Powder Bed Layer Geometry

Michael McGlauflin, Shawn Moylan
Engineering Laboratory
National Institute of Standards and Technology[1]
Gaithersburg, MD, USA

ABSTRACT

This paper investigates the measurement of machine performance errors associated with the powder bed geometry of a commercially available laser additive manufacturing (AM) machine. The methodology is based on existing ISO and ANSI standards as employed in computer numerically controlled machining centers. The paper describes the design of the tests and sign conventions. A discussion is presented on which error sources can affect both the powder layer thickness and part geometry. Finally, it is shown that these existing standards can be applied Laser Based Powder Bed Fusion (LPBF) machine metrology and includes a discussion of where modifications may be necessary.

INTRODUCTION

LPBF type machines employ a composite build process. Four discrete processes interact at various times throughout the build to achieve final part specifications. They are: creating the powder layer by the recoater arm, positioning of the workpiece by the build platform, positioning the laser beam by scanner optics, and controlling the speed and power of the laser through process parameters. The first three of these are subject to error motions that can affect final part geometric errors and build quality. Build platform and optical path errors contribute directly to geometric part errors, while errors in the motions of the recoater arm and build platform can affect powder layer thickness, thickness variation and flatness. Process parameters, like laser power, scan speed, etc., govern the build process, and are input by the user and controlled by the machine software. These parameters are optimized for a nominal layer thickness and powder density.

Current AM machine verification procedures call for building a test artifact which is independently measured on a coordinate measuring machine (CMM). Geometry errors, if any, are then corrected by making software corrections to scaling. Individual machine manufacturers have their own specific artifact designs and currently no standardized artifact design has been designated. While this is a useful procedure for acceptance, it falls short in differentiating the source(s) of the error(s). Research at the National Institute of Standards and Technology on test artifact design has shown geometry errors in the range of 30 µm [1]. As LPBF technology advances, improvements in accuracy and repeatability must be realized through a more comprehensive process. Reducing the errors of the recoater arm, scanning mirrors and build platform may ultimately contribute significantly to advances in accuracy.

National and international standards exist which appear to meet many of the requirements for additive machine tool metrology. Specifically, ISO 230-2 [2], ANSI B5.54 [3], and ISO 230-3 [4] contain numerous tests and procedures that at first principles should quantify many of the error motions for AM equipment [5]. Tests were conducted to evaluate the effectiveness of these standards for a commercially available LPBF machine using well established metrology equipment such as a displacement laser interferometer, capacitance probes, and precision levels. Measurements were carried out at ambient temperature and, when practical, compared with similar measurements performed at the machine's operating temperature of 80°C.

 The full descriptions of the procedures used in this paper require the identification of certain commercial products. The inclusion of such information should in no way be construed as indicating that such products are endorsed by NIST or are recommended by NIST or that they are necessarily the best materials, instruments, software or suppliers for the purposes described.

NOMENCLATURE AND SENSITIVE ERRORS

Errors associated with an axis can be described using a simple three letter terminology for each of the Six degrees of freedom. For example, a linear error of the Z-axis in the Y direction (straightness) can be denoted as E_{YZ}. Likewise, an angular error around X in the Z axis would be described as E_{AZ}. This descriptive terminology works well for machine tools but is complicated by LBPF technology. (FIGURE 1)

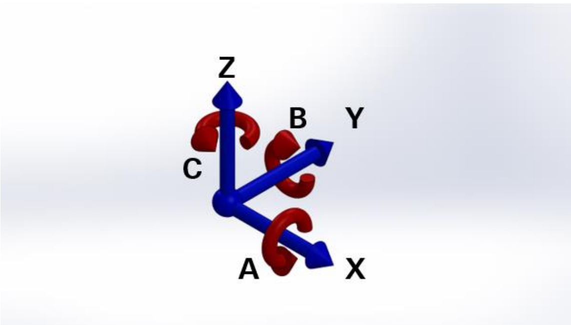

FIGURE 1: Axis Designation

While it can be argued that the motion of a typical recoater arm is in the X direction, it by current definition is not the X axis [6]. X and Y axes are orthogonal to the Z axis, which is defined as "normal to the layers," so the X axis is likely more closely tied to laser spot motion. As such, for the purposes of this paper and subsequent discussion, the authors have chosen to use the letter R to designate error motions of the Recoater Arm.

