8

Machine Performance Evaluation

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CONTENTS

8.1 Introduction

This chapter focuses on evaluating the performance of metal additive manufacturing (AM) machines. Given the focus of this book on the production of precision AM parts and the introduction of precision engineering principles to AM, much of the attention in this chapter will be paid to quantifying the ability of AM machines to repeatably and predictably produce parts with the desired geometry. Characterising a machine to achieve other outcomes, for example to produce parts with a desired microstructure or mechanical properties, will also be discussed, and this distinction will be noted where appropriate. Many of the concepts of machine performance evaluation are consistent despite the desired outcome, but certain priorities and requirements may be different for varied applications.

Discussion in this chapter is limited to machines used to directly produce metallic AM parts. This essentially limits the discussion to powder bed fusion (PBF) machines and directed energy deposition (DED) machines. Some binder jetting machines are capable of producing metal parts, but these are often with a multi-step process, including production of a green part with AM technology and post-process heat treatment for consolidation (or sintering) or infiltration of the part with other materials to create a fully dense part (Gokuldoss et al. 2017). Regardless, the similarities between binder jetting machines and PBF machines mean that many of the same concepts apply. Some sheet lamination systems are also capable of producing metal parts, but parts from these machines are usually machined in a post-process step to achieve the desired geometry. Again, similarities in the machine design between these systems and DED systems mean that many of the same concepts still apply. Hybrid machines – where traditional processes, such as machining, and additive processes are found on the same platform – are outside the scope of the chapter, but once again, some general principles will still apply. Machines built upon a machining centre or turning centre frame and using DED processes will likely be characterised in a similar manner to a traditional machine tool (ISO 230 series, ASME B5.54, ASME B5.57). Machines that are built upon a PBF frame will likely benefit from many of the methods outlined in this chapter.

The test methods detailed in this chapter will be mostly applicable to users of AM systems. Some of the methods may require a level of control over the machine that is not typically available to a user, and these methods may be more appropriate for machine builders. Such methods are discussed nonetheless because there may come a time in the near future when various aspects of the machines become more available to users.

8.1.1 Definitions

Part geometry – As covered in detail in Chapter 10, surface topography is essentially everything that makes up the geometry of an object's surface. In addition to the surface topography, a part's shape is determined by its geometric dimensions. The dimensions, surface form and surface texture combine to describe the *part geometry*. Most of the discussion in this chapter will focus on realising accurate dimensions and achieving desired form, with only cursory discussion on measuring a machine's ability to create a particular surface texture.

Machine coordinate system – The coordinate systems for AM machines, that is, the definitions of the *X*-axis, *Y*-axis, *Z*-axis and origin, are governed by ISO/ASTM 52921 (2013). This definition is also consistent with ISO 841 (2001). The discussion of axes and coordinate systems in this chapter will generally follow the conventions detailed in these specification standards. In general, the machine coordinate system is a right-hand rectangular system with three principal axes labelled as *X*, *Y* and *Z*, with rotary axes about each of these labelled *A*, *B* and *C*, respectively. However, it should be noted that axes in machines are normally defined either by a specific motion direction or associated with a physical artefact (for example, the axis of a cylinder) (see, for example, ISO 230-1 2012). ISO/ASTM 52921 (2013) does not follow this convention, defining the *Z*-axis as perpendicular to the layers and the *X*-axis as perpendicular to the *Z*-axis and parallel to the front of the machine. These definitions make the machine axes and the machine coordinate system very difficult to physically realise, which can present ambiguities. Many PBF machines that use a linear motion actuator in the recoating system refer to the direction of the motion as along the *X*-axis. However, by the definition in ISO/ASTM 52921, the *Z*-axis is perpendicular to the layers and the *X*-axis is perpendicular to the Z-axis and parallel to the front of the machine. The recoating axis is independent of these and, therefore, will be referred to as the recoating axis, or *R*-axis, in this chapter.

Functional point – Most often, the functional point in a machine is the point where the workpiece or part is being formed (see, for example, ISO 230-1 2012). For example, in a PBF machine, the functional point is where the energy beam meets the top surface of the powder bed. The functional point is a single point that can move within the machine's working volume. The methods of moving the functional point are different for PBF and DED processes. For example, the movement of DED machines is generally accomplished by motors driving linear axes, whereas movement in a PBF machine is accomplished by electromagnetic scanning or galvanometer systems.

Machine error motions – Each linear axis of a machine has six error motions (ISO 230-1), i.e. unwanted linear and angular motions of a commanded move along a nominally straight line (see Leach and Smith 2018 for a detailed general discussion on error motions). Linear positioning error motion is the unwanted motion in the direction of motion of the axis. Straightness error motions are the unwanted motions in the two directions orthogonal to the direction of travel. For example, if the direction of travel is along the *X*-axis, there will be straightness errors in the *Y*-direction and the *Z*-direction. Finally, there are three angular error motions: the unwanted rotations around each axis of the coordinate system. These rotation errors are commonly referred to as *roll* (around the axis of motion), *pitch* (around the horizontal orthogonal axis) and *yaw* (around the vertical orthogonal axis). Simple nomenclature can denote errors in any primary axis with an *E* (for error) followed by a subscript letter for the direction of the error motion, followed by a subscript letter for the axis of interest. For example, a rotation error about the *Y*-direction of the *Z*-axis is denoted as E_{BZ}.

System, machine and process – The convention in this chapter is to refer to the AM 'system' as the combination of the AM machine and the AM process. The AM machine is the actual equipment and components, including control software, used to build the AM part. The AM process is the physics of melting and re-solidifying metal to form the AM part. This chapter will focus primarily on the machine. This is an important distinction, because phenomena such as residual stresses have a major impact on part geometry and mechanical properties but are considered outside the scope of this chapter since they are the results of the process more than the machine (see Chapter 3).

Artefact – an artefact is a physical reference part or object that is measured for the purpose of determining errors. A test artefact, as referred to in this chapter, is a specific part that is built by the machine of interest. The test artefact is measured to determine the errors in the artefact, which can inform a user about the performance of the machine of interest. This differs from a reference artefact, which is a part of known (or independently determinable) geometry that is measured to assess a specific aspect of a machine's performance. For example, when testing the straightness error motion of a machine's axis, the measurement may be the linear displacement of the axis relative to a reference artefact, such as a straightedge.

8.1.2 Motivation

The idea behind precision engineering for metal AM is not meant to imply that AM parts will soon have the same levels of accuracy or achieve the same levels of tolerance as precision parts, or even traditionally manufactured parts. However, the principles of precision engineering, such as error budgeting, determinism, etc. (Slocum 1992, Leach and Smith 2018), are still relevant, and their adoption by the AM community can lead to significant improvement for AM parts. For example, the principles of error budgeting for part geometry permeate this chapter, with the concept that errors contributed by the machine can be separated from errors contributed by the process, and understanding the relative contributions of each will help users concentrate on the areas where they can make the largest and/or quickest improvements. The general idea here is that AM, a relatively new technology, can benefit from, and build upon, knowledge developed over many years in other fields. AM culture might lean toward 'trial and error' or 'guess and check' approaches, because one of the advantages of the process is that changes can be made and implemented quickly, with little or no need for changes to the tooling or setup. Balancing these tendencies with the more deterministic approaches found in precision engineering should lead to better AM parts.

