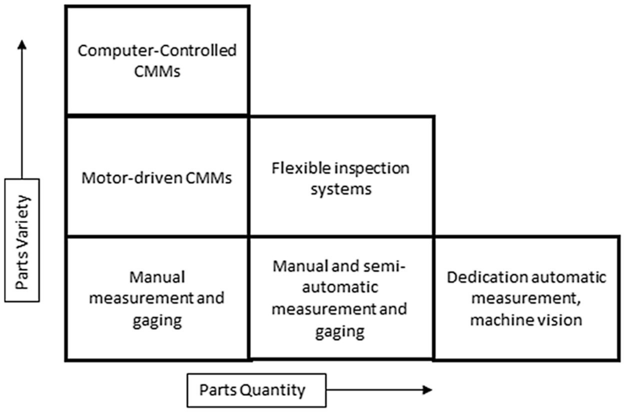


Figure 2 PQ chart indicating most appropriate measurement equipment as a function of parts variety (P) vs. part quality (Q), reproduced from Ref. [44]

optics and computer science have directly contributed to the development of coordinate metrology systems that uses dimensional, optical and imaging metrology based on modern contact or contactless systems and modern multi-sensor systems. The common basis of the various coordinate measurement systems are enumerated in Table 6. These kinds of measurement not only provide 3D (dimensional and surface) data, but also provide GD&T data, and enable quick and precise detection of external (surface finish, etc.) and internal (porosity, etc.) defects in the 3D domain.

In general, the coordinate metrology provides high precision and accuracy in measurements, but the systems are more expensive and measurements are time-consuming. However, the correct selection of conventional methods versus coordinate metrology primarily depends on parts variety (P) and parts quantity (Q), as shown in Fig. 2 [43, 44]. The comparison of resolution and relative speed of several inspection technologies is enumerated in Table 7. The following subsection describes some of the coordinate measurement techniques in brief.

2.3.1 Coordinate measuring machine

A coordinate measuring machine (CMM) is a measuring device that consists of (1) contact (tactile) probes that physically contact the surface of the test object, (2) a mechanical structure that moves the probe in three axes (X, Y, Z) and (3) a manual or automatic drive/controller to collect and record the three-dimensional coordinates data of each axis. There are several variants of CMMs available with variation configuration in probe (contact or contactless, single or multiple), mechanical structure (cantilever, moving bridge, fixed bridge, horizontal arm, gantry, column, etc.) and drive controller (drive system: manual or motor-drive or fully automatic, computer-assisted data processing, direct computer control, post-processing software, etc.) [43]. Today,

Table 7 Comparison of resolution and relative speed of several inspection technologies [44]

Inspection technology	Typical resolution	Relative speed of application
Conventional instruments		
Steel rule	0.25 mm (0.01 in.)	Medium speed (medium cycle time)
Vernier caliper	0.025 mm (0.001 in.)	Slow speed (high cycle time)
Micrometer	0.0025 mm (0.0001 in.)	Slow speed (high cycle time)
Coordinate measuring machine	0.0005 mm (0.00002 in.)	Slow speed for single measurement High speed for multiple measurements on same object
Machine vision	0.25 mm (0.01 in.)[a]	High speed (very low cycle time per piece)

[a] Precision in machine vision is highly dependent on the camera lens system and magnification used in the applications.

non-contact probe systems like optical sensors are used to provide faster measurement speed, and increase the number of measurement points in a shorter amount of time [45].

2.3.2 Multilateration optical GPS

Optical interferometry is used in high-accuracy CMMs. Three reference points are needed to provide a coordinate in space, and a fourth reference point is introduced to provide a known position from the start. This allows the system to self-calibrate such that the accuracy of the system is dependent on the stability of the reference points. The white light is produced from a single optical fiber and is refocused by three satellites where the absolute distance is measured from the intensity of the white light interference [45]. This method has been widely used in radio navigation since World War II. In radio navigation, this method is called hyperbolic navigation.

2.3.3 X-ray computed tomography

X-ray computed tomography (CT) has been used mostly in the medical industry as a medical diagnostic tool [45]. CT has increasingly been of interest in the dimensional measurement for engineering parts as it is the only method that can measure the inner and outer geometry of a component without destroying it (NDT/NDE, as described in Sect. 3.2). CT can be used to provide information on the internal structures of objects for dimensional metrology in parts, wall thickness analysis, size and voids [46]. L De Chiffre et al. promulgated the industrial application of CT [47]. JP Kruth et al. proposed the application of X-ray computed tomography in dimensional metrology [48].

2.3.4 Automated inspections

Automated inspections are possible with the increasing use of high technology manufacturing processes that integrate a flexible manufacturing system (FMS), providing complete automations of work cells and a computer-integrated manufacturing system (CIM) using an on-board computer that drives CMM functions. Automated inspections provide assessments for dimensional accuracy and surface finish. Since it is difficult for humans to monitor the entire manufacturing operation when components are produced in large quantities, automated inspections improve productivity by eliminating human errors and reducing labor costs [40].

2.3.5 Machine vision

Machine vision is typically used in high volume automation, laborious and repetitive inspection operations. The process of imaging, analyzing the information and making necessary decisions is essential in the field of inspection and quality control. Hence, machine vision can be utilized in many functions, such as capturing shapes of specimens, measuring distances, determining ranges, determining the orientations of parts, quantifying motion and detecting surface shading [49].

2.3.6 Magnetic resonance imaging

Magnetic resonance imaging (MRI) was invented by Paul C. Latenburg [50]. MRI systems are noncontact coordinate measurement and imaging systems [43]. MRI systems are typically used as a medical diagnostic tool. Instead of using ionizing radiation as seen in CT scans and X-rays, MRI systems use strong magnetic field and radio-frequency pulses to produce the images of the organs and other internal body structures. MRI is based on the principle of nuclear magnetic resonance. By the action of powerful magnets, a sharp magnetic field intensity gradient is generated which affects the hydrogen atoms. These changes are captured by a computer to create a cross-sectional image [51, 52].

2.4 Geometrical dimensioning and tolerancing

This section briefly discusses the principle and measurement techniques of geometrical dimensioning and tolerancing (GD&T). It is well known that in manufacturing, simply providing the dimensioning and tolerancing (plus/minus) of the design drawing is not enough. Therefore, the information on GD&T variables such as straightness, flatness, squareness, roundness, parallelism, cylindricity and runout is essential to evaluate parts and process capabilities. Previously discussed dimensional, surface and coordinate metrology techniques can be effectively utilized to evaluate GD&T characteristics. Table 8 lists some of the possible techniques.

2.5 Measurement of material properties

Measurement of material properties is very important in evaluating the part performance. Mechanical testing and in-situ metrology can be effectively used to evaluate material properties. Mechanical testing is one of the essential elements of the inspection methods to evaluate the functional and mechanical properties of the parts. Table 9 lists the commonly used mechanical testing methods. The advancement of manufacturing processes brings a lot of metrological challenges and these challenges can be effectively tackled using in-situ metrological methods. In addition, the main advantages of in-situ metrology are the use of these methods for real-time process monitoring and control. Table 9 shows some common methods of in-situ metrology [31, 53–69].

Table 8 Common GD&T characteristics and measurement techniques

Characteristics	Measurement techniques
Straightness	Spirit level, dial indicator, laser-based measurement devices, interferometry technique, autocollimator, optical profilometer, CMM, etc.
Flatness	Gage block, beam comparator method, optical flat, interferometry technique, laser beam measurement, optical profilometer, CMM
Parallelism	Gage block, dial indicator, CMM
Squareness	Standard square, dial gauge, autocollimator, optical flat, CMM
Circularity	V-block and dial gauge, CMM
Cylindricity	Dial indicator, CMM
Angularity	Clinometer, angle dekkor, angle gauges
Perpendicularity	Protractor, sine bar, tiltmeter, theodolite, sine bars
Profile of a line	Optical projector, CMM
Profile of a surface	Stylus profilometer, optical profilometer, fringe interferometer, confocal microscopy, optical microscopy, photogrammetry and fringe projection systems
Position	CMM, machine vision, systems performing laser triangulation, laser tracker systems
Symmetry	Comparators, machine vision, optical projector
Concentricity	Plug gauge
Runout	Dial indicator, CMM

2.6 In-situ metrology

In measurement, in-situ refers to the way a measurement is taken with the system without altering the original conditions of the test. In-situ metrology is essential in providing confidence for manufactured parts. As machines are made with varying complexity, new challenges are introduced to standardize methodologies for advanced in-situ processes. There are constant efforts in enhancing the in-process monitoring and control algorithms for machine operation [20]. Some of the common in-situ metrology methods are shown in Table 10.

3 Metrology and inspection methods for AM

For several years, great effort has been devoted to the study of AM processes, with special attention on improving quality, establishing repeatability and interchangeability, and developing a standard for manufacturing, testing and measurement science. As discussed earlier, AM can produce parts with the highest geometric complexity (freeform fabrication) and varieties of materials, demanding the equally challenging metrology techniques to measure the AM performance [7, 10, 12, 15, 33, 70]. The focus of recent research is not only on designing and printing/manufacturing the part, but also on the needs of metrology to check the conformance of the dimensional and functional quality of the part. The following subsections systematically discuss the various metrology and inspection methods that can be effectively used for producing AM parts/artifact.

3.1 Effect of post-processing methods on metrology and inspection

In AM, post-processing of parts is inevitable and recommended to meet the requirements of the application for polymers, metals and composites. The AM parts are also subject to shrinkage and cracks [71, 72]. The support structures are an integral part of the AM parts having overhanging structures [73]. To prevent warpage of the AM part, support structures must be removed before end-use [74]. Removing these support structures imparts poor surface finish on the component [75], which is improved by post-processing operations [76]. This practice is observed in the case of sintering-based AM processes. Shrinkage of AM parts during solidification is an issue that can be compensated by accounting for shrinkage allowances. Hence, these post-processing methods need to be incorporated while designing parts to ensure proper GD&T [77–79]. These dimensional compensations are incorporated in the CAD model before slicing process [80]. This emphasizes the importance of the role of metrology in AM. The various post-processing methods in additive manufacturing are as follows:

1. Hot isostatic pressing
2. Warm isostatic pressing
3. Pressure infiltration
4. Subtractive manufacturing
5. Sand blasting
6. Abrasive flow finishing
7. Chemical etching
8. Electrochemical polishing
9. Support removal process