Powder layer geometry is determined by the interaction of the recoater arm and the build platform. The recoater arm can be viewed as a rigid body in that the motion is repeated in the same plane throughout the build process. The build platform motions are comprised of small incremental changes as each layer is completed. The powder reconstitution process (see FIGURE 2) involves lowering the dispenser platform, lowering the build platform, moving the recoater arm to the far right location, raising the dispenser to its original position plus an amount determined by process parameters, raising the build platform to a position 0.02 mm (equal to one layer thickness) below the previous level then moving the recoater arm to its far left position; thus spreading a layer of powder over the build plate.

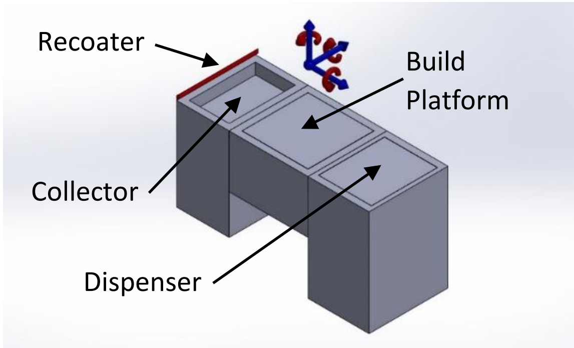

FIGURE 2: Chamber Layout of the test machine

The combined error motions of both the recoater arm and build platform determine deviation in the powder layer geometry. Error motions of the recoater arm directly affect the powder layer while build platform motions can affect both powder layer and part geometries. As the recoater arm is spreading the next powder layer, only two error motions contribute directly to variations in the powder layer. Those motions are: straightness in the Z direction, or E_{ZR} and angular error in A, or E_{AR}. The recoater likely has errors in the other four directions, but they do not influence layer thickness. All six error motions of the build platform have some effect on the build. E_{YZ}, E_{XZ}, and E_{CZ} only affect part geometry, not layer thickness. E_{AZ}, E_{BZ} and E_{ZZ} affects both the part geometry and the layer thickness.

TESTS AND ANALYSIS

Data is presented here as evidence of the efficacy in applying machine error equipment and procedures to a new technology. No inferences should be drawn as to the performance of the AM machine being tested.

In keeping with ISO suggested procedures, all measurements were taken between the recoater arm the, "(tool") and the build platform (the," part"). To accomplish this a Metrology Adapter (see FIGURE 3) was designed which was attached to a convenient rectangular bar placed by the manufacturer for aligning the build plate prior to starting a build. This adapter held the capacitance probes for Recoater Arm measurements, a target for environmental tests, the reference level, and optics for laser displacement measurements.

Environmental Temperature Variation Error (ETVE) quantifies the effect of thermal changes in the machine structure caused by the environment and start-up of a machine tool. A precision target (see FIGURE 3) consisting of two gage spheres is mounted to the metrology adapter, and a nest of five capacitance probes to the build platform. Relative changes in location due to thermal expansions can be recorded and analyzed to show both linear and angular displacements.

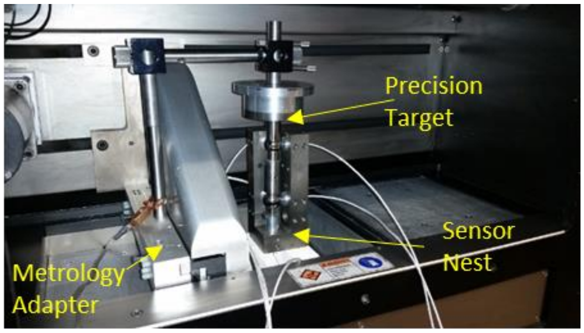

FIGURE 3: Instrument Layout for ETVE Measurements

For the purposes of this study the test consisted of three elements; machine off, machine on (computer and mechanical systems), and build plate heating. The test spanned a period of 8 hours.