The need for machine performance evaluation is two-fold:

1. There is a need for quantitative criteria to judge system performance. The information gained in measuring machine performance will be vital in demonstrating conformance to specifications, standards or quality management systems. Furthermore, this information will be used extensively in communications about machine performance, whether those are between a vendor and customer or within an individual supply chain.
2. Understanding machine performance allows a user to make more informed decisions. These decisions might be anything from where in the build volume to place a part with particularly tight tolerances to when to schedule preventative maintenance or how to compensate for measured errors.

The Standardization Roadmap for Additive Manufacturing published by ANSI and America Makes (ANSI 2018) identified 'machine calibration and preventative maintenance' as a high priority, stating that there is 'an urgent need to develop guidelines on day-to-day machine calibration checks'. The Roadmap also identified a medium priority for machine qualification. Both of these areas still have required research and development needs before specification standards can be developed. However, much of what has been learned to date in these areas will be discussed in this chapter.

8.1.3 Background

Perhaps counterintuitively, AM has much in common with many traditional processes, especially machining. For example, raw material or feedstock is input into the machine and the process is performed by the system to create the part. This is true whether the material is a cast ingot or metal powder, or whether the process is milling or PBF. There is a significant divergence when examining the material or mechanical properties of additive versus traditional parts, but there is less breakdown if the examination is focused on part geometry. As such, much of the background for AM machine performance evaluation is actually the history of machine tool metrology.

Part geometry errors are the result of error motions of the machine combined with the physics of the process. For a traditional process, the process physics usually play a small role compared to the error motions of the machine, and measuring the well-known parametric and geometric errors of each machine axis goes a long way to predicting part geometry. For AM, the process physics play a relatively larger role (Cooke and Soons 2010) due to the relatively large size of the melt pool (compared to typical error motions) as well as the dynamic nature of the melt pool. As a result, attention needs to be given to separating these sources of error to allow efficient compensation or adjustment for systematic errors. For example, it is often desirable to quantify the systematic and non-systematic portions of the error so that adjustments can be made for the systematic errors and expected performance limitations can be drawn from the non-systematic errors.

Methods for machine tool performance evaluation have been standardised for some time now, and most of those standards have been through several revisions (Donmez et al. 1986, Slocum 1992, ISO 230-1 2012, ISO 230-2 2014, ASME B5.54 2005, ASME B5.57 2012). As a result, the methods have been rigorously tested and validated over the years, and consensus has led to good practice and expected results from a variety of machines and measurement processes. Much of the knowledge in machine tool metrology is well summarised in the ISO 230 series of standards (there are ten individual standards in the series) as well as in ASME B5.54 (2005) for machining centres and ASME B5.57 (2012) for turning centres. Most of the methods detailed in these standards involve individual, independent measurements of the components of a machine tool. However, ASME B5.54 (2005) and ISO 10791-7 (2014) describe test artefacts, notably the circle-diamond-square artefact, that can be used to characterise machine tool performance. It is worth mentioning here how the circle-diamond-square artefact was designed with each feature intended to highlight a well-known error motion of machine tools, similar to how the test methods for individual machine components isolate a specific type of error motion.

Within the field of AM, standards exist requiring the need for machine performance evaluation, verification and compensation (these terms are defined in Chapter 10), but the methods of performing the measurements are not detailed. SAE AMS7003 (2018) includes these requirements and adds an appendix listing the minimum measurement elements. Similarly, a NASA standard, MSFC-SPEC 3717 (2017) requires that 'calibration' and machine qualification be part of a *Qualified Metallurgical Process.* (Note that 'calibration' is used differently in the standard compared to this book. Typically, 'calibration' refers to a measurement [BIPM 2012] rather than compensation of manufacturing machines. It is used here for consistency with the standard.) Notably, both of these standards prioritise material and mechanical properties over part geometry. Furthermore, the standards do not require specific quality metrics to be met. Part of the reason for this is that different applications may have slightly different requirements, but another part of the reason is that the expected performance and limitations of the machines are constantly changing as new machines with new capabilities become available and are not fully known. To wit, the *Standardization Roadmap for Additive Manufacturing* (ANSI 2018) states that research and development are needed 'to determine how errors in machine components affect output quality so that tolerances can be developed for machine calibration'. In contrast, many of the process-specific machine tool metrology standards (for example, ISO 10791-7) list specific tolerances for machine performance.

8.1.4 Organisation of the Chapter

Although it may be appropriate for standard specifications, such as AMS7003 (2018) and MSFC-SPEC 7317 (2017), not to require certain methods to meet their requirements, instead allowing vendors to meet requirements in innovative and cost competitive ways, it is difficult for new users and for widespread adoption when the learning curve is long. The benefit of highly descriptive test methods in standards such as ISO 230-1 (2012) is that it is clear for everyone how the measurements are done and how the information is gathered, allowing for more open communication. This chapter attempts to address some of these details. Included in the discussion will be what needs to be measured and often multiple methods for measuring it. Composite measurement methods, such as when using test artefacts (see Section 8.2), are discussed in detail with some good practice for users designing their own artefacts. Component methods are evaluated (see Section 8.3), often with comparisons to machine tool metrology, with suggestions on what changes might be appropriate when adapting the methods for AM machines. A middle ground, using a two-dimensional (2D) artefact (see Section 8.4) as a test that isolates beam scanning but is a composite for the entire scanning system, is also discussed in detail. Finally, gaps in the knowledge base and potential areas for research are discussed (see Section 8.5).

8.2 Three-Dimensional Test Artefacts

Manufacturing and measuring a three-dimensional (3D) test artefact results in a composite test of machine performance. This means that most, if not all, of the errors in the system combine to create errors in the test artefact. The major advantage of this approach is that building a test artefact is directly aligned with the intended purpose of the machine – to make parts. It may be tempting for users to build and test a functional part that is typical of their application, or even the actual part itself, then measure that part as a sort of test artefact. This might be acceptable if the user expects to only make this one part with their machine. However, a standardised test artefact that is optimised to the intent of evaluating machine performance is usually a superior approach. The test artefact can, and should, be designed to highlight specific expected errors in the machine or specific characteristics in actual parts that need to be achieved. Furthermore, the test artefact can be designed to accommodate the best measurement equipment available to the user, whereas actual 3D parts tend to be difficult to measure with low uncertainty. A standard test artefact can lead to easy comparisons across machine platforms or over the course of time.

8.2.1 Key Contributions to 3D Test Artefacts

Thousands of AM test artefact designs likely exist in practice. Indeed, it is common for teachers of AM courses to assign their students the task of designing a part to highlight the capabilities of an AM machine or of AM processes generally. Furthermore, machine vendors and users often have their own designs for test artefacts that highlight their machines' capabilities or allow for adjustments to machine settings or process parameters. The vast majority of these artefacts are not discussed in the literature, so little is known about their specific characteristics or the specific intents of the designs.

Many test artefacts are discussed in the literature, and review articles have captured many of the different designs (Moylan et al. 2012, Rebaioli and Fassi 2017, Toguem et al. 2018, Leach et al. 2019). A couple of these designs have been highly influential. In an early book about rapid prototyping with the stereolithography process, Richter and Jacobs (1992) laid out rules to consider when designing a test artefact for stereolithography processes. The National Institute of Standards and Technology (NIST) provides an AM test artefact geometry that is freely available by download from their website (NIST Additive Manufacturing Test Artifact) (see Figure 8.1). Moylan et al. (2014b) describe the criteria used in designing the NIST artefact and details how it was used to measure and adjust the performance of a PBF machine. Notably, these rules, and the vast majority of artefacts proposed in the literature, lead to variations on the theme of one relatively large part with many features intended to highlight different aspects of machine performance.