Table 9 Common methods to evaluate materials properties

Methods	Materials properties	Merits and demerits
Tension, compression, modulus and hardness test	Yield strength, tensile strength, rupture strength, compressive strength, ductility, Young's modulus, shear modulus, hardness number, indentation hardness, Poisson's ratio	*Merits*: Simple, inexpensive, and many material properties can be obtained from one test *Demerits*: Destructive methods and are undesirable
Fatigue, fracture toughness, creep and impact test	Number of cycles to failure, stress/strain ranges, strain ratio, fatigue life, tensile and compressive stresses, residual strength, creep crack growth rate, crack resistance curve	*Merits*: Simple, inexpensive, and many material properties can be obtained from one test *Demerits*: Destructive methods and are undesirable
Visual test	Detect surface flaws	*Merits*: Can be applied to any material to detect surface cracks, voids and surface finish or roughness *Demerits*: Can only give a qualitative evaluation. They are limited by visual access, which are prone to human error and can only inspect surface defects
Dye or liquid penetrant test	Detect open-to-surface discontinuities	*Merits*: Can be used on a variety of materials, inexpensive and simple to operate with no risk of surface damage *Demerits*: Test surface must be free of all contaminants, cannot be used on porous specimens and only work for surface flaws
Magnetic particle inspection test	Detect open-to-surface and just-below-surface flaws	*Merits*: Works on any type and size of magnetic object shape, inexpensive and simple to operate *Demerits*: Components having complex shapes require numerous tests, which can be cumbersome and time-consuming. They also need to demagnetize test specimen and only ductile materials can be applied
Eddy current test	Detect surface flaws	*Merits*: Work on both ferromagnetic and non-ferromagnetic materials can be automated and inexpensive *Demerits*: Limited to materials that are good conductors of electricity and limited to detection of surface and close-to-surface defects
Radiographic test	Detect internal flaws	*Merits*: Good for all types of materials, including metallic, non-metallic and plastics, magnetic and non-magnetic, conductors and non-conductors *Demerits*: Can be expensive to operate and maintain, and cause danger to the operator's health due to exposure to radiations
Ultrasonic test	Detect flaws deep in the test specimen	*Merits*: Tests have deep detection of flaws and are not hazardous *Demerits*: Require experienced technicians and can be expensive. The test surface needs to be accessible and smooth

Table 10 Common in-situ metrology devices

Device	Description or methodology	Merits and demerits
Thermocouple	Measures temperature using Seebeck effect	*Merits*: They are cost-effective and are immune to shock and vibrations, which makes it suitable to harsh environments *Demerits*: Their accuracy depends on the reference junction temperature. They are also susceptible to noise and corrosion
High-speed camera	Capture and analyze images of high-speed processes, which is impossible with naked eyes	*Merits*: They capture images at the rate of 250 frames per second *Demerits*: Photo error occurs due to lens distortion, location mismatch and non-alignment of sensor elements and pointing inaccuracy
Thermography, thermal camera	Uses infrared region of electromagnetic radiation to create a thermal image of the object	*Merits*: It is a non-contact device that indicates the measure of thermal content and gives the information of relative heat distribution in the object *Demerits*: The accuracy depends on the efficiency of the radiation detector
Photodiode and camera	Gives the visual image of the object using the visual region of electromagnetic radiation. It works based on the principle of photoelectric effect	*Merits*: It gives a visual first-hand information of the object *Demerits*: Any other further technical information requires post processing of the obtained image
Pyrometer	Detects the temperature of an object by non-contact method	*Merits*: Non-contact method of measuring temperature makes this device suited in thermal hazardous environments *Demerits*: The thermal radiation spectrum from the object suffers loss, which directly affects the efficiency of the measurement
Near IR camera	Uses the visual as well as the infrared region of the electromagnetic radiation to produce an image of the object	*Merits*: The process of capturing the near-infrared region of spectrum of an object gives the advantage of obtaining thermal information of the object along with the visual image
Laser ultrasonic testing	Detects the surface imperfections of an object	*Merits*: It has the capability to detect the imperfections, which cannot be detected by ultrasonic testing
Neutron diffraction	Detects the atomic structure in a material	*Merits*: This method has the advantage of providing high accuracy information about the atomic structure *Demerits*: The deviations in the neutron beam may result in loss of accuracy in the measurement
X-ray diffraction	Detects the internal imperfections in a material and gives information about the crystal structure of the material	*Merits*: It gives information about the internal defects as well about the internal structure of the object

Table 10 (continued)

Device	Description or methodology	Merits and demerits
In-situ process monitoring control	Monitors the processing of a material to check for the deviations in the properties, which can be used to modify the input parameters to correct the subsequent deviation in the process	*Merits*: The process of continuous feedback collection helps in reducing the errors in the process and ensures high accuracy and precision in the finished products *Demerits*: The consistency of the in-situ process monitoring control system depends on the feedback execution algorithm to alter the input parameters

10. Heat treatment
11. Laser surface treatment
12. Ultraviolet curing
13. Ultrasonic curing
14. Chemical treatment
15. Ion implantation
16. Thermal spraying
17. Debinding/washing and sintering

3.1.1 Hot isostatic pressing

Hot isostatic pressing (HIP), is a post-processing technique to reduce the porosity of the components and increase the green density. It is a method of compacting the component by pressurizing inert gases uniformly in all directions, usually done at elevated temperatures. The inert gas atmosphere ensures that the chemical reaction is averted at high temperature. The high pressure compacting ensure that the voids are closed [81], reducing porosity and dimensions due to compaction. Thus, allowances must be provided for AM components that require HIP, and the parts should be designed with greater dimensions than the required specifications.

3.1.2 Warm isostatic pressing

Warm isostatic pressing (WIP) is also a recommended post-processing technique for AM parts. In this method, the component is immersed in a silicone oil bath which is maintained at elevated temperature by heating the die. A uniform isostatic pressure is applied to the part by pressurizing the silicone oil bath. This method is used particularly in the compaction of polymer and polymer-based composites. This process also compacts the component. Hence, tolerances and allowance must account for the shrinkage of the component during WIP.

3.1.3 Pressure infiltration

Pressure infiltration (PI) is a post-processing method to fill the surface porosities in AM parts. This technique is not suitable for compacting the internal voids and cracks. However, in this method, the AM part is immersed in a resin, which is usually a suspension of a solvent and the powder of the component material. A unidirectional pressure is applied to the bath of the suspension, which causes the material particulates to adsorb on the surface of the component.

3.1.4 Subtractive manufacturing processes

Conventional machining processes generally reffered to as subtractive manufacturing (SM) or machining are important post-processing techniques employed for removing supports, rafts and undesirable topological features in an AM part.

Hence, machining allowance is an important design consideration and compensates for material loss during the SM. Researchers have developed an integral approach to employ AM and SM in a synergetic combination for specific applications, where a welding torch for material deposition is inserted in tandem with tool cutter.

3.1.5 Sand blasting

Sand blasting is a surface finish operation, where surface roughness is reduced, and small unintended topographical features are ablated. This method uses a high-pressure jet of sand to scour the surface until the desired finish is obtained [82].

3.1.6 Abrasive-flow finishing

Abrasive-flow finishing (AFF) is a surface finishing operation, like sand blasting, where a high-velocity abrasive jet is used to provide high degrees of surface finish [83].

3.1.7 Chemical etching

Chemical etching (CE) is a subtractive method where industrial etchants remove surface material. The AM component is placed in a temperature-regulated etchant bath, which etches or removes the material [84]. Part designs need to account for a material loss during the CE to maintain the required tolerances.

3.1.8 Electrochemical polishing

Electrochemical polishing (EP) improves the surface finish of a metal part by removing surface material electrochemically; it has been found to be a good post-processing method for AM components [84]. The material being polished is made the anode and a suitable cathode is placed in an electrolytic bath maintained at an optimum temperature. The electrolyte is usually a salt of the metal part being polished.

3.1.9 Support removal process

Due to the layer-by-layer AM process, support structures that are necessary to print overhanging parts. The support structures are generally removed by cutting, grinding and polishing operations. Few subtractive processes are used in the removal of AM support structures, which are usually the support structures are designed to be broken easily [85]. Crump et al. patented the process and equipment for removing support structures in the fused deposition modeling (FDM) method [86].

3.1.10 Heat treatment

Most metal AM components are subjected to residual thermal stresses, which results in distortion, and it is important that residual thermal stresses are eliminated by heat treatment processes. Annealing is the most common heat treatment process in the AM metal post processing [87]. Annealing eliminates the residual stresses in the metal component and is also advantageous in degasifying resulting gas entrapment that is common in AM [71].

3.1.11 Laser surface treatment

Ramos et al. researched improving the surface roughness of selective laser-sintered metal parts, employing laser surface polishing to enhance the surface finish of the parts [88]. An intense ultraviolet laser beam typically used with this method. Lamikiz et al. found that laser surface polishing of metal parts is advantageous when compared to other surface finish and surface treatment processes because it is devoid of the heat-affected zone and associated thermally induced residual stresses [89].

3.1.12 Ultraviolet curing

The parts printed/fabricated in stereo lithography (SLA) process are still in green state, having lower mechanical strength and poor surface finish. A post-processing process called curing is generally followed to enhance the strength and performance of the printed parts. Fundamentally, during the SLA printing process, the parts get the final geometrical shape and form, but the photo-polymerization process is still not fully completed; hence the mechanical properties are not obtained after printing. Ultraviolet (UV) curing, the most popular form of post-processing step, usually follows after a washing step. For the part during the post processing, UV curing is generally conducted in a combination of heat and UV light exposure for a set amount of time that mainly depends on the size and material of the part. Colton, et al. experimentally studied the post-build ultraviolet curing of stereolithography parts [90]. In this process, the part is exposed to ultraviolet light for about an hour to improve the mechanical strength and surface finish.

3.1.13 Ultrasonic curing

Ultrasonic curing has also been found to be effective in improving the surface finish of stereolithography parts. In this method, the component is cured by vibrating in ultrasonic waves to reduce the surface roughness (R_a) of the component [91].

3.1.14 Chemical treatment

Several chemical treatments are employed in the post processing of AM components. Usually in fused deposition modeling (FDM) and stereolithography (SLA) methods of AM, rinsing the parts in a bath of solvent is a common post-processing practice. Galantucci et al. investigated the effect of post-processing treatment of dimethylketone (acetone) on acrylonitrile butadiene styrene (ABS) manufactured by FDM method [92]. Bredt et al. patented the post-processing of 3D printed parts with chemicals such as isopropyl alcohol and esters to improve surface finish [93]. Since this method has a leaching action, resulting in a loss of materials, careful considerations to compensate for this loss should be included in the design step of these parts that will be chemically treated.

3.1.15 Ion implantation

Ion implantation is a popular surface modification and a finishing technique in AM. With this method, ions of special materials are implanted on the surface of the AM component to impart superior surface qualities to it [94]. Ions are accelerated by an electric field and is directed to bombard the target material. Due to the high-speed impact, the ions get embedded in the voids and micro-depressions on the surface.

3.1.16 Thermal spraying

Thermal spraying is a post-processing method used to coat material at elevated temperature with the hard, wear-resistant and anti-corrosive surface [95]. The coating increases tensile strength and surface hardness of the material [96]. Nickel is commonly used [97] for thermal spraying.

3.1.17 Debinding/washing and sintering

There are two leading metal additive manufacturing processes: (1) atomic diffusion additive manufacturing (ADAM) developed by Markforged Metal X and (2) bound metal deposition (BMD) developed by desktop metal, which utilizes the fused deposition modeling (FDM) technology with a filament made of metal powder rod embedded inside a wax-and-plastic filament along with a proprietary binder. In addition, the part is printed using two filament materials: (1) a main part and supports with metal powder filament and (2) a ceramic release material to print interface between the part and the support/raft, to allow for easy separation of the support/raft after sintering. The part is printed in a layer-by-layer fashion with compensations are made during the design step to account for part shrinkage. The printed part has the requires final form and shape but still in the green state with poor mechanical properties. Thus, it required two-stage post processing starting with washing or debinding followed by a sintering process. In several cases, subtractive post-processing methods are also needed to obtain the right dimensions and surface finish of the printed parts.