Results are shown in FIGURE 4. Surprisingly, the plot shows what is best described as a step change behavior as opposed to the expected exponential effect of thermal saturation.

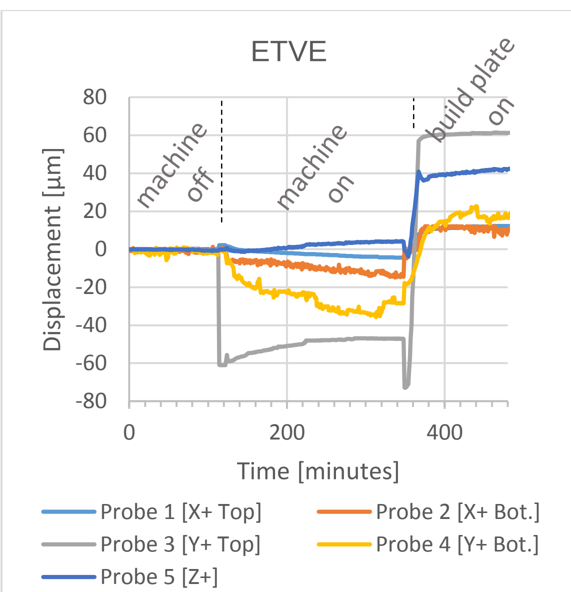

FIGURE 4: ETVE measurement results

Errors in linear axis motion

For linear motion tests, it is important to note that bidirectional axis motions were not employed during this study for two reasons. First, the build process is a series of unidirectional motions. In the case of the recoater arm, the powder is spread only as it traverses from right to left. Secondly, the build platform nominally moves in a negative Z direction as the build progresses. Notably the manufacturer has built a reversal motion into its positioning sequence. As the platform repositions in the negative direction it first overshoots the desired location by approximately 1 mm then moves in an upward, or positive motion to its target. This motion only occurs as the build platform moves in the negative, or downward direction.

Another fact worth noting is that all tests were run with the build chamber door open. With the exception of laser displacement tests it is possible to run most tests with the door closed by routing wiring through access ports.

Capacitance Probes were also utilized to measure Recoater Arm errors E_{ZR} and E_{AR}. The probes were oriented downward in two locations in the metrology adapter 175 mm apart. A build plate was bolted to the Build Platform to act as a reference artifact. Separate CMM measurements were conducted on the plate to remove artifact errors from the data.

Data were taken as the recoater arm traversed from right to left at 20°C. Results are shown in FIGURES 5 and 6.