The recently published ISO/ASTM 52902 (2019) takes a different approach, demonstrating the evolved thinking of the practicality of a test artefact. Instead of proposing one part that attempts to fit all needs, ISO/ASTM 52902 describes several parts intended to highlight different aspects of machine performance. Many users have different requirements, and many additive machines have very different performance expectations. This approach recognises those facts and allows the user to configure the test artefacts in the build in a way that best addresses their needs (see Figure 8.2). Furthermore, rather than having one part that spans the entire build volume, ISO/ASTM 52902 (2019) describes several relatively smaller artefacts. This allows a user to position the artefacts in different places in the machine volume, such as at the centre and at the outer edge of the build platform, to characterise performance in different locations of the machine, either quantitatively or qualitatively or

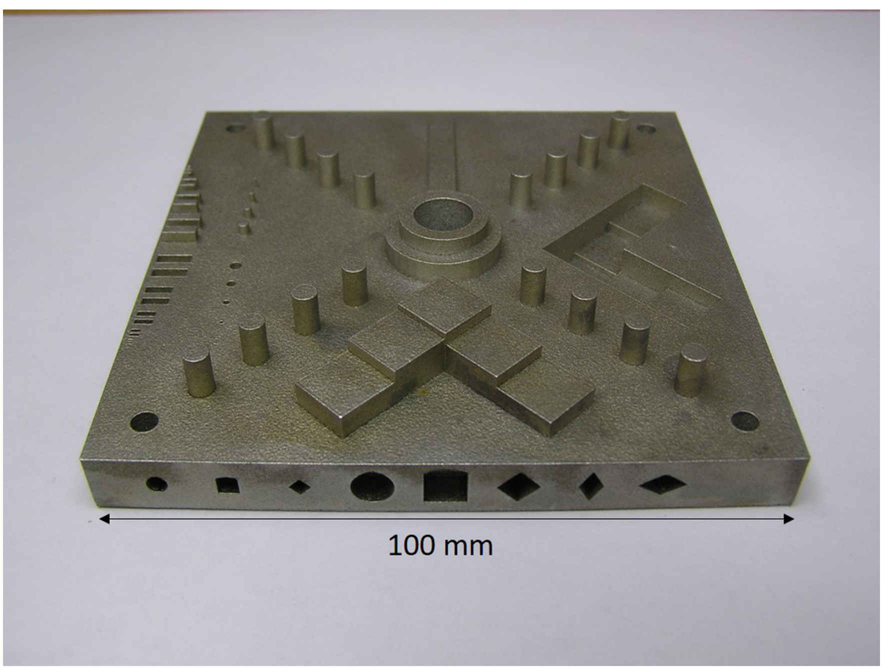

FIGURE 8.1
The NIST AM Test Artefact is designed to highlight potential errors seen in a variety of AM systems. The main structure of the artefact is 100 mm × 100 mm.

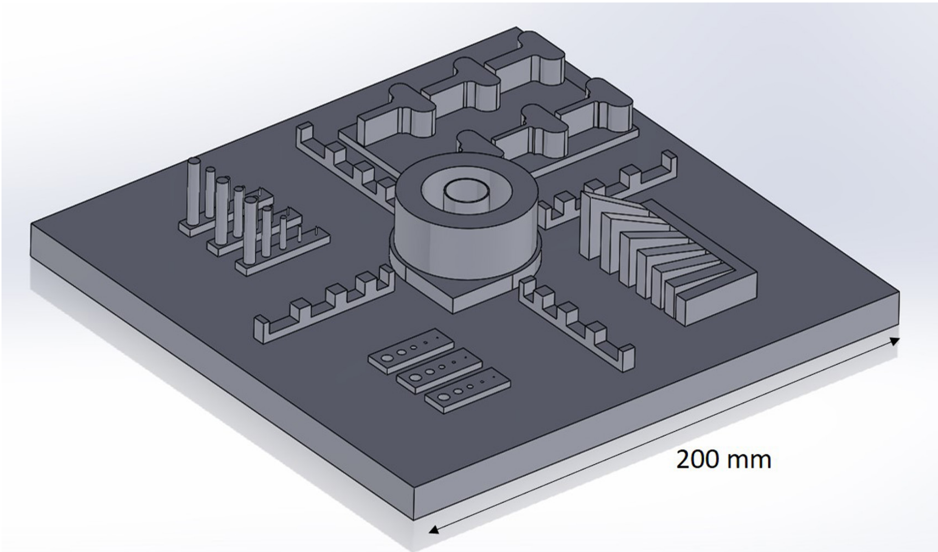

FIGURE 8.2
The test artefacts in ISO/ASTM 52902 (2019) can be configured by the user to best fit their need. In the example shown here, the configuration allows a quick test of *X*- and *Y*-axis performance of a machine with expected coarse resolution. Note that an artefact for evaluating surface texture is also available, but not pictured here.

both. The standard describes a linear accuracy artefact, a circular accuracy artefact, four sets of artefacts intended to test resolution or minimum feature size and an artefact to test surface texture. The resolution artefacts are available in different sizes and different aspect ratios, allowing users to choose the artefacts that best test the limitations of their machine.

8.2.2 Strengths and Challenges of 3D Test Artefacts

The main strength of 3D test artefacts was mentioned earlier, but there are other reasons why this method of machine performance evaluation may be preferred. The fact that many different aspects of machine performance, such as its ability to create a desired geometry, desired microstructure, desired density, etc. all in one part is often attractive to users. It is also worth considering what a physical test artefact can do that direct measurement of components (discussed in more detail in Section 8.3) cannot. It is rather difficult for direct measurement to efficiently and effectively measure the minimum feature size achievable by a system. It is also difficult to predict the achievable surface texture by measuring machine components. The MSFC-STD 3716 (2017) standard recognises that the quality of surfaces and level of detail resolved are often representative of the overall 'health' of a PBF machine, and changes in these characteristics can be among the earliest indicators of changes in the system. Fortunately, these two characteristics are easy to assess using test artefacts.

Unfortunately, test artefacts have some challenges and limitations. Building parts costs time and resources. For this reason, most test artefacts are relatively small, and a test build is rather sparse, minimising the amount of time needed for the build and the amount of feedstock material consumed in the test build. Furthermore, it may be difficult to determine the cause or reason for the observed error in the test artefact. Related to this, it may be difficult to separate machine errors from process errors; systematic errors from non-systematic errors; and errors resulting from poor performance of one component of the machine from that of another component of the machine (for example, errors resulting from poor performance of the energy beam from errors resulting from poor performance of the positioning system). There is a trade-off between capturing a lot in one relatively simple test and being able to easily determine the cause(s) of errors and acting to correct.

8.2.3 Considerations for 3D Test Artefact Design

Careful design of a test artefact will allow a user to maximise the benefits and minimise or overcome the challenges. While great care has gone into all of the designs discussed in the literature and in standards, the challenge with these artefact designs is that they are meant for the general user. Designs intended to be used broadly will get most of the users most of the way there for assessing the performance of their machines. However, given the breadth of the AM industry, even limiting only to metal parts, it is unlikely that these broad-based solutions will address every aspect of machine performance evaluation needed for an individual user, let alone all individual users. Standard specifications, such as MSFC-SPEC 3717, acknowledge that there will be cases where users need to design their own test artefacts: 'the design of the reference part(s) is not specified and may vary with the design needs and priorities of the organization'.