During the washing or debinding post-processing step, the green part is immersed inside a heated debinding basket that circulates Opeteon SF79 solvent (Markforged Metal X) around the parts. This breaks down the polymer binding material and creating an open-pore channel structure to prepare the part for sintering. It is recommended to run this process in the batch to achieve higher efficiency. The parts remain inside the system for a preset amount of time (provided by the system software) and are later dried outside and ready to be weighed. The debind process converts the part from the green state to brown state and makes it ready for the sintering process. However, as per the manufacturer's recommendation (Markforged Metal X), the debind/wash process will be considered completed if the total mass loss is more than 4.2%. To calculate % mass loss, subtract the mass of the washed (brown) part from the mass of the unwashed (green) part, then divide by the mass of the green part. If the part has less than the required mass loss, then it again goes to the washing cycle until the required mass reduction is obtained. After the required mass loss is obtained, the part is still in the brown state and are more fragile than a green state but are still bound together with metal powder and polymer.

After the debind cycle, the air-dried part is placed inside the sintering furnace where it is heated to preset temperature cycles under the controlled atmosphere filled with a blend of inert and mixed gas. The sintering process eventually removes all the remaining binder, causing the metal particles to fuse together and transform from a lightly bound metal powder to a full metal part. This step necessitates design considerations unique to ADAM and BMD because sintering has implications for part features, build orientation, and support structures. In the early stages of the temperature ramp, the furnace burns away the remaining binder through the tiny channels created by the washing process. As the temperature reaches its peak, the part shrinks about 17% to its final size while the ceramic supports turn from filament to dust. The machine slowly cools from its peak temperature until it is safe to remove from the furnace.

3.1.18 Summary of post-processing methods

As a summary, Table 11 suggests the various post-processing methods suitable for various AM processes.

3.2 Non-destructive testing and evaluation

Based on the findings of the various meetings, workshops, journal articles offered by the industry, academia and government, the universal need of the non-destructive testing (NDT) and non-destructive evaluations (NDE) for AM are

Table 11 AM processes and suitable post-processing methods

AM process	Post-processing method
SLS/SLM/EBM	Hot isostatic pressing, warm isostatic pressing, pressure infiltration, subtractive methods, sandblasting, grinding, ion implantation, chemical etching, electrochemical polishing, thermal spraying
SLM	Hot isostatic pressing, warm isostatic pressing, pressure infiltration, subtractive methods, sandblasting, grinding, ion implantation, chemical etching, electrochemical polishing, thermal spraying, support removal process, base plate removal process
EBM	Hot isostatic pressing, warm isostatic pressing, pressure infiltration, subtractive methods, sandblasting, grinding, ion implantation, chemical etching, electrochemical polishing, thermal spraying, support removal process, base plate removal process
LENS	Hot isostatic pressing, warm isostatic pressing, pressure infiltration, subtractive methods, sandblasting, grinding, ion implantation, chemical etching, electrochemical polishing, laser surface treatment, heat treatment, support removal process
FDM	Subtractive methods, abrasive flow finish, pressure infiltration, laser surface treatment, chemical treatment, ultraviolet curing, ultrasonic curing, support removal process
Material jetting	Subtractive methods, abrasive flow finish, pressure infiltration, support removal process
Binder jetting	Subtractive methods, abrasive flow finish, pressure infiltration
LOM	Abrasive flow finish, subtractive methods
SLA	Abrasive flow finish, subtractive methods, chemical treatment, ultraviolet curing, ultrasonic curing, support removal process
ADAM/BMD	Debind/wash, sintering, hot isostatic pressing, warm isostatic pressing, subtractive methods, sandblasting, grinding, ion implantation, chemical etching, electrochemical polishing, thermal spraying, support removal process

commonly identified [2, 98, 99]. Research shows AM technology is more capable of producing huge part variety (geometrical or material) when compared to the part quantity (few parts), and it is advisable to adopt the non-destructive testing (NDT) and non-destructive evaluation (NDE) techniques (preferably contactless methods) to reuse the tested parts. Recent technical memorandum (NASA/TM-2014-218560) from the National Aeronautics and Space Administration (NASA) also advocated the need for NDT or NDE and provided the major gaps and recommendations to successfully apply NDT/NDE for AM parts and artifacts [98].

In addition, the roadmap study of the National Institute of Standards and Technology (NIST) for metal AM (Fig. 3) identified the limitation in AM in four areas: (1) AM materials, (2) process or equipment, (3) qualification or certification, and (4) modeling and simulation. Nonetheless, the need for NDT or NDE is common in all these four areas [2]. NASA and NIST both suggested using the NDT/NDE techniques for AM parts and artifacts with contactless, in-situ and real-time metrological equipment for dimensional and materials property measurement to establish real-time process measurement, monitoring and control on AM technology [2, 98]. Several commercial AM systems are available, but they are not equipped with in-situ process and property measurement with closed-loop process control systems due to the complexity of the underlying dynamics of AM processes and the lack of formal statistical models needed for process control.

Currently, little research has been done on the internal defects and surface texture metrology in AM-specific applications [100]. Figure 3 shows the various challenges in AM. AM generates engineering parts with rough surfaces due to frequent discontinuities, vertical walls, re-entrant features and support materials. This creates challenges where tactile methods may face loss-of-contact and tip damage due to steep sides of surface asperities, and optical methods may be affected by high image contrasts and diffuse reflections [101]. To select the best inspection method for AM, it is advisable to closely look at the industry requirements for part dimensions and measurement uncertainty (tolerances) [100, 102].

Table 12 lists all common NDT/NDE methods, comparing their merits and demerits according to the nature of the measurements involved and their rank of applicability using a scale of 10, where a score of ⓪ is applied if the inspection method is less-likely, ⑤ is applied for likely, and ⑩ for most-likely to be used for AM processes. Applicability is a term used here to indicate the suitability and capability of the method being applied for AM processes. Table 12 not only provides the merits and demerits of each inspection method, but also distinguishes the nature of each inspection method in terms of four broad categories: (1) non-destructive testing (NDT), (2) contactless (CL), (3) in-situ (IN), and (4) real-time (RT). The last column of Table 12 specifically provides the suitability of the inspection methods for the listed AM processes. For better reference and aid in selecting the correct metrological tool, Table 13 enlists various metrology and inspection methods and their capabilities for part dimension, shape complexity, materials and surface traceability [102].

3.2.1 Example of non-destructive testing and evaluation

3.2.1.1 Computed tomography For several years, significant research has been devoted to using computed tomography (CT) for metrological evaluation of the AM parts and

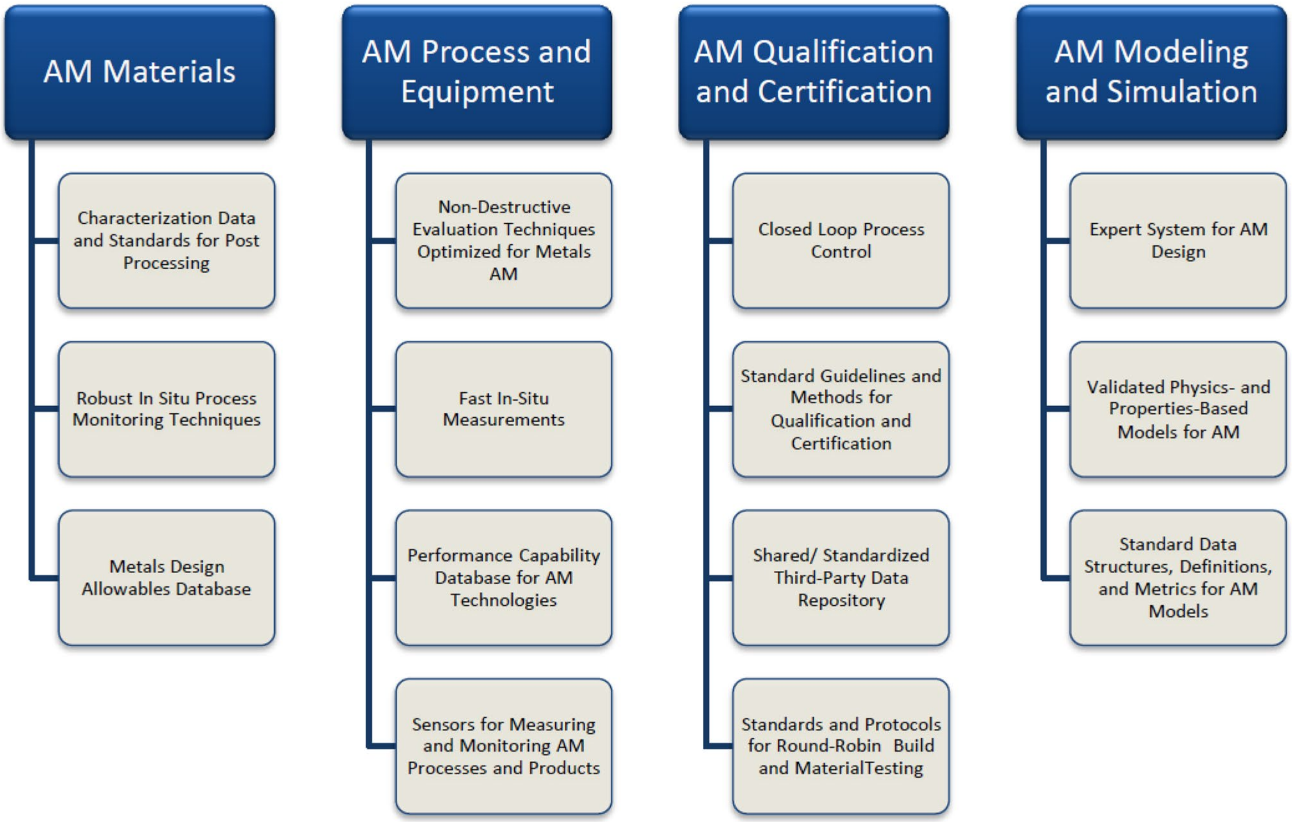


Figure 3 Important technology and measurement challenges for AM [33]

artifacts [46, 48, 103–110]. Computed tomography can be used to provide information on the internal structures of objects for dimensional metrology [64, 111]. This special case is due to the large and anisotropic grains in AM, which can cause attenuation of ultrasonic waves. The epitaxial growth of grains in AM results in a peculiar surface finish, which is sensitive to liquid dye penetration testing, magnetic particle testing, eddy current testing, etc. Considering all these challenges. CT has been successful in the in-situ, real-time process monitoring in AM [112].

3.2.1.2 Coordinate measuring machine Coordinate measuring machines (CMMs) are widely used as semi-to-fully automated inspection methods best suited for the manufacturing environment. They are integrated with computer controls and are used extensively in metrology where dimensions for straightness, flatness, squareness and parallelism can be easily measured with very high precision. CMMs are increasingly used to aid the inspection process for AM [8, 10, 24, 113–117].

3.2.1.3 Penetrant testing AM parts have higher porosity compared to conventional manufacturing methods with irregular or rough surfaces. NDT methods, such as penetrant testing (PT), can be used to detect defects specific to AM [49, 65, 98, 118].

3.2.1.4 Structured light testing Complicated parts produced by AM machines introduce challenges in controlling both geometry and property variation [98]. Structure light testing (ST) methods, allow real-time imaging performance and are widely used in many 3D-imaging applications [119].