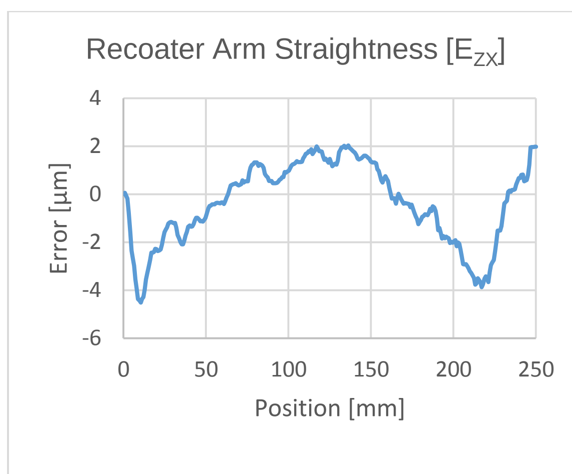

FIGURE 5: Recoater Arm straightness in Z

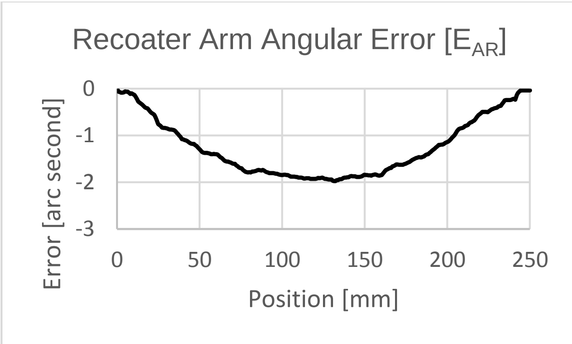

FIGURE 6: Recoater Arm error in A

<u>Interferometer</u> tests for position and angular errors A and B of the build platform motion (Z-axis) were conducted throughout the z-axis range. Interferometer optics were mounted to the metrology adapter and target optics to the Build Platform (see FIGURE 7). The full axis travel was measured in 10 mm increments and four randomly chosen locations (20, 75, 125, and 187 mm) were selected for 20 µm (the nominal powder layer thickness) tests over a 1 mm range. Results are shown in FIGURES 8, 9, and 10.