The first consideration for designing the artefact is to assess the needs and priorities of the organisation. Some organisations may need to demonstrate the ability of the system to achieve certain tolerances described in geometrical product specification standards such as ISO 1101 (2017) or ASME Y14.5 (2018). Other organisations may need an artefact to build at regular time periods as quick checks on performance. Some organisations will need to test the entire work volume of their systems; others may only be interested in one or a few particular areas of the build. The possibilities are endless. Some organisations will need to assess only one specific type of PBF machine; others may need to assess only DED machines; and others may need to assess multiple machine platforms with the same design. Each of these considerations could lead to a unique configuration of standard artefacts or a unique test artefact design. If the needs and priorities are less clear, a standard artefact design is probably the best approach.

The next consideration for the design of the artefact should be how the artefact will be measured. The primary objective for any test artefact should be establishing quantitative metrics for machine performance. Quantitative metrics require measurement. This is not a major limitation for this type of method, since most users interested in making parts need to be able to somehow measure those parts. The user should assess whether or not the test artefact, including each of its individual features, is easily accessed by the measurement techniques on hand. One of the most impressive aspects of AM is its ability to produce freeform surfaces and internal geometries. It is tempting to include these features in a test artefact to demonstrate capabilities, but these types of features tend to be difficult to measure with low uncertainty without high-end metrology equipment (for example, a metrology X-ray computed tomography system) (Carmignato et al. 2017). Low measurement uncertainty is paramount. Ideally, the task-specific measurement uncertainty would be ten times smaller than the expected geometric error being measured on the test artefact, but this is often just a 'rule of thumb'; it becomes difficult to draw unambiguous conclusions if the measurement uncertainty is less than four times smaller than the measured geometric error (Khanam and Morse 2009; ANSI Z540.3). The upshot of all of this is that simple shapes and features are often preferred because they are easier to access, and measurement procedures (including fitting reference geometry and number of samples) are rigorous. Rivas Santos et al. (2019) discuss the 'design for metrology' for test artefacts and present measurement results for a specific artefact with different measurement methods.

The priority for any remaining considerations may depend on the needs and priorities of the user or may be considered of equal importance with each other. These considerations are the features to be selected, the sizes of the features and artefact(s), the placement of the test artefact(s) and the machine configuration being tested. Regarding the features to be tested, the MSFC-SPEC-3717 (2017) calls for features examining detail resolution (i.e. minimum feature size) and surface texture on prominent surfaces, such as horizontal, vertical, inclined and free-standing (i.e. overhang) surfaces. Other guidance (see Rebaioli 2017) calls for evaluating the fourteen geometric dimensioning and tolerancing call outs, such as flatness, straightness, circularity, profile, position, etc. Again, these may vary depending on the specific needs and priorities. In general, it is likely beneficial to have both protruding (for example, posts) and recessed (for example, holes) features. Regarding the size, the original thinking in the community (Richter and Jacobs 1992, Byun and Lee 2003, Campanelli et al. 2007) was that a test artefact needed to be large enough to test the entire machine volume. While testing throughout the volume, especially at the outer extremities, is still considered good practice, thinking has evolved to favour smaller geometries that can be replicated in various positions in the build volume (ISO/ASTM 52902:2019). Small artefacts have the benefit of building quicker, consuming less feedstock material and being less prone to distortion from residual stress. Placement and orientation of the test artefacts may be best considered in coordination with the machine configuration. For example, when evaluating a DED machine with stacked linear axes, it might be beneficial to align the artefact(s) or features with the individual axes, allowing the errors in the aligned features to be more easily linked with the individual axes during evaluation. Such a configuration may be more difficult on a PBF machine where the energy beam is actuated by a scanning system that does not necessarily align with the machine coordinate system.

Note that some sources in the literature suggest using multiples of the same feature or test artefact in a build to assess repeatability (Scaravetti et al. 2008). It is often beneficial to include multiple similar features in different locations in the build volume, but this does not test the machine's repeatability. Repeatability is generally considered to be the ability to independently repeat performance over a short period of time under similar circumstances. Multiple parts or features in one build are not independent; the presence of one part influences the properties of other parts in the build, for example, spatter particles, local thermal history or vibration in the recoating system caused by the presence of other parts. Many errors are position-dependent, including many systematic errors (for example, beam shape in laser PBF machines or angular error motion in a DED axis), whereas repeatability (or lack thereof) is more a measure of non-systematic errors (BIPM 2012). Furthermore, when positioning multiple parts or features throughout the build volume, it is likely good practice to use a non-uniform – perhaps even a pseudo-random or stratified-random target position – approach to avoid masking any periodic errors in the machine.

8.3 Component Testing

Breaking down the potential sources of error in a part and building an error budget from the bottom up usually requires isolating the components in the error budget and quantifying them individually. This approach is often better for making fine adjustments to reach precision tolerances, because it is often easier to tweak an individual component than to tweak the entire interconnected system. Furthermore, this approach often highlights that certain components perform much more poorly than others in the machine, allowing a user to concentrate their time on adjusting the most sensitive components. For these reasons, some users may wish to pursue an evaluation and qualification scheme that uses more measurements of individual components than building of test artefacts. This may be especially true of machine builders who have more access to the individual components than machine users.

8.3.1 Key Contributions to Component Testing

The topic of measuring individual components of a machine to derive a better understanding of machine performance and expected AM part tolerances has seen little mention in the literature (Lu et al. 2018) but has been a consistent topic of discussion at precision-engineering conferences focused on AM (see Moylan et al. 2014, McGlauflin and Moylan 2016, Jared et al. 2018). Much of this discussion is based on the approach of building upon standard measurement methods in machine tool metrology. In this way, the ASME B5.54 and ISO 230 series of standards (especially ISO 230-1 on geometric errors, ISO 230-2 on linear positioning error and ISO 230-3 on thermal effects) are key contributions themselves. The key differences between error motion tests for AM machines and tests for machine tools will be discussed in more detail later in this section.

Of course, error motions are not the only sources of geometric error in AM parts, with the energy source also playing a major role. However, there is a dearth of literature in this area. For electron beam systems, the focus is on the scanning system more than the electron beam itself (Guo et al. 2015). For laser beam systems, researchers may look at beam diagnostics as a solved problem, because standards such as the ISO 11146 series (for example, ISO 11146-1:2005, ISO/TR 11146-3:2004) for beam shape and ISO 11554 (2017) for power have existed for some time and have gone through several reviews. Alternatively, the view among AM researchers may be that measuring the energy beam is further along in the technology readiness level (TRL) scale and, therefore, is the domain of industry development, not basic or applied research. Indeed, many commercial providers of beam diagnostic equipment have offerings targeting AM users and applications (for example, Koglbauer 2018, Bergman 2016, Kirkham 2017, Dini 2018). The topic more popular in research is intentional beam shaping (Metel et al. 2019, Faidel et al. 2016).

Other components likely contribute as well, for example build platform heating or gas handling, but they are not discussed as much in the literature.

8.3.2 Strengths and Challenges of Component Testing

In addition to the strengths related to error budgeting, evaluation and adjustment mentioned earlier, direct measurement of components provides some other benefits to the user. Direct measurement can often be done with much lower measurement uncertainty, which may be necessary to achieve precision tolerances. Also, direct measurements do not consume raw materials.