3.2.1.5 Ultrasonic testing Ultrasonic testing (UT) can be used to detect voids or weak deposition layers in AM.

3.3 Physical reference standard

AM components are effectively inspected using CT with the aid of ET, PT, RT and UT to examine/verify their internal structure. To produce consistent data, a physical reference standard can be developed to aid the inspection process. Test artifacts can be used in evaluating surface roughness as well as dimensional accuracy [120]. Test artifacts do not provide the characteristics of the surface texture on actual manufactured parts; however, they do provide information on the real conditions and challenges to be addressed for AM during the manufacturing process. Artifacts from different

Table 12 List of common measuring and inspection methods of AM processes

Measuring and inspection methods	Merits	Demerits	NDT	CL	IN	RT	Applied to AM
Visual (naked eyes)	Applied to any materials to detect surface cracks, voids, and surface finish or roughness	Only give a qualitative evaluation, limited by visual access, prone to human error, only inspects surface defects	⑩	⑩	⑤	⑤	⑩
Direct comparison—scale, caliper, micrometer, and dial gauge	Simple to use Inexpensive	Limited to flat, smooth surfaces. Prone to human error, low accuracy	⑩	⓪	⓪	⓪	⑩
Laser tacker	Measure large parts, portable CMM, superfast automatic measurement	Sensitive to temperature and environmental condition, need to calibrate often	⑩	⑩	⑩	⑤	⑩
Tactile CMM	High precision, automatic, portable model are available	Contact methods only provide data of few points, slow, expensive, can't use for small features. Needs post-processing	⑩	⓪	⑩	⓪	⑩
Optical CMM	Contactless methods, high precision, automatic, portable model are available, can be used for smaller features	Only provide data of few points, slow, expensive, need post-processing	⑩	⓪	⑩	⓪	⑩
Computer topography	Contactless methods, high precision, automatic	Material dependent, slow, expensive	⑩	⑩	⑩	⓪	⑩
Fringe projection	Contactless methods, high precision, exact and easy generation of very fine patterns	High cost, difficult to produce ideal beam geometry, produce speckle noise, self-interference	⑩	⑩	⑩	⑩	⑩
Interferometry	Provide high contrast and resolution, can measure smooth surfaces	Expensive, cause error when measuring rough surfaces	⑩	⑩	⑩	⑩	⑩
Tactile surface topography and profilometer	Simple to use for basic roughness, inexpensive, high lateral resolution depends on stylus tip radius	Contact methods, lower measurement speed, might cause damage or contamination to surface	⑤	⓪	⑩	⑤	⑩
Optical surface topography and profilometer	Contactless methods, high measurement speed, 3D measurements, easy to use, automated	Material surface requirement, limited surface slope	⑩	⑩	⑩	⑩	⑩
Confocal microscopy	High lateral resolution	Cannot measure steep flanks	⑩	⑩	⑩	⑩	⑩
scanning force microscopy	3D surface profile, works in both ambient air and liquid environment, higher resolution than SEM	Contact method, slow scanning speed	⑩	⓪	⓪	⓪	⑩
Dye or liquid penetrant	Works on small surface flaws, not dependent on orientation, low cost, simple to operate, no risk of surface damage	High loss in test sensitivity and reliability due to contaminants, toxic and flammable, only works for surface flaws, due to the presence of indentations in AM products, somewhat difficult to use in AM inspection	⑩	⓪	⑤	⓪	⑤
Magnetic particle	Works on any type, size and shape of magnetic objects, low cost, simple to operate	Components having complex shapes require numerous tests which become cumbersome and time-consuming, need to demagnetize test specimen after testing, only works on ductile materials, surface finish in AM is too complex to be investigated, this can be explained due to epitaxial growth	⑩	⓪	⑤	⓪	⑤
Eddy current	Works on both ferromagnetic and non-ferromagnetic materials, can be automated, low cost	Limited to materials that are good conductors of electricity, limited to detection of surface and close-to-surface defects, surface finish is too complex to be investigated	⑩	⓪	⑤	⓪	⑤
Radiographic	Good for all types of materials, including metallic, non-metallic and plastics, magnetic and non-magnetic, conductors and non-conductors	Beam orientation towards defect is important, exposure to radiation can be hazardous to the operator, expensive to operate and maintain	⑩	⑩	⓪	⓪	⑩

Table 12 (continued)

Measuring and inspection methods	Merits	Demerits	NDT	CL	IN	RT	Applied to AM
Ultrasonic	Deep detection of flaws, not hazardous	Requires experienced technicians, surface needs to be accessible and smooth	⑩	⑩	⓪	⓪	⑤
Machine vision	Automatic, good for repetitive inspections	Can be expensive, requires experienced technicians	⑩	⑩	⑤	⓪	⑩
Thermocouple	They are cost-effective and are immune to shock and vibrations which makes it suitable to harsh environments	Accuracy depends on the reference junction temperature, susceptible to noise and corrosion	⑩	⓪	⑩	⑩	⑩
High speed camera	They capture images at the rate of 250 frames per second	Photo error may occur due to possible lens distortion, location mismatch and misalignments of sensor elements and pointing inaccuracies	⑩	⑩	⑩	⑩	⑩
Thermography, thermal camera	Relative heat distribution in the object	Accuracy depends on the detector efficiency	⑩	⑩	⑩	⑩	⑩
Photodiode and camera	It gives a visual first-hand information of the object	Post processing of the image is required	⑩	⑩	⑩	⑩	⑩
Pyrometer	Suitable in hazardous thermal environments	Radiation loss affects the efficiency	⑩	⑩	⑩	⑩	⑩
Near IR camera	Provides thermal information of the object along with the visual image	Accuracy depends on specification and efficiency of the camera	⑩	⑩	⑩	⑩	⑩
Laser ultrasonic testing	Detects imperfections that cannot be detected by ultrasonic testing	Relatively expensive and requires precautionary measures against possible laser hazards, efficiency is a function of materials absorption properties	⑩	⑩	⑤	⑤	⑤
Neutron diffraction	Provides high accuracy information about the atomic structure	The deviations in the neutron beam may result in loss of accuracy in the measurement	⑩	⑩	⑤	⑤	⑩
X-ray diffraction	It gives information about the internal defects; residual stresses can also be measured	Crystal arrangement can be studied accurately however, inner atomic arrangements cannot accurately investigated alike the neutron diffraction method	⑩	⑩	⑤	⑤	⑩
X-Ray computer topography	It gives information of internal defects which cannot be accurately furnished by other methods in AM	Relatively expensive and operational precautions are required	⑩	⑩	⑩	⑩	⑩

NDT non-destructive, *CL* contactless, *IN* in-situ, *RT* real-time. Rank of applicability in the scale of 10: ⓪ for less-likely, ⑤ for likely, and ⑩ for most-likely

Table 13 Comparison of various metrology and inspection methods with their capabilities [102]

	Laser tracker	Direct Comparison	Tactile CMM	Optical CMM	X-ray tomography	Fringe projection	Fringe reflection / Deflectometry	Photogrammetry	Interferometry	Tactile Surface topography & Profilometry	Optical Surface topography & Profilometry	Confocal Microscopy	Scanning Force Microscopy
Part dimensions													
large	●	◔	●	●		◑		●	◔				
medium	●	◑	●	●		◕		●	◑				
small		●	●	●	●	●	●	●	●	◑	◔	◔	
micro			◑	◑	●	◑	◔		●	●	●	●	◕
Shape complexity													
low	●	●	●	●	●	●	●	●	●	●	●	●	●
medium	◑	◑	●	●	●	◑		◔		◔	◔	◑	◔
high	◔		◑	◑	●								
Material and surface													
hard, not sensitive	●	●	●	●	●	●	●	●	●	●	●	●	●
deformable	●	◔	◔	●	●	●	●	●	◑	◑	●	●	●
specular	●	●	●		●		●		●	●		◑	●
transparent	●	◑	●		●			●		●		◔	●
opaque	●	●	●	●	●	◑	◑	●	●	●	●	●	●
Traceability													
	◕	◕	●	◕	◑	◑	◑	◑	●	●	◑	◕	●

Legend:	full match:	●
	little match:	◔

AM systems can be compared to study the relationships between surface texture and orientation of the build direction using traditional measuring devices, such as CMM or optical microscope [101, 120].

3.4 Inspection procedure

Currently, no standardized inspection procedure exists for finished parts made by AM. Specific requirements need to be addressed for AM, such as the complexity of geometry, porosity, surface finish and deeply embedded flaws. Newer procedures are needed to address AM specific issues [20, 98, 121, 122].

3.5 Modeling and simulation in metrology of AM

Modeling and simulations play a vital role in assessing the properties of AM products before the actual production starts. It helps optimize input parameters to obtain desired properties and characteristics in the AM products. Actual metrology results help validate the results obtained from modeling and simulation. It also helps the feedback loop of obtaining real-time values into the modeling and simulation algorithms to further reduce the discrepancy between real-time processing results and those of modeling and simulations. Research in AM has employed models to simulate the process and has used appropriate metrology methods to measure deviations from the simulation results with manufactured parts. In certain cases, real-time measured values are fed back into the algorithm of the simulation to obtain higher accuracy results. Moylan et al. emphasized that a complete comprehension of modeling and metrology aspects in direct-process monitoring of AM will improve performance and will result in greater adoption of AM. Further, they substantiated that infrared thermography can provide direct-process metrology for validating results obtained from theoretical models [30]. Gong et al. found that thermal modeling and subsequent temperature metrology are significant factors in deciding the process performance, which directly correlates with the properties of the component [123].

3.6 Real-time in-process monitoring

In real-time in-process monitoring of additive manufacturing, the melt pool dimensions are monitored as a function of time to check deviations, and the processing input parameters are modified accordingly to maintain the constant melt pool size. The dimensional accuracy, temperature, surface roughness (R_a) and residual stresses are other parameters which are monitored continuously and fed back to the control system. The algorithm manipulates the input control parameters to check deviations [124, 125]. This is a reiteration of the call for an integrated computational material engineering (ICME) approach in AM, which is envisioned as a strategy for its wide-scale adoption [30]. Various instruments employed in in-situ monitoring of AM process are described in Table 12.

3.7 Qualification and certification

It is difficult to inspect AM since no guidelines exist to qualify and certify AM products; furthermore, disparities in AM machines types and processing parameters create a gap in process qualification and certification [20, 98, 121, 122]. However, standardization organizations, such as International Organization for Standardization (ISO), American Society for Testing and Materials (ASTM), and National Institute of Standards and Technology (NIST) have tried to bridge the gap in the process of qualification and certification of AM. In 1997, NIST organized a workshop, “Measurement standard issues in Rapid Prototyping”, and Jurrens et al. at NIST developed certain standards for the rapid prototyping industry in 1999 [126]. ASTM F-42 committee was responsible for charting the standards for classifying the AM process and evolved seven classifications of AM. ASTM E-28 committee developed the standards for tensile testing of AM components. Later, the joint technical committee (TC) of ISO and ASTM formed the group ISO/TC 261-ASTM F 42 to provide international standards for AM [127]. In addition, several organizations, like NIST, NASA, National Science Foundation (NSF), Office of Naval Research (ONR), Defense Advanced Research Projects Agency (DARPA), National Institutes of Health (NIH), and Air Force Research Laboratory (AFRL) together developed a roadmap for research in AM for next decade, emphasizing the development of process standards for AM.