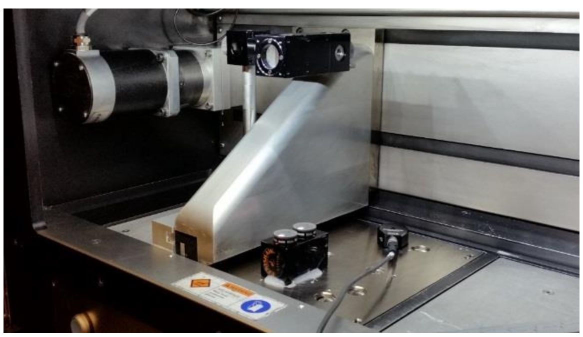

FIGURE 7: Instrument layout for laser measurements of the Build Platform axis

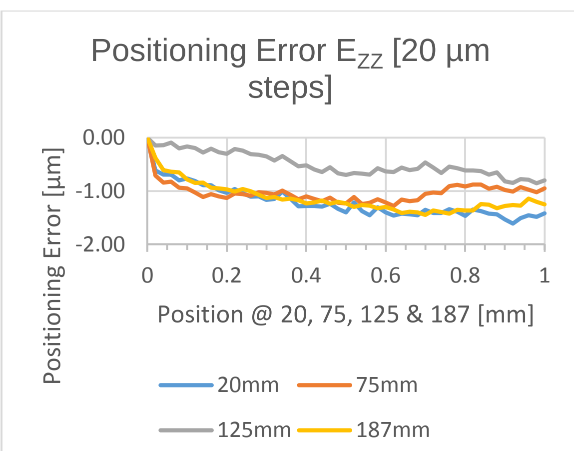

FIGURE 8: Random location 20 µm steps

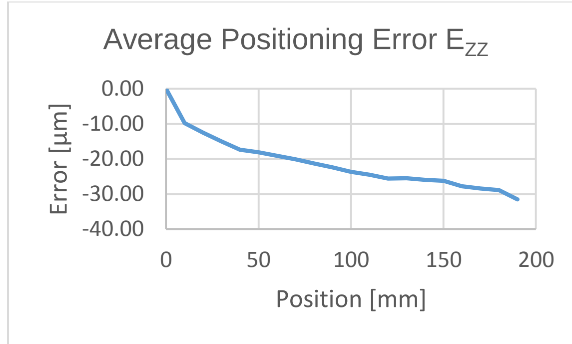

FIGURE 9: Build platform positioning error

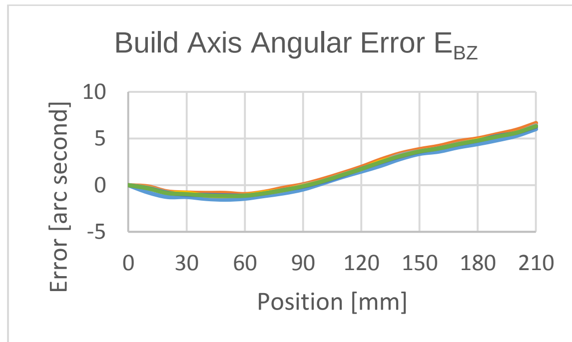

FIGURE 10: Build Platform rotation in B

<u>Precision Differential Level Measurements</u> for build platform rotations A and B were conducted for both applicability and comparison to laser results. A reference level was placed on the Metrology Adapter (see FIGURE 11), located at the far left position for clearance reasons, and the measurement level on a thermal isolation block on the Build Platform. This measurement series provided the best opportunity for taking data at 80 °C. While the addition of the thermal block reduced the range of motion, it was considered necessary to protect the equipment. Results can be seen in FIGURES 13 and 14.

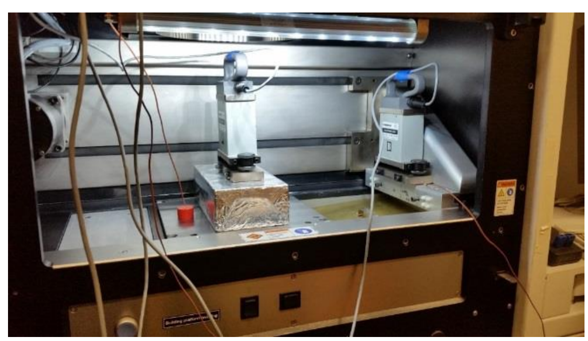

FIGURE 11: Instrument Layout for Differential Level Measurements

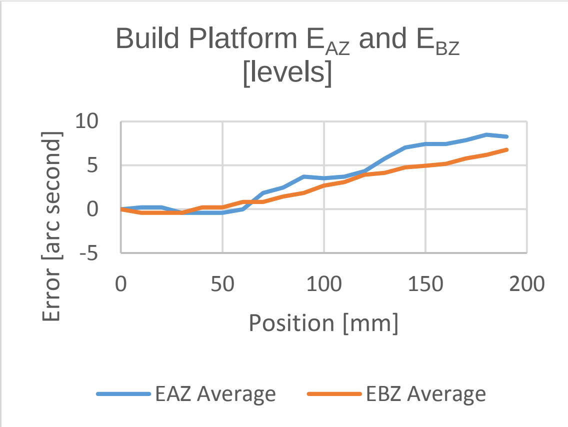

FIGURE 13: Build Platform angular errors

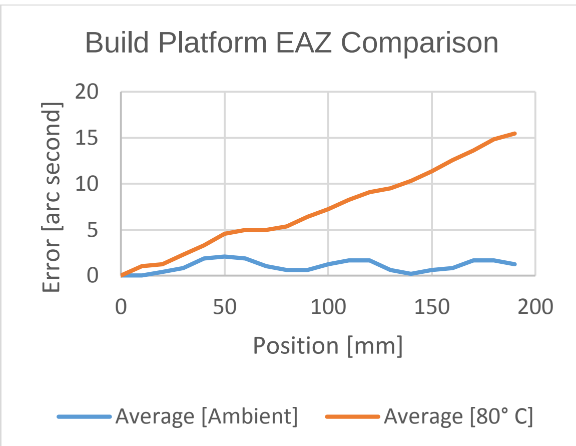

FIGURE 14: Comparison of angular error A at ambient and operating temperatures

Estimated uncertainty calculations [2, 3] are $U_{Expanded}$ = 5.91 µm (k=2) for the laser displacement measurements, U_{Device} = 0.014 µm capacitance probes, and U_{Device} = 0.4 arc seconds for the Differential Levels.