However, the hurdles and challenges of direct measurement of components are often significant. One of the reasons that measurement uncertainty can be much lower is that direct measurement of components often requires specialised equipment. A larger organisation with many AM machines may benefit from purchasing some of this equipment, but a small or medium manufacturer with only one AM machine may find the cost of the equipment too high compared to the benefit. Another major challenge is that not all of the components may be accessible to the users. This is especially true in PBF systems. The access may be limited by proximity, space or control. For example, gaining access to individual mirrors in a laser PBF (L-PBF) machine is problematic; machine builders often buy these systems off the shelf and do not even have that level of access themselves. Furthermore, build chambers tend to be smaller in size, and measurement equipment larger than a build platform may not fit into the machine to perform the desired measurement. Another example is that machine builders and their maintenance staff may have access to a level of control that allows the laser beam to be fired and translated across a beam profile measuring device, but a user might not have access to the same level of control and may have to go through a complicated work-around to complete such a test.

One other consideration when performing these tests is the impact of not operating the machine in the same state as when it builds. Making discrete, targeted movements or individual commands to individual machine components is something that is usually best accomplished in the 'stand-by' or 'jog' mode of the machine, but some machines may exhibit different performance in these modes, especially if velocity or positioning direction are different between jog mode and building. Furthermore, some measurement equipment may need to reside outside the build chamber, which may require machine operation with a door open or window removed. Both of these cases mean that the machine will not be at the operating temperature and will not have the same environment (whether that be vacuum, circulating gas or shield gas) as when the machine is building. Users need to take care that the measured deviations during testing will actually reflect the deviations when the machine is operating.

8.3.3 General Principles of Component Testing

The approaches discussed in this section stem from machine tool metrology and laser beam metrology standards, methods and good practice. These tests tend to be a progression of measurements starting with an environmental test for machine drift, while very little is changed in the machine. This initial test helps to set the baseline and contribute to the measurement uncertainty estimation for tests that follow. Next are tests to determine the error motions of the individual motion components of the machine. Once the individual error motions are determined, the alignment errors between the machine axes are determined. The error motions and alignment errors can be used to create an error map of the machine, leading to an empirical model, often using homogeneous transformation matrices (Leach and Smith 2018), that can predict geometric errors at any location within the work volume (or within the ranges of the error measurements) (Donmez et al. 1986). The likely next progression is to perform additional component measurements (for example, spindle performance on a machine tool or laser performance on an AM system). Alternatively, additional motion measurements may be desired, such as thermal drift when repeatedly exercising axes or coordinated motion of pairs of axes.

A principle that permeates all the measurements of error motions is the concept of the functional point. In machine tool metrology, the functional point is where the cutting tool would contact the part. Good practice is that tests of geometrical characteristics apply setups that represent the relative point between the tool and the workpiece. While a similar principle applies to measurement of AM systems, some slight differences deserve attention. For a DED machine, the functional point is relatively simple: the workpiece is the same as for machine tool metrology, and the tool is represented by the point where the feedstock material intersects the centre of the energy beam. For PBF, the functional point is where the energy beam intersects with the top of the powder layer. Note that the top surface of the powder bed is created by movement of the recoating system, not movement of the *Z*-axis. Furthermore, the tool analogy here is more difficult because the energy beam does not have the same physical presence. Best application of the 'tool-to-workpiece' measurement for PBF systems likely involves measuring the workpiece movement (*Z*-axis) relative to the recoating system that creates the top surface of the powder, and measuring the laser system also relative to the recoating system. However, more research is needed to verify this practice (Moylan et al. 2014).

8.3.4 Z-axis

AM, by definition, involves building a part layer upon layer, which means that nearly every AM machine has a linear actuator for a *Z*-axis. Slight differences may exist between machines, such as a moving tool versus a moving workpiece, but measurement of the *Z*-axis error motion is common across nearly all machines. Additionally, the *Z*-axis is very similar to a machine tool's *Z*-axis and, therefore, can be measured in a similar manner.

Tests for linear positioning error (ISO 230-2 2014), straightness error (ISO 230-1 2012) and angular errors (ISO 230-1 2012), many of which can be conducted simultaneously, can follow setups nearly identical to the setups described in machine tool metrology standards. For PBF machines, the only difference in the setup is the previously mentioned measurement of the *Z*-axis relative to the recoating system. For DED systems, the setup is identical to that in the standards. The equipment is also applicable, with laser interferometers, gauge block/dial indicator, straightedge/dial indicator and differential level setups having been described in the literature (McGlauflin and Moylan 2016, Lu et al. 2018, Moylan et al. 2014) (see Figure 8.3).

The differences in the measurements come in the procedure. First, AM machines typically only position in one direction during a build. As such, bi-directional tests of the *Z*-axis are not needed, only uni-directional tests. Another difference is that the error motions must be measured at different scales. The geometry of large parts might be affected by error motions over the entire range of the *Z*-axis. This calls for measurement of the entire *Z*-axis, likely hundreds of millimetres. However, the geometry of an individual layer has impact on the part's surface texture (see Chapter 11) and on the process stability and consistency (and, therefore, the material or mechanical properties). This calls for testing on the scale of individual layers, likely tens or hundreds of micrometres. Combining these two into one test is impractical. A solution to this is to perform two slightly different tests. One test is of the entire range of the *Z*-axis, almost exactly as described in machine tool metrology standards. These standards provide guidelines on the number of intermediate targets, locations of the targets, etc. It is likely that users will want to conduct multiple uni-directional runs, using random or pseudo-random spacing of the targets on the order of several millimetres. A second test is of positioning at the layer scale. With this test, the target spacing should be the same as a typical layer thickness, and the range of the entire test should be on the order of a millimetre or two. Users will likely want to perform layer-level tests at multiple (probably more than two) positions along the *Z*-axis range. The positions for layer level tests may be chosen randomly (or pseudo-randomly), or the location closest to the top of build platform (where a regular build would begin) may be given preference, since it will certainly factor into nearly every build. Furthermore, locations furthest from the platform in PBF machines may be tested under loads similar to a full bed of powder. More research is needed to verify that these tests are good practice, but early research is promising (McGlauflin and Moylan 2016). Furthermore, more research is needed to test