In particular, ISO and ASTM are the main organizations that played a big role in developing standards for AM. The various subcommittees and their roles in the development of standards for AM are listed below [127].

- ASTM F42.01—test methods
- ASTM F42.04—design
- ASTM F42.05—materials and processes
- ASTM F42.90—executive
- ASTM F42.91—terminology
- ASTM F42.94—strategic planning
- ASTM F42.95—US TAG to ISO/TC 261
- ISO/TC 261—additive manufacturing
- ISO/TC 261/JAG—ASTM F42 steering group on JG activities
- ISO/TC 261/JG 51—joint ISO/TC 261-ASTM F 42 group: terminology
- ISO/TC 261/JG 52—joint ISO/TC 261-ASTM F 42 group: standard test artifacts
- ISO/TC 261/JG 54—joint ISO/TC 261-ASTM F 42 group: fundamentals of design
- ISO/TC 261/JG 55—joint ISO/TC 261-ASTM F 42 group: standard specification for extrusion-based additive manufacturing of plastic materials
- ISO/TC 261/JG 56—joint ISO/TC 261-ASTM F 42 group: standard practice for metal powder bed fusion to meet rigid quality requirements
- ISO/TC 261/JG 57—joint ISO/TC 261-ASTM F 42 group: process-specific design guidelines and standards
- ISO/TC 261/JG 58—joint ISO/TC 261-ASTM F 42 group: qualification, quality assurance and post-processing of powder bed fusion metallic parts
- ISO/TC 261/JG 59—joint ISO/TC 261-ASTM F 42 group: NDT for AM parts
- ISO/TC 261/JG 60—joint ISO/TC 261-ASTM F 42 group: additive manufacturing—non-destructive testing and evaluation—standard guideline for intentionally seeding flaws in parts
- ISO/TC 261/JG 61—joint ISO/TC 261-ASTM F 42 group: guide for anisotropy effects in mechanical properties of AM part
- ISO/TC 261/JG 62—joint ISO/TC 261-ASTM F 42 group: guide for conducting round-robin studies for additive manufacturing
- ISO/TC 261/JG 63—joint ISO/TC 261-ASTM F 42 group: test methods for characterization of powder flow properties for AM applications
- ISO/TC 261/JG 64—joint ISO/TC 261-ASTM F 42 group: additive manufacturing file format
- ISO/TC 261/JG 66—joint ISO/TC 261-ASTM F 42 group: technical specification on metal powders
- ISO/TC 261/JG 67—joint ISO/TC 261-ASTM F 42 group: technical report for the design of functionally graded additive manufactured parts
- ISO/TC 261/JG 68—joint ISO/TC 261-ASTM F 42 group: Environmental Health and Safety (EH&S) for 3D printers
- ISO/TC 261/JG 69—joint ISO/TC 261-ASTM F 42 group: EH&S for use of metallic materials
- ISO/TC 261/JG 70—joint ISO/TC 261-ASTM F 42 group: optimized medical image data
- ISO/TC 261/JG 71—joint ISO/TC 261-ASTM F 42 group: powder quality assurance
- ISO/TC 261/JG 72—joint ISO/TC 261-ASTM F 42 group: machine—production process qualification
- ISO/TC 261/JG 73—joint ISO/TC 261-ASTM F 42 group: digital product definition and data management
- ISO/TC 261/JG 74—joint ISO/TC 261-ASTM F 42 group: personnel qualifications
- ISO/TC 261/JG 75—joint ISO/TC 261-ASTM F 42 group: industrial conformity assessment at additive manufacturing centers
- ISO/TC 261/JG 76—joint ISO/TC 261-ASTM F 42 group: Revision of ISO 17296-3 and ASTM F3122-14

- ISO/TC 261/JG 77—joint ISO/TC 261-ASTM F 42 group: test method of sand mold for metal casting
- ISO/TC 261/JWG 10—joint ISO/TC 261—ISO/TC 44/SC 14 WG: Additive manufacturing in aerospace applications
- ISO/TC 261/JWG 11—joint ISO/TC 261—ISO/TC 61/SC 9 WG: additive manufacturing for plastics

Table 14 listed all the 37 AM standards that are approved as well as under development [128]. The status of the standard can be found by International Harmonized Stage Codes (column 2) and the International Classification for Standards (ICS) (column 3).

It is significant to note that Dave Abbott of GE aviation has successfully qualified the GE9X T25 sensor and the LEAP ("Leading Edge Aviation Propulsion") jet engine's fuel nozzle from the Federal Aviation Administration, which has been set as an example for qualification facilitating mass production of AM products [30].

3.8 Feedstock material properties

Many parameters contribute to a consistent 3D-printing part. Properties of filament and powder feedstock are important to yield a reliable and repeatable result. For example, the reliability and reproducibility of the part printed from FDM/fused filament fabrication (FFF) processes highly depends on the moisture level of filaments, while for other additive manufacturing methods, the feedstock material is in powder form. One of the important properties is the particle size distribution, which directly affects the packing behavior of the powder bed and the quality of the final parts. Morphology, chemical composition, density, thermal properties and rheology are other characteristics of metal powder that are crucial to qualify metal powder for printing. Specific standard methods for determining a characteristic of powder used for AM process are needed for the future development of AM [129].

3.8.1 Filament storage and humidity measurement

Generally, low-end FDM/FFF processes use the filaments that are open in the room temperature and have print failure due to the higher moisture contents. This problem is related to storage and usability. The filament spool generally comes in a vacuum-sealed bag and can be stored for a longer time. However, once the bag is open, the filament interacts with the atmosphere and absorbs moisture that changes its properties. Several researchers have pointed out the adverse effect of print failure and mechanical properties, due to the higher moisture content of the filaments [130–132]. The common issues with the higher moisture content filaments are: (1) filaments become more brittle and more prone to breakage, (2) need higher extrusion temperature than its preset value, and have (3) poor tensile (mechanical) strength and (4) poor dimensional accuracy and finish due to the steam and bubbling of filaments after passing through the hot end. For low-end applications, the moisture issues are not considered at all. On the contrary, for high-end applications, a simple dry box with humidity and temperature measurement sensor is popularly used to store the used filament spools and avoid such problems. There are some high end and expensive 3D printers available that store the filaments in a dry box (attached to the 3D printer) and a clear bowden tube, until it feeds into the extruder head, to avoid any direct contact with the air. Other strategies are: (1) keep the used filament spools in vacuum bags, (2) keep the dry-packs of silica gel desiccants inside regular or weather shield plastic storage boxes with lids while storing the used filament spools, (3) use a mini dehumidifier inside the storage box, and (4) conduct fan drying or oven (even common household oven) drying of the filaments that have higher moisture contents.

On the other end, optical sensors are generally used to control (or stop) the 3D printer, if the filament is out. However, the filament diameter is overlooked (assumed to be consistent) and, therefore, there is no instrument available to verify the diameter consistency along the length of the filament. Here, the simple Vernier caliper or micrometer can be effectively used to measure filament diameter before installing the filament spool on the 3D printer.

3.8.2 Apparent density

Apparent density is one of the fundamental properties of a powder. It is the weight per unit volume of loose, or untapped powder, including metal particles and empty space, in contrast to the weight per unit volume of only the individual particles. Apparent density defines the mass of loose powder that occupies a unit volume. This property is crucial to process parameters, such as the design of powder bed, compacting tool and the amount of force necessary to densify loose powder. For example, to press the loose powder to a certain height or volume, the presses operate either to a fixed position or a fixed pressure. If the apparent density of the powder fluctuates significantly without compensating the position or the pressure value of the presses, the result will not be repeatable. The presence of moisture, oils, stearic acid, stearates, waxes and the temperature of powder mass may also affect the characteristics of the powder [129, 133–136]. The methods and apparatuses used for determining the apparent density of metal powder, as specified by ASTM standards, are Hall flowmeter funnel, Carney funnel, Scott meter and Arnold meter. These methods are discussed briefly in the following.

3.8.2.1 Hall flowmeter funnel The Hall flowmeter funnel method for determining apparent density for free-flowing

Table 14 ISO/TC 261—additive manufacturing standards [128]

Standard and/or project under the direct responsibility of ISO/TC 261 secretariat (total 37)	Stage	ICS
ISO 17296–2:2015 Additive manufacturing—general principles—part 2: overview of process categories and feedstock	90.20	25.030
ISO 17296–3:2014 Additive manufacturing—general principles—part 3: main characteristics and corresponding test methods	60.60	25.030
ISO 17296–4:2014 Additive manufacturing—general principles—part 4: overview of data processing	90.92	25.030
ISO 27547–1:2010 Plastics—preparation of test specimens of thermoplastic materials using mouldless technologies—part 1: general principles, and laser sintering of test specimens	90.93	83.080.20
ISO/ASTM 52900:2015 Additive manufacturing—general principles—terminology	90.92	25.030 01.040.25
ISO/ASTM DIS 52900 Additive manufacturing—general principles—fundamentals and vocabulary	40.99	25.030 01.040.25
ISO/ASTM 52901:2017 Additive manufacturing—general principles—requirements for purchased AM parts	60.60	25.030
ISO/ASTM 52902:2019 Additive manufacturing—test artifacts—geometric capability assessment of additive manufacturing systems	90.92	25.030
ISO/ASTM AWI 52902 Additive manufacturing—test artifacts—geometric capability assessment of additive manufacturing systems	10.99	25.030
ISO/ASTM DIS 52903-2 Additive manufacturing—standard specification for material extrusion-based additive manufacturing of plastic materials—part 2: process—equipment	40.60	25.030
ISO/ASTM FDIS 52903-1 Additive manufacturing—material extrusion-based additive manufacturing of plastic materials—part 1: feedstock materials	50.20	25.030
ISO/ASTM 52904:2019 Additive manufacturing—process characteristics and performance—practice for metal powder bed fusion process to meet critical applications	60.60	25.030
ISO/ASTM DTR 52905 Additive manufacturing—general principles—non-destructive testing of additive manufactured products	30.99	25.030
ISO/ASTM CD TR 52906 Additive manufacturing—non-destructive testing and evaluation—standard guideline for intentionally seeding flaws in parts	30.00	25.030
ISO/ASTM 52907:2019 Additive manufacturing—feedstock materials—methods to characterize metal powders	60.60	25.030
ISO/ASTM AWI 52908 Additive manufacturing—post-processing methods—standard specification for quality assurance and post processing of powder bed fusion metallic parts	20.00	
ISO/ASTM AWI 52,909 Additive manufacturing—finished part properties—orientation and location dependence of mechanical properties for metal powder bed fusion	20.00	
ISO/ASTM 52910:2018 Additive manufacturing—design—requirements, guidelines and recommendations	60.60	25.030
ISO/ASTM 52911–1:2019 Additive manufacturing—design—part 1: laser-based powder bed fusion of metals	60.60	25.030
ISO/ASTM 52911–2:2019 Additive manufacturing—design—part 2: laser-based powder bed fusion of polymers	60.60	25.030
ISO/ASTM CD TR 52912 Additive manufacturing—design—functionally graded additive manufacturing	30.99	25.030
ISO/ASTM 52915:2016 Specification for additive manufacturing file format (AMF) Version 1.2	90.92	25.030 35.240.50
ISO/ASTM FDIS 52915 Specification for AMF Version 1.2	50.20	25.030 35.240.50
ISO/ASTM WD 52916 Additive manufacturing—data formats—standard specification for optimized medical image data	20.20	
ISO/ASTM WD 52917 Additive manufacturing—round robin testing—guidance for conducting round robin studies	20.00	