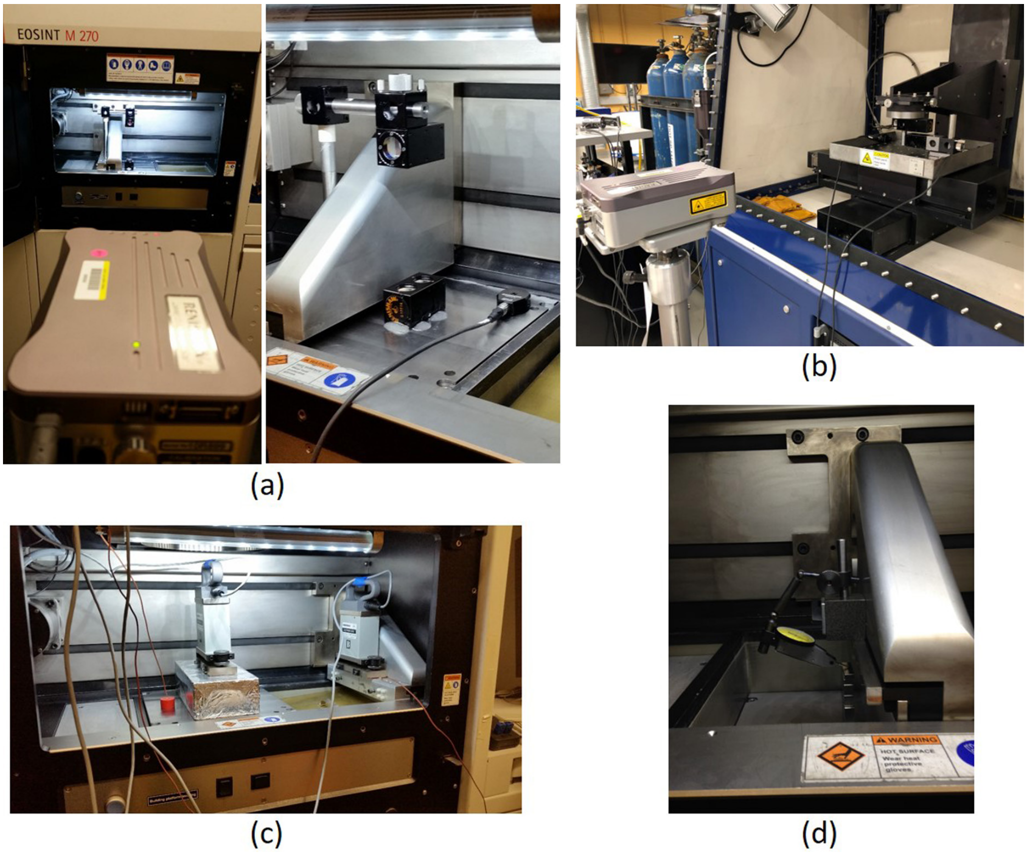

FIGURE 8.3
Typical setups to measure linear axis error motions described in ISO 230-1 (2012) and ASME B5.54 (2005) can also be used for a *Z*-axis in PBF and DED machines: (a) a laser interferometer setup for pitch error of the *Z*-axis, E_{AZ}, in a PBF machine; (b) a laser interferometer setup for yaw error of the *Z*-axis, E_{BZ}, in a DED machine; (c) an electronic level setup in a PBF machine for E_{AZ}; and (d) an indicator and gauge block setup for measuring linear displacement error of the *Z*-axis, E_{ZZ}, at individual layer height targets.

whether or not the two tests can be combined, spacing some targets by millimetres and other targets by layer thicknesses in the same run.

8.3.5 Directed Energy Deposition Machine Error Motions

DED machines are essentially vertical machining centres with energy beam and material feed in place of a spindle. Beyond the parametric tests outlined in ISO 230-1 (2012) and IOS 230-2 (2014), which apply to the *X*- and *Y*-axes completely, multi-axis motion tests, such as the circular tests described in ISO 230-4 (2005) and diagonal tests described in ISO 230-6 (2002), are also applicable (see Figure 8.4). The main benefit of these multi-axis tests is the speed of evaluation. Multi-axis tests can often give users a sense of the overall geometric performance of their machine in a matter of minutes or a few hours with only three or four setups, compared to multi-day tests of each individual error motion. However, the trend in machine tool performance evaluation toward a single metric for volumetric accuracy (Weikert 2004, Schwenke et al. 2008, Muralikrishnan et al. 2016) is likely not applicable to

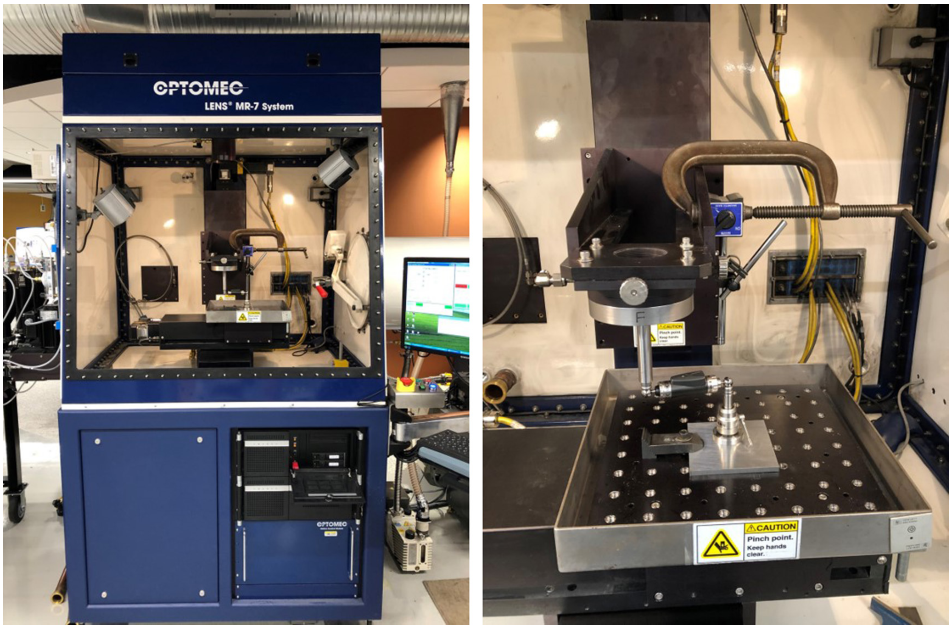

FIGURE 8.4
An overall view (left) and close-up (right) of a circular test using a telescoping ball-bar on a DED machine.

DED because the process contributes more to part errors than in machining, and the layer-upon-layer building makes complex motion evaluation less important.

8.3.6 Powder Bed Fusion Machine Error Motions

Movement of the energy beam in the machine *X*- and *Y*-axes in a PBF machine is usually carried out by a galvanometer (a combination of two rotating mirrors that deflect the laser beam in L-PBF) or by an electromagnetic scanner (in the case of electron beam PBF). Either way, the motions of components are usually not measurable individually. If the rotating mirrors were accessible, a simple axis of rotation measurement could capture error motions similar to a machine tool's rotary stage. Regardless, an alternative approach is a 2D artefact, which is described in Section 8.4.

The overall part geometry is mostly insensitive to error motions of the recoating axis, but certain error motions directly impact layer thickness and, therefore, process stability and consistency. The recoating system of a PBF machine is often an actuator that resembles actuators on a machine tool, either a linear actuator or a rotary stage. Again, tests similar to those conducted on machine tools are likely warranted. For a linear motion recoating system, only two error motions impact the geometry of the top layer of powder: straightness in the *Z*-direction (E_{ZR}) and roll (E_{AR}) (see Figure 8.5).

8.3.7 Energy Beam Diagnostics

Given that a central premise of PBF and DED processes is delivery of energy to the work surface, understanding the characteristics of the energy beam should be of critical importance. The size, shape, power, power density, position (centroid and focal plane) and beam

FIGURE 8.5
A close-up of the sensor nest mounted to the recoating arm and the underlying reference artefact (a flat plate). This setup was used to measure straightness (E_{ZR}) and roll (E_{AR}) of the recoating axis simultaneously.

quality, among others, will all have significant impact on the process physics and thereby the final parts being produced. Since the overall focus of this chapter is on geometry, this subsection will exclude discrete power measurement in favour of other characteristics that impact geometric performance more directly.