Table 14 (continued)

Standard and/or project under the direct responsibility of ISO/TC 261 secretariat (total 37)	Stage	ICS
ISO/ASTM CD TR 52918 Additive manufacturing—data formats—file format support, ecosystem and evolutions	30.00	25.030 35.240.50
ISO/ASTM WD 52919-1 Additive manufacturing—test method of sand mold for metalcasting—part 1: mechanical properties	20.00	
ISO/ASTM WD 52919-2 Additive manufacturing—test method of sand mold for metalcasting—part 2: physical properties	20.00	
ISO/ASTM 52921:2013 Standard terminology for additive manufacturing—coordinate systems and test methodologies	90.92	25.030
ISO/ASTM DIS 52921 Additive manufacturing—general principles—standard practice for part positioning, coordinates and orientation	40.60	25.030
ISO/ASTM DIS 52924 Additive manufacturing—qualification principles—classification of part properties for additive manufacturing of polymer parts	40.00	25.030
ISO/ASTM DIS 52925 Additive manufacturing processes—laser sintering of polymer parts/laser-based powder bed fusion of polymer parts—qualification of materials	40.00	25.030
ISO/ASTM AWI 52931 Additive manufacturing—environmental health and safety—standard guideline for use of metallic materials	20.00	
ISO/ASTM WD 52932 Additive manufacturing—environmental health and safety—standard test method for determination of particle emission rates from desktop 3D printers using material extrusion	20.20	
ISO/ASTM DIS 52941 Additive manufacturing—system performance and reliability—standard test method for acceptance of powder-bed fusion machines for metallic materials for aerospace application	40.60	25.030
ISO/ASTM DIS 52942 Additive manufacturing—qualification principles—qualifying machine operators of laser metal powder bed fusion machines and equipment used in aerospace applications	40.60	25.030 03.100.30
ISO/ASTM DIS 52950 Additive manufacturing—general principles—overview of data processing	40.60	25.030

metal powder and mixed powder is described in ASTM B21. The process allows a volume of powder to flow through the flowmeter into a container with the measured volume of ~ 25 ± 0.03 cm^3, under controlled conditions. The powder should be slightly overflown to cover the entire container's volume; the excess is leveled off using a nonmagnetic spatula. The filled container is then transferred to the balance, gently taped to the side of the container to prevent spilling in transfer, and weighed to determine the mass of the powder, which is calculated by subtracting the mass of the filled container by that of the empty container; then the apparent density is the measured mass divided by the volume.

3.8.2.2 Carney funnel A Carney funnel is used to measure the apparent density of non-free-flowing metal powders described in Test Methods ASTM B417-13 [129, 133–136]; on the other hand, a Hall funnel is used to measure free-flowing metal powders. This suggests that for the metal powders that cannot freely flow through the Hall funnel, these powders should be tested using the larger diameter Carney funnel. The testing procedures to measure apparent density are also similar for both funnels.

3.8.2.3 Scott volumeter A Scott volumeter is used to determine the apparent density of free-flowing metal powders and compounds referred to in ASTM B329-06 [137]. The dry and lump-free metal powder is poured into the powder funnel on top of the mesh sieve and rubbed through the mesh using a non-metallic spatula. The powder travels through the funnels, then through a series of glass baffles to finally reach the density cup or receiving cup. After allowing the powder to be slightly filled, the receiving cup is carefully levelled with a spatula without compression to ensure that the powder loosely fills the entire volume of the cup. The filled container is then transferred to the balance and weighed to determine the mass of the powder, which is calculated by subtracting the mass of the filled container by the mass of the empty container; then the apparent density is the measured mass divided by the volume.

3.8.2.4 Arnold meter The apparent density of metal powder can also be measured using an Arnold meter as described in ASTM B703-10 [137]. To measure the apparent density, a sheet of pre-weighed weighing paper is laid underneath the steel block, and the powder delivery cylinder is filled with 50 cm^3 of test sample metal powder and placed on either side of the steel block. Downward pressure is applied to the delivery cylinder, which is slowly and smoothly slid with rotation across and backward to the cavity hole in the center. This process causes the powder to fall into the cavity. After the cavity is filled with the test metal powder, the steel block is lifted to allow the powder to fall onto the pre-weighed weighing paper. The pre-weighed paper is transferred to the balance to determine the mass of the powder collected in the 20 cm^3 cavity to the nearest 0.01 g. The apparent density is the measured powder mass divided by the cavity volume.

3.8.3 Tap density

Tap density is defined as the density of powder when the loose powder is tapped or vibrated under specified and controlled conditions. By applying an external condition such as tapping or vibrating the loose powder, the externalities introduce movement between powder particles, which increases powder packing and powder density. Therefore, tap density is always greater than the apparent density. The tap density also depends on the particle's shape, size distribution, the degree of powder-packing in a container and the apparent density of the powder [138].

Tap density can be measured using a tapping apparatus, consisting of a balance, an apparatus capable of tapping the graduated cylinder at a rate of 100 to 250 impacts per minute. The testing procedure starts by pouring powder into a graduated cylinder, where the mass of the metal powder is pre-measured. Vibration or tapping is generated using the mechanical apparatus. The final volume of the powder is measured when no more decrease in volume is observed. The tap density is calculated by dividing pre-measured mass of the powder by its final volume [139].

3.8.4 Powder particle density

Particle density or true density of a metal powder is the sum of the mass of the elements that make up the metal particles divided by its occupied volume, in contrast to bulk density or apparent density, which measures the density of powder by dividing the mass of the loose metal powder by the volume of the container including the medium or spaces between particles [138].

Helium pycnometry is used to measure the density of solid backbone of metal powders with an assumption that all the pores are accessible by helium gas. In addition, the metal powder particles are assumed to be fully dense, which means that particles have no internal porosity. The principle of this technique is to measure the actual occupied volume of all the metal powder; the mass of the metal powder is pre-measured prior to placing into a pycnometry container of known volume. In the helium pycnometer, by measuring the pressure and temperature of the helium inside the container, using the Ideal Gas Law, the mass of helium occupied the space surrounding the metal particles can be precisely measured. The pycnometer performs two tests, one with an empty container, and one with a filled container and measures the volume of helium with the difference in volume between the two tests and the volume of the metal powder. With the volume and mass of the metal powder, the density of it can be calculated by dividing mass by volume [129, 140].

3.8.5 Particle size distribution

Powder particle size in AM dictates the minimum layer thickness or the resolution of a buildable feature on a part. Particle size distribution determines the apparent and tap density of the powder; a powder with a wide range of size distribution typically has higher density due to the variety of particle size, where the gap between large particles is filled with smaller ones, increasing overall powder density. Test methods for particle size distribution are described in several ASTM standards, in which scanning electron microscopy and light scattering technique are the two examples [129, 141].

Laser diffraction measures particle size distributions by measuring the angular distribution in the intensity of scattered light produced by a laser beam that passes through a dilute dispersed particulate sample [142] Mie scattering is the complex electromagnetic theory that describes the scattering of light by spherical particles; it is usually applied to particles with diameters that are close to the wavelength of the incident light, and the real and imaginary indices of light refraction of the particles are needed [143]. To perform the laser diffraction method, the particles are required to be dispersed in a suspending medium, in liquid (suspension) or air (aerosol). Laser diffraction method is applied to many different types of powder; ASTM B822-10 [135] provides a standard test for light scattering method for metal powders; the standard is applicable for measurement of particulate materials in the range of 0.4–2000 μm. The laser diffraction method is operated with an assumption that the metal particles are spherical, and particles are properly dispersed. Since particles in metal powder are reasonably spherical, the laser diffraction method is reliable.

3.8.6 Particle rheometer

The powder rheometer is an instrument that measures the powder flow properties and powder behavior [144, 145]. The powder rheometer measures the resistance of the powder to flow while the powder is in motion. A blade is rotated and moved downwards through the powder to establish a precise flow pattern that causes many thousands of particles to interact, or flow relative to one another, and the resistance experienced by the blade represents the difficulty of this relative particle movement or the bulk flow properties. The reproducibility and sensitivity can be achieved by moving the blade in a precise and reliable way. The advanced control systems of the instrument can accurately set the rotational and vertical speeds of the blade, which defines the Helix Angle and Tip Speed. This method is effectively utilized for AM processes to predict a powder behavior during build jobs, ensuring high quality and reduced cost by quality control of the recycling steps.

3.8.7 Particle morphology

Main characteristics of powders are the particle size (granulometry) and particle shape (morphology). Technological properties of powders (bulk density, flow ability, surface area, etc.) as well as the potential areas of their application, depend on these characteristics.

The morphology of a powder particle is characterized by description (spherical, angular, dendritic, dish-shaped, circular) or quasi-quantitatively, for example, by means of geometrical shape parameters. The shape parameter characterizes mainly the shape, without considering the size. Qualitative descriptions of particle visual appearance, such as rounded, semi-angular, or angular, have been used to classify and differentiate between various groups of abrasive particles. Several attempts have been made to characterize particle shape using various numerical descriptions [136]. The morphology of metal particles plays a role in that angular particles tend to interlock and also dig into a wall surface, creating more friction [138].

3.8.7.1 Scanning electron microscopy Scanning electron microscopy (SEM) instruments require computers to display the digital images that are taken from the surface of interest [146]. SEMs may be useful for viewing topography, morphology, and orientation of grains, and may be able to give information about crystallography. Add-ons may equip SEMs to perform chemical analysis of the sample near the surface. Multiple detectors are used to catch the various types of electrons that are ejected from the sample because of the impinging primary electron beam from the SEM. These include backscattered electrons, secondary electrons, and Auger electrons in addition to X-ray and cathodoluminescence radiation. The impinging electron beam is scattered in the sample both elastically, and inelastically giving rise to the various signals that can be detected in the pear-shaped interaction volume. The intensity of these signals is related to the atomic number of the elements impinged upon. Brighter images correspond to larger atomic number and may give useful information about the distribution of elements on the surface only.

For proper imaging, samples must be electrically conductive and small enough to fit within the specimen chamber. For most samples, electrical conductivity is provided by either low-vacuum sputter coating or high-vacuum evaporation coating of conductive materials such as gold, tungsten, platinum and graphite. Coating the sample can help reduce buildup of charge on the sample that may interfere with signal retrieval and prevent good imaging [147].

3.8.7.2 X-ray computed tomography The X-ray computed tomography (CT) method gives the user the capability to visualize the inside of an object without performing an invasive procedure. CT scan results are acquired from the combination of computer-process technologies and X-ray measurements taken from a sample at hundreds of different angles. The contrast between different materials, such as the contrast between air and human tissue or the contrast between air and metal, comes from the variation in X-ray absorbability of different types of material. Metal can absorb more X-ray compared to air, and appears whiter in comparison in the X-ray image. Many cross-sectional images are combined using mathematical algorithms to reconstruct the interior and a 3D image of the sample. Metal particles have a variety of shapes; spheres and ellipsoids shapes are straightforward, but for realistic, irregular shapes, different mathematical algorithms are required to analyze random particles. These random particles are called “Star-shaped”. A special analysis procedure utilizing X-ray CT and spherical harmonics are used to calculate analytical, differentiable mathematical functions for the 3D shape of star-shaped particles [148, 149]. Spherical harmonics series and special software packages are available that could analyze several characteristics of the particle including volume, surface area, integrated mean curvature, length, width and thickness [129, 150, 151].

3.8.8 Particle crystalline phases

X-ray diffraction (XRD) analysis is one of the most common techniques in the study of materials science. XRD may be used to identify single and multi-phase materials including minerals, chemical compounds and engineered materials as well as the crystal structure of identified materials. XRD can determine the amounts of different phases of multi-phase materials and crystallite size and shape. XRD analysis is represented by peaks that correspond to the diffraction of the impinging X-rays by atoms of the specimen [129].

The X-rays interact with the sample atoms in constructive or destructive interference. Inter-atomic d-spacing/lattice spacing between planes of atoms and the wave behavior of the X-rays are taken into account in Bragg’s Law to analyze the peaks in XRD analysis [152, 153].

3.8.9 Particle element composition

Element composition is an important characteristic of a metal powder. It suggests the type and percentage of impurity, which are the factors that determine particles' properties such as hardness, impurities and melting point. Impurity encompasses not only the mechanical properties of powders but also their chemical properties, such as magnetic and electrical. The inconsistency in impurity causes a decisive effect on sintering, which is the technique used in AM processes. Thus, to have confidence in repeatedly producing AM parts, a standard technique of chemical analysis should be applied to ensure the consistent chemical properties of the metal powder [154].

3.8.9.1 Energy dispersive elemental analysis Energy dispersive elemental analysis (EDEA) is an analytical technique used for the elemental analysis or chemical characterization of a sample. EDEA is based on the idea that each element has a unique atomic structure. When a sample surface is exposed to a beam of high-energy electrons, the interaction may excite an electron from an inner shell of an atom in the specimen to be ejected/knocked off, thereby creating an electron hole/empty site for an electron. An electron from the outer, higher-energy shell of the atom fills the hole and releases the energy difference between these two shells in the form of an X-ray photon. Different elements have unique energy levels; therefore, different type of signals are emitted from the elemental composition of targeted area. They have different characteristics. Secondary electron beams, where low energy electrons scattered when hitting the surfaces, are detected from the sample to form a high-resolution image. Aside from the secondary beam, the energy-dispersive emission spectrum also measures the number and energy of the X-rays emitted from a specimen. As discussed above, the energies of the X-rays are characteristic of the atomic structure of the emitting element. Due to the fundamental principle that each element has a unique atomic structure allowing a unique set of peaks on its electromagnetic emission spectrum, different elements composed in the specimen can be characterized [152, 155].

3.8.9.2 X-ray photoelectron spectroscopy X-ray photoelectron spectroscopy (XPS) is used to analyze the surface or the outermost layers to provide information about element composition, empirical formula, electronic state and chemical state of the building elements of the material [153, 156]. XPS is used to determine the composition of elements in a different types of metal powder for AM.

XPS follows the Einstein's photoelectric law, which states that the maximum kinetic energy of the ejected photoelectrons KE = PE – BE, where PE is the energy of the impinging X-ray photons, and BE is the binding energy of the ejected photoelectrons to the atom. From this equation, given PE and measurement of KE, BE can be calculated. Since ionization may occur in any shell for an atom, the spectrum for that element is unique and composed of a series of peaks corresponding to electron emission from the different shells. Therefore, elements with higher atomic numbers have peaks reflecting the spin–orbit energy separations. Many of these transitions are characteristic of the element in an oxidation state, which is of particular interest for powder surfaces that have been exposed to oxygen in the environment, nitrogen, and other gases at high temperature during the additive manufacturing process [129].

3.9 Recommendations

Table 15 lists all AM processes and suggests suitable inspections methods for various AM processes. It also reflects the rationale behind the measurements and inspection methods recommended in Table 12. As AM continues to advance, the only way to ensure that these new technologies fit as reliable pieces of the industrial toolset, as well as the warfighter arsenal is to prioritize the development of the process-specific standardized metrology and inspection methods for the parts made by AM. The following sections discuss how U.S. Navy is playing an important role in addressing these AM metrology challenges.

4 Navy metrology and calibration (METCAL) program

Metrology matters to the U.S. government because of its effects on American industry. In 1988, the U.S. Congress passed the Omnibus Trade and Competitiveness Act of 1988 as "a bill to enhance the competitiveness of American industry, and for other purposes" [157]. Part of the bill included changing the name of the National Bureau of Standards (NBS) to the National Institute of Standards and Technology (NIST). The bill states that by functioning as the lead national metrology laboratory, NIST will support U.S. commerce, technological progress, improved product reliability, manufacturing processes and public safety [158].

The mission of the U.S. Navy is to maintain, train and equip combat-ready naval forces capable of winning wars, deterring aggression and maintaining freedom of the seas [159]. To accomplish that mission, Naval forces include over 289 ships and submarines, over 3700 operational aircraft, and over 300,000 active-duty personnel. Keeping these forces operational requires approximately 1.65 million pieces of test equipment. The Navy requires that test equipment used on Navy systems be calibrated to ensure that they can accurately assess system measurement parameters during research, test, maintenance, repair, or operation [160].

Table 15 Suitable inspection methods for AM processes

Categories	Technologies	Materials	Power source	Suitable inspection methods
Material extrusion	Fused deposition modeling (FDM)	Thermoplastics, ceramic slurries, metal pastes	Thermal energy	Thermography Near infrared camera
	Contour crafting			
Powder bed fusion	Selective laser sintering (SLS)	Polyamides/polymer	High-power laser beam	Thermocouple High-speed CMOS-camera
	Direct metal laser sintering (DMLS)			
	Selective laser melting (SLM)			
	Electron beam melting (EBM)		Electron beam	
Vat photo-polymerization	Stereo-lithography (SLA)	Atomized metal powder (17-4 PH stainless steel, cobalt chromium, titanium Ti-6Al-4V), ceramic powder	Ultraviolet laser	High speed CCD Camera
Material jetting	Polyjet/inkjet printing	Photopolymer, ceramics (alumina, zirconia, PZT)	Thermal energy/photo-curing	Thermography
Binder jetting	Indirect inkjet printing (binder 3DP)	Photopolymer, wax	Thermal energy	Thermography High speed CCD camera
Sheet lamination	Laminated object manufacturing (LOM)	Plastic film, metallic sheet, ceramic tape	Laser beam	Pyrometer
Directed energy deposition	Laser engineered net shaping (LENS) Electron beam welding (EBW)	Molten metal powder	Laser beam	High-speed CCD cameras Pyrometer Inline coherent imaging

Measurement traceability is defined as the process by which the assigned value of a measurement is compared directly or indirectly through an unbroken chain of calibrations to the value assigned to the U.S. national standard or to natural physical constants [160]. These U.S. national standards are maintained at NIST and serve to transfer measurement traceability from the International System of Units (SI) to the United States.

The Navy has established a hierarchy of calibration laboratories across the naval enterprise. Lower level labs generally calibrate low accuracy, high volume equipment (pressure gages, temperature devices, torque wrenches, etc.). Higher level labs are staffed with experienced calibration artisans and are responsible for the calibration of reference standards for the lower level laboratories as well as more complicated and more accurate test equipment used in Navy applications. The highest echelon standards laboratory for the Department of the Navy (DoN) is the Navy Primary Standards Lab (NPSL) located in San Diego, California. NPSL maintains the Navy's highest-level measurement standards and provides calibration services for reference standards from Navy and United States Marine Corps calibration laboratories [161]. The DoN measurement traceability hierarchy is depicted in Fig. 4.

In the 1950s, the Navy was experiencing costly missile system failures due to inconsistencies in measurements between the manufacturing community and the Navy. This led to the development of the Metrology and Calibration (METCAL) Program. The METCAL Program is designed to ensure the readiness of test equipment and systems, provide valid test data, limit the number of erroneous test decisions resulting in false acceptances or rejections of prime systems and other equipment being tested, and maintain overall measurement integrity and traceability. Implementation of the program was assigned to Naval Ordnance Laboratory, Corona (NOLC), which is now the Measurement Science and Engineering Department at the Naval Surface Warfare Center, Corona Division (NSWC Corona) in Norco, CA [160].

4.1 Interface assessment

In specific relation to dimensional metrology, the improper interface definition of dimensional requirements was determined to be a primary cause of high failure rates and limited capability for early guided missiles. Different manufacturers used different definitions and standards of length in their facility. Consequently, due to the

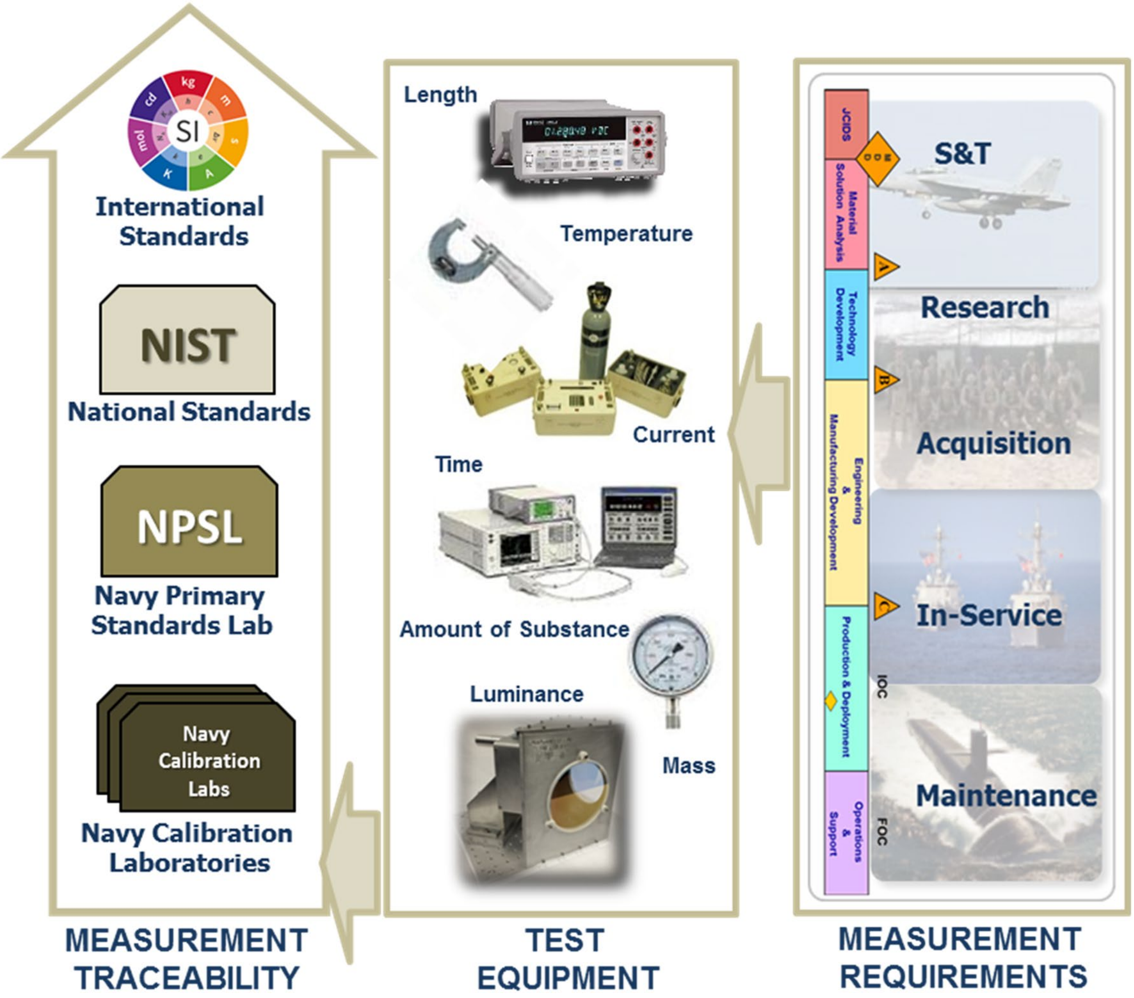


Figure 4 Navy's measurement traceability hierarchy

variation in standard dimensions used for manufacturing, imprecise part fitting was often found when assembling components from multiple sources. To address this issue, NAVSEAINST 4855.10B recommends the establishment of a Navy Special Interface Gage Program when parts are produced by multiple sources, acquired via numerous contracts or assembled away from production site, and when important interfaces require special inspection equipment to verify dimensions or envelopes of components. For these reasons, the interface assessment (IA) process was created to serve the following purposes.