As mentioned in Section 8.3.1, the main concepts of laser beam diagnostics are well established in standards (ISO 11146-1 2005, ISO/TR 11146-3 2004). In fact, the laser included in any commercially available AM system likely already conforms to specifications related to these standards in benchtop tests when the laser system was provided to the AM machine builder (since most laser systems are sourced from reputable laser providers, not built in-house by AM machine builders). However, in the AM machine, the energy beam usually passes through a scanning system and focusing optics, so it is good practice for the user to perform beam diagnostics at the point of application (i.e. in the AM machine itself) where all potential influences on the beam are captured, such as distortion or thermal lensing (Bergman 2016).

Measuring the energy beam in the AM machine offers some advantages but more challenges. The main advantage is that the motion system is integrated into the AM machine, so evaluation of beam shape by scanning over a slit or of beam propagation (which is generally one of the more difficult characteristics to measure) by testing at multiple Z-axis locations is simplified. However, for L-PBF machines, where the beam is scanned using a galvanometer and often focused using an f-theta lens, there are a range of incidence angles, sometimes as large as 20° (Koglbauer et al. 2018). This is a challenge because most beam diagnostic systems are only able to measure when they are aligned with the laser (either in-line or perpendicular), so measurement may be limited to only one position (i.e.

0,0). Furthermore, a lack of control of the beam position may prevent users from accomplishing some tests. Moving the beam to specific positions often involves programming the system to build a 'test part' that has a geometry that will ensure the beam will move to a specific point along a specific path. However, a typical user may not be able to program the machine to position the laser at a certain point and remain at that point to conduct a test. PBF build chambers tend to be rather confined and impenetrable, so bulky equipment, or some that requires cooling, may not fit in an AM machine and will certainly make testing at multiple locations difficult.

Good practice for energy beam diagnostics is a little notional at this point in time because there is little literature on the topic or standards that are specific to AM applications. However, following existing standards that govern beam diagnostics generally, such as ISO 11146, is certainly a good starting point. Testing the beam in multiple locations in the build envelope, especially at the extremes, will likely provide helpful information, but there may be large uncertainty for these measurements if alignment of the sensor and the beam is difficult. Users should consider the interactions between the beam, scanner, optics, and all other components between the beam output and the workpiece. Measurements of the beam characteristics in the machine can be compared to benchtop test results (if available) and repeated over time to diagnose causes of any problems.

With the current trends toward high-speed compound measurements or sensor fusion (Bergman 2016, Kirkham 2017, Koglbauer 2018), users must take care to understand tradeoffs. In these applications, speed or additional measurands may be favoured over precision or completeness of measurement. If precision is a priority, it is often preferable to perform separate measurements for individual characteristics. For example, Koglbauer et al. (2018) present a method to measure beam characteristics as well as scan speed and scanning position. However, beam waist with this method is confined to two predefined perpendicular orientations, not a complete representation of power density distribution. It may be preferable to have separate beam diagnostics and complement those with a 2D artefact, as discussed in Section 8.4.

8.3.8 Non-Geometric Measurements

Scanning speed is often cited as one of the most critical process parameters that affect part quality. However, little attention is paid to actually measuring the speed and quantifying any error compared to the programmed speed. Koglbauer et al. (2018) discuss the potential for their recently developed method to measure scan speed. Also, a fixed-field-of-view high-speed camera can be used to quantify scan speed (Criales et al. 2017). For DED machines, tests for machine tools likely apply (ISO 10791-6 2014). According to anecdotal evidence, the difference between actual speed and programmed speed at steady state is small compared to other error motions in the machines, but deviations during the transient stage of motion (i.e. while accelerating or decelerating) may be comparatively large.

Another aspect related to scanning speed is the timing of switching the energy beam on and off. Because most machines attempt to use short scan lengths, the energy beam is switched off and on very frequently. Any error in this timing could result in geometric errors, poor surface texture and sub-surface porosity. The most common method of evaluating this characteristic is usually as part of a 2D artefact, discussed in more detail in Section 8.4.

Other aspects of machine performance should likely be part of a larger evaluation or qualification scheme (AMS 7003), but their influence may be more on mechanical properties, microstructure or defect formation than on part geometry. For example, the gas flow inside an AM build chamber can affect cooling rates, which directly affect microstructures (Heigel et al. 2015). However, gas flow can also impact powder denudation, which can have a second-order effect on geometry or surface texture (Matthews et al. 2016). One challenge in measuring gas flow is that, although the measurement method may be rather simple (Heigel et al. 2015), there is large uncertainty in how much the method itself (i.e. the size, shape and positions of the measurement devices) affects the flow.

8.4 Two-Dimensional Test Artefacts

A middle ground between quantifying machine performance using 3D test artefacts exclusively or testing individual components of the machine exclusively is using a 2D test artefact to quantify some aspects of machine performance. This approach is most beneficial when the individual components of the lateral positioning (i.e. in the machine *X*- and *Y*-axes) and the energy beam may be inaccessible to the user. This is most often the case in PBF machines, so users of these machines will likely find the most benefit, whereas this is rarely the case in DED machines, and those users will have little or no use for this approach.

Creation of a 2D artefact is mentioned in MSFC-SPEC-3717 as part of the optical system evaluation. Although this might seem to validate approaches that combine beam diagnostics with beam positioning (discussed in Section 8.3), the standard seems to call for a separate test. The standard states in a note, 'lasing purposeful markings into a flat, solid plate, and evaluating the marking against metrics (based on past performance) may provide sufficient evidence of scanner head health' (MSFC-SPEC-3717 2017).

8.4.1 Strengths and Challenges of 2D Test Artefacts

The general approach for creating 2D test artefacts is to use the energy beam and positioning system to mark (sometimes referred to as etching) a solid plate. Similar to a 3D test artefact, the 2D artefact is then measured, and the deviations in the marked pattern from the designed pattern can inform a user on error motions of the positioning system or poor performance of the focusing optics. The benefit of this approach is that it isolates the beam scanning and the beam performance from other aspects of the system, such as feedstock delivery, gas circulation and error motions of the *Z*-axis. This test method would likely be part of a larger evaluation or qualification approach that also involves direct measurement of other aspects of the machine.

Beyond the fact that the 2D artefact method has not been as rigorously tested as other methods discussed in this chapter, it suffers from two main challenges. The bigger challenge is the measurement of the 2D test artefact. Optical coordinate measuring machines or machine vision systems with high-resolution cameras (see Chapter 10) are likely needed to quantitatively measure the marked pattern. A scanner with a calibrated scale may be useful for certain patterns, but these provide quantification only relative to the scale, and the uncertainty in the scale position may be large. Many machine users may not have access to such equipment. Furthermore, measurement by optical instruments may show increased uncertainty when little contrast exists between the marked pattern and the overall texture of the plate. This is discussed in more detail in Section 8.4.3. Furthermore, the determination of the laser position using the actual scan pattern may not be simple, especially if the melt-pool boundary is difficult to determine or the melt pool is not symmetrical. The second challenge is that programming the pattern may be challenging, or even inaccessible, for some users. Many of the metal AM machines on the market, especially PBF machines, have closed or 'black-box' controllers, meaning that the user may not be able to easily program simple lines or curves. This is usually overcome by designing an actual part where one layer of that part will create the desired pattern. Single lines and curves can be generated by designing very thin-walled parts or by designing solid parts but turning off the infill pattern.