- Assure weapons systems designs have proper interface definition, requirements, specifications to assure interchangeability and proper function of design
- At time of production, assure that components conform to design parameters to ensure systems will reliably function as intended
- Validate contractor verification methods
- When appropriate, provide Government verification methods (Navy Special Interface Gages)

The IA process should be an integral component of dimensional verification for AM applications in the same way as it is for traditional manufacturing applications.

4.2 NSWC Corona's role and responsibilities

The Chief of Naval Operations has assigned NSWC Corona as the Scientific and Technical (S&T) Advisor for the Navy METCAL program. NSWC Corona's role is to ensure that the Navy's calibration requirements are identified and that measurement capability and calibration standards are properly planned, implemented, and supported. NSWC Corona provides centralized direction and coordination to advance the state-of-the-art in metrology and calibration, validates measurement requirements for Navy systems, determines whether calibration capability (calibration laboratories,

Table 16 Summary of NSWC Corona AM efforts

Project title	Problem statement	The proposed solution	Description of the experiment(s) and analysis
Predictive analytical modeling of metal AM builds	The metal Additive Manufacturing process is known to develop dimensionally accurate parts, however many parameters during the build process can cause failures and geometric distortion	Investigate the capabilities of build simulation software packages to test the geometric tolerance conformance of metal AM parts. Develop standardized test to understand limitations of the software	Collaborate with warfare centers currently using build simulation software and develop the geometric test parameters toward developing standardized test specimens. Work with national standards groups and develop DoD standards on build simulation process. Conduct test builds and measure builds at Corona and report findings
Non-destructive testing (NDT) for AM	Additive manufacturing currently produces parts with high variability. This is likely due to insufficient metrology and control. Naval applications require the final products to be high quality and accurate. Metallic products properties are determined by their internal features which cannot be analyzed using traditional measurement techniques	Research non-destructive testing (NDT) techniques to determine the paramount method for assessing the internal composition of 3D printed metallic parts. Develop metrics to determine accuracies of these techniques	Research NDTs such as computed tomography (CT), ultrasound, X-rays and flash thermography. Collaborate with universities and warfare centers that are currently using NDT to evaluate 3D printed parts. Document and analyze the different techniques to determine most applicable ones for the Navy
MET-D 3D printing	MET-D drawings are designs utilized to build fixtures used in calibration of Navy equipment. Fabrication depends on finding in-house or commercial vendors to build in small quantities for per unit high cost and delays in procurement	Fabrication of equipment based on MET-D drawing designs could be cost-effectively built in a timely manner whenever and wherever a 3D printer is available	An analysis of current MET-D drawings would find several likely candidates. Then experimental units would be built via a 3D printer, and they would be compared to existing units
In-situ Monitoring of metal AM: laser power	Multi-kilowatt lasers are used for creating melt pools in metal additive manufacturing, as well as for achieving reproducible quality laser joining in laser-welding industries. Material response in such complex laser materials processing depends on energy coupling mechanisms which is a function of laser power above the melting point. Accurate, traceable in-situ laser power metrology does not exist in metal AM machines	Use a newly developed portable high accuracy radiation pressure power meter (RPPM) and test it on board a metal AM machine. RPPM is the world's latest primary standard (< 50 kW) for CW laser power measurements, developed by NIST with Navy metrology R&D funding and partnership with NSWC Corona	Partner with NIST for installation of RPPM on a metal AM machine; determine the laser in-situ monitoring test and calibration procedures for RPPM; conduct tests/builds to print existing metal AM standards to verify geometric and material conformance; initiate modeling and simulation (M&S) of the process
Feasibility of "3D Printing" a 3D Printer	3D printing has been used by DoD to build prototypes for some time now. The 3D print technologies have evolved more rapidly and make it possible to create nearly any form with the help of design software. However, industrial 3D printers are not economical and can be expensive over time when one component fails and cannot be easily replaced while deployed	Small 3D printers can be built on ships using commercial-off-of-the-shelf (COTS) materials to produce as-needed simple geometries, such as nuts, bolts, supporting structures for electronic boards and devices, etc. Using this capability, the 3D printer can also replicate itself, or "3D printer prints your 3D printer." Like a personal computer, the 3D printer will be upgradable and fully supported in-house	Determining components and providing solutions to current 3D printer challenges faced towards printing parts that can be assembled to develop basic 3D printers

Table 16 (continued)

Project title	Problem statement	The proposed solution	Description of the experiment(s) and analysis
Development of internal geometric standards for AM	Geometric Dimensioning and Tolerancing (GD&T) variations are difficult to predict for complex internal geometries within the parts produced using Additive Manufacturing processes. The computerized tomography (CT) scanners used to inspect AM parts have known limitations, for example, in the choice of part materials and scanning power techniques. Internal geometric standards should be developed to address both GD&T and CT limitations	Investigate the limitations of CT scanning in measuring internal and external geometries. Develop standards to test the measurement viability for AM parts	Collaborate with warfare centers that currently use CT scanning. Document and analyze the process to determine the gaps within the technology from a measurement perspective. Determine artifacts that would best challenge the CT scanning process and compare the measurement accuracies with existing measurement processes
AM metallic standards' vertical part variation	Consensus among warfare centers is that the high cost of metallic powder used for metal AM renders the current artifacts and methodologies designed for polymer builds too expensive to evaluate AM metal machines. New artifacts that optimize the metal build chamber must be designed to analyze the capability of metallic AM machines to produce accurate parts across warfare centers	Develop artifacts built specifically for metallic AM machines which consider the support structures in vertical orientation, to begin with. Artifact maturation will occur through iterative design, printing and evaluation of artifacts printed on AM machines across the warfare centers. The final artifact design will become the standards, which will be used to evaluate AM metal machines	Development of the standards will be conducted by interfacing with multiple warfare centers utilizing metal AM and with NIST. Designs will be validated by having multiple warfare centers and Industry print the artifacts. These artifacts will then be measured at the in-house laboratory and conclusions on the ability of the standards to evaluate metal AM machines will be made
AM of multi-materials with E&M	The Navy focus on payload optimization including light weighting weapons, shelters, communications equipment etc. requires integrated solutions involving multi-materials. Additive manufacturing of multi-materials is currently expensive and poorly understood	Use electricity and magnetism (E&M) to place nano-particles or another lightweight AM feedstock with nanometer accuracy. Multiple feedstock types (insulators, conductors, semi-conductors) will be placed with this AM method and bonded into multi-material end products	This is a feasibility study. Calculate charge/velocity required on particle of given mass to be placed with Mass Spectrometer type E&M fields. Estimate accuracy of particle placement. Calculate discharge time once particle has been deposited. Determine heating time to raise particle to bonding temperature and timeframe for placement after heating. Determine which amorphous materials could be compatibly co-printed
Additive manufacturing GD&T Optimization	Some parts made by additive manufacturing do not meet the GD&T requirements for Naval applications	Determine the difference between the file sent to a printer and the part produced. Generate a correction function using a mathematical method called convolution to modify the original file so the new part produced matches the desired dimensions. Print the modified file and compare the updated printed part to the original desired dimensions	Compare coordinate measurement machine (CMM) measurements to Computer-aided design (CAD) file of parts. Generate correction function. Correct CAD file to account for printer error. Print new part with updated CAD file. Measure new part with CMM and see if it matches desired dimensions

Table 16 (continued)

Project title	Problem statement	The proposed solution	Description of the experiment(s) and analysis
Additive manufacturing powder control	Metal parts made by additive manufacturing are not as strong as conventionally prepared parts	COTS metallic powders have irregular non-spherical shapes. Feedstock powders which are more spherical will result in fewer geometric imperfections in printed parts, yielding stronger parts. By heating the COTS powder under an inert atmosphere, the particles will become more spherical	Treat stainless steel, aluminum, tool steel and other powders by heating them to their melting point in an inert atmosphere. Steps will be taken to prevent agglomeration of the heated powder, by dropping them through a heated tube. The powder will melt, and surface tension will cause the powder to become spherical as it falls. Characterize particle shape of both treated and COTS feedstock powders

equipment, procedures, etc.) exists to support the requirements, and provides in-service and life-cycle management support for Navy organic measurement and calibration capability to ensure that the Navy METCAL community keeps up with continuous advancements in weapons, test equipment technology, and evolving measurement requirements. NSWC Corona have been constantly working on several mission critical projects in support of the Navy METCAL program. Several publications [162–165] were specifically targeted on this topic. Table 16 summarized some of these efforts related to AM. Recently, utilizing the Naval Engineering Education Consortium (NEEC) program of the Naval Sea Systems Command (NAVSEA), NSWC Corona successfuly funded and collaborated with the University of California, Los Angeles (UCLA) on a research project towards enhancing the precision of 3D printing via in-situ metrology. A high-speed optical scanning system was integrated with a FDM type 3D printer to demonstrate an approach for layer-by-layer mapping of 3D printed parts, which can be used for validation of printed models and in-situ adjustment of print parameters [166]. Looking beyond the immediate future, U.S. Navy AM has the potential to print ammunition, guided weapons, specialized vehicles and even electronics [167, 168]. The possibilities and benefits increase nearly every day.

5 Conclusion

A comprehensive review of generic metrology and in-situ real-time inspection methods used in conventional manufacturing processes is presented in this review article. A detailed review of metrology and in-situ real-time inspection methods is presented in view of employing the discussed methods for the parts produced from AM processes. In this article, recommendations of the appropriate metrology and inspection methods are made for AM processes.

AM technologies demonstrate huge promise and may revolutionize design, manufacturing, logistics, maintenance and acquisition in real-world scenarios. However, there are still multiple hurdles to overcome before AM becomes an effective component in the industry toolset. As AM continues to advance, the only way to ensure that these new technologies fit as reliable manufacturing capabilities is to prioritize the development of corresponding measurement techniques and calibration schedules. In collaboration with industry and academia, the U.S. Navy is one of the leading agencies that is currently working on multiple 3D printing projects to improve upon the abilities to support and calibrate this growing technology.

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