8.4.2 Key Contributions to 2D Test Artefacts

Unfortunately, there is not much discussion on the use of 2D artefacts to evaluate AM machines in the literature. However, the use of 2D targets or patterns for evaluating performance of office printers (i.e. 2D printers) or imagers is well established. For example, Rochester Institute of Technology (RIT) has produced eight books of test targets for this purpose (Chung et al. 2008), and the United States Air Force (USAF) resolution test chart, originally standardised in 1951, is still readily available from many major optics providers (MIL-STD-150A 1951). Some of these patterns, such as the Siemens star (ISO 15775 1999), have provided inspiration for 3D test artefact designs (Jared et al. 2014, Chang et al. 2015). However, the focus of these artefacts and associated analyses tends to be on resolution more than positioning accuracy or geometric error motions (Li et al. 2018).

Analysis of 2D patterns is limited to only a few works in the literature. Tang et al. (2004) describe a method for evaluating and compensating distortion and scaling by placing a piece of white paper on the build platform, using the laser and scanner to 'draw' a 300 mm × 300 mm square and measuring deviations. Land (2014) detailed the use of a grid pattern to create an error map and adjustment scheme. Land's work found + or × markings on the plate to be most effective for lower uncertainty measurement. This work also discussed some of the challenges encountered with a lack of contrast between the marking and the plate and suggested that using a chrome-on-glass plate may be good practice. Lu et al. (2018) describe a pattern that combines a grid of circular shapes, rectangles, lines, concentric circles and a quadrifolium (see Figure 8.6). Preliminary experiments in this work established an optimum density of the circular shapes in the grid, settling on 2 mm diameter and 6 mm pitch. The shapes included in the pattern were chosen to produce an error map (using the grid) and test the machine's ability to satisfy the geometrical tolerance call outs in ASME Y14.5 (2018).

8.4.3 Considerations for Designing a 2D Test Artefact

Because there are no standards and little literature detailing patterns or 2D artefact designs for AM, users are likely to design their own. When doing so, much of the considerations for designing 3D artefacts (see Section 8.2.3), such as individual needs and priorities, apply here as well. However, some slight differences do exist, where the guidance below should be helpful. It should be noted that this guidance is more targeted towards PBF machines because the need for 2D artefacts to test beam scanning is more applicable to users of these machines.

Measurement is again a critical consideration in the design and use of 2D artefacts, but for different reasons than with 3D artefacts. Because of the 2D nature of these artefacts, they will almost certainly be measured optically. As such, a high contrast between the marked portion and un-marked portion of the test plate is beneficial. This may be

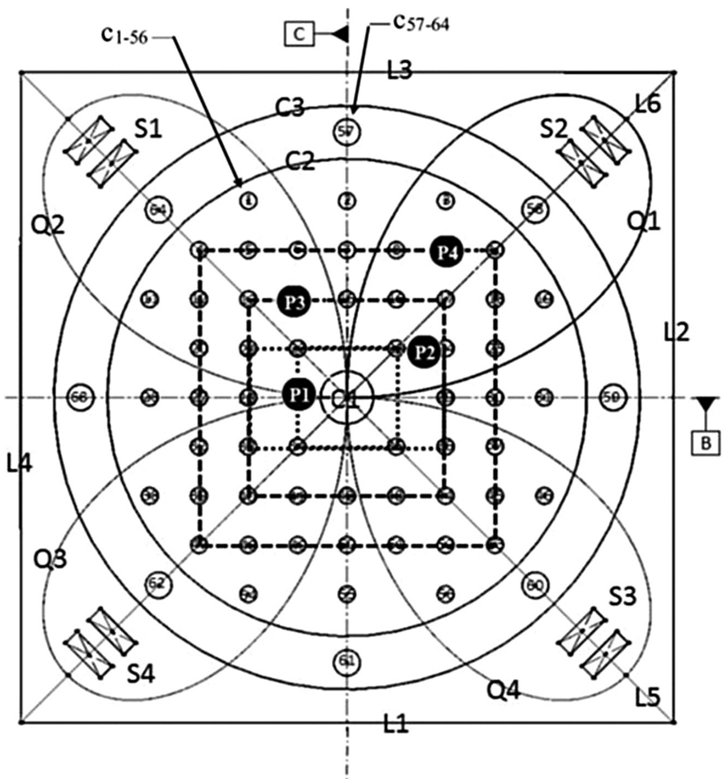

FIGURE 8.6
From Lu et al. (2018), an example 2D artefact combining a grid pattern, concentric circles, a large square, and a quadrifolium.

accomplished with a coating on a plate (for example, chrome on glass) or a surface treated plate (for example, anodised aluminium) where the energy beam removes the surface layer, exposing the underlying material with high contrast. It should be noted that surface treated plates may have larger flatness error, which may negatively impact measurement uncertainty.

Although a grid pattern is a simple and logical 2D artefact, it might not be the best choice for machine users. The benefit of the grid pattern is that it can lead directly to an error map and compensation of the scanner (Halme et al. 2010). As such, builders of scanners and AM machines likely use these patterns when setting up machines. A user looking to quantify residual error after the builder has tuned their positioning system might inadvertently replicate the pattern used for initial compensation, which would mask or minimise residual errors. It is likely advantageous for a machine user to program a different pattern, with various radii, angles and spacings between lines, arcs and other shapes. This should be done on a bare plate (i.e. no powder), exposing only one layer of this part.

It is good practice to include elements or features in a 2D artefact to test different aspects of machine performance. For example, a user might want to include a Siemens star or other diminishing artefact to test resolution as well as concentric circles to test coordinated motion and scaling errors, and a large square to test for scanner system distortions. Furthermore, it is good practice to have features or elements at the extreme positions (i.e. the edges) of the build envelope as well as at the centre. Again, machine configuration should be considered so that certain components can be isolated; users of L-PBF machines should be aware that lines parallel to the machine *X*- and *Y*-axes may still require coordinated motion between the two rotating mirrors (Tang et al. 2004).

Analogous to all of this would be to scan the beam directly onto a position-sensitive device (for example, a photosensitive diode focal plane array). This would allow a direct measurement of the pattern, removing the post-process measurement as a source of uncertainty. However, to do this would need the beam to be attenuated to a level that would not destroy the measurement device, and to do so in a way that ensures the performance of the positioning is the same as during a regular build. Furthermore, uncertainty in these measurements would depend on the resolution of the photo sensitive diode focal plane array. Preliminary research has started in this area but is still inconclusive.

8.5 Areas for Future Research

The fact that many of the methods discussed in this chapter have been fine-tuned over the years in other applications gives confidence that they will continue to be relevant for AM machines in the years to come. As such, the research is likely to be less focused on developing brand-new methods and more on improving the applicability of the test methods to AM machines and processes. More research is needed in determining how sensitive AM part geometry is to errors in various machine characteristics, to better inform the required level of measurement uncertainty for each test. For example, if it is determined that DED part errors are relatively insensitive to common error motions, quicker tests, such as circular tests with a telescoping ball bar, may be more appropriate than time-consuming laser interferometer tests.

The trend in AM machine design seems to be toward bigger and faster machines. For L-PBF machines, this often means multiple lasers acting in the same build envelope. One of the major machine performance challenges posed by multiple lasers is measuring their relative positions and alignments. This will likely be a topic for research in the coming years. In a similar direction, new machine designs that allow for continuous building (versus iterating exposure and recoating) are emerging. Again, the concepts of measuring these machines will not change, but the specifics of the measurements will need to change to match the new designs and applications.

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