DISCUSSION

As can be seen in the previous section, we were able to complete all of the required measurements without major changes from the methods prescribed in the standards. The largest required change is the selection of target positions for the Z-axis. ISO 230-2 [2] suggests target positions derived from an equation resulting in a stratified random pattern of targets that avoids complications of periodic error. ANSI B5.54 [3] does not suggest specific targets, but does require selection of target positions over the full travel range of the axis. Both standards require a minimum of five targets following a specific serpentine test cycle. For testing the errors in positioning for layer thickness, the obvious target interval is equal to the nominal layer thickness. We wanted to test throughout the entire range of travel for the axis because positioning error may vary throughout, but testing a target interval of 20 µm over the entire range (210 mm) is impractical. We arbitrarily chose four areas in the range of axis motion to test 20 µm intervals over 1 mm travel. For standardization, a more systematic approach to choosing the areas to test at layer thickness intervals may be desired. Further, the appropriate number of areas to test at these finer intervals may require more thought. The parameters described in the standard for the ETVE test [3] are logical for the typical thermal saturations seen in machine tools, but the data seen here in FIGURE 4 may suggest that the time intervals for testing could be altered for testing LPBF machines. On one hand, the displacements seem to reach steady state rather quickly. On the other hand, an AM build may last days. More data, analysis, and thought are needed before any specific recommendations can be reached. It is also worth noting that our study ignored one test discussed in ISO 230-3. Thermal displacement due to axis motion was deemed insignificant considering the slow infrequent motion of the Recoater and Z-axis during a build and the fact that the build platform heating to 80 °C is likely much larger than any heat generated by motion.

Not surprisingly, experimental results suggest that temperature plays a large role in the positioning error as well as the measurement of positioning error. Measuring at the elevated operating temperature would likely be desired to give a better estimation of how the machine performs during actual operation. However, we found that some measurement equipment, the laser interferometer specifically, did not work when the build platform was heated to this temperature.

Measuring at higher temperatures has a large impact on measurement uncertainty. Because the laser interferometer would not work properly, a device with larger uncertainty would be needed to perform the measurement. Further, the standards state that if measurements are carried out at temperatures other than 20 °C, the relative expansion between the machine and the measurement device must be compensated. This task requires knowledge of the coefficients of thermal expansion, which also have uncertainty. If we assume an uncertainty in coefficient of thermal expansion of 2 µm/m °C (the “typical range” given in ISO 230-2), the expanded measurement uncertainty when the build platform is at 80 °C is approximately 0.07 µm when the measurement length is 1 mm, as is the case for the finer interval measurements. However, when testing over the entire range of Z-axis or Recoater axis motion (≈ 200 mm), the expanded measurement uncertainty increases to approximately 14 µm, more than half of a layer thickness and approximately half of the total deviation observed here. Note that these values do not account for uncertainty in the measurement of temperature, nor do they account for uncertainty in the measurement device, both of which may increase with increasing temperature.

Another minor complication, the challenge of aligning the measurement device with the motion of the axis, also has implications on measurement uncertainty. Of the commercially available metrology tools used in this study, only the laser displacement measurements presented challenges during setup. In a typical setup on a machine tool, where one motion axis can usually be used to aid in alignment, it is relatively easy to align the laser with the return beam within 1 mm, resulting in an expanded uncertainty due to misalignment of less than 1 µm. Because the laser head is relatively large compared to the AM build chamber, it was necessary to place the laser outside the machine and to use a turning mirror to align the beam to the axis being tested. The lack of a motion axis orthogonal to the measurement axes (aligned to the laser head) made the initial alignment of the laser beam more difficult. This is simply overcome by the addition of linear and rotary stages to the optical fixturing, allowing for small adjustments of the optics. However, with this method it is often more convenient to accept alignment when the return beam has sufficient intensity, rather than estimating the actual alignment error. In this case, alignment error is assumed to be on the order of 2 mm, increasing the expanded uncertainty due to misalignment to approximately 6 µm.

CONCLUSIONS

This study shows that existing machine tool metrology equipment and standards can be effectively applied to LPBF type machines. What is needed is a standards document providing guidance specific to AM machines om which test(s) to perform and the respective conditions. The direct measurement of individual machine errors provides manufacturers and end users with diagnostic information and error models applicable to a wide range of part geometries.

REFERENCES

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[2] ISO 230-2:2014, Test Code for Machine Tools – Part 2: “Determination of Accuracy and Repeatability of Positioning of Numerically Controlled Axes”

[3] ANSI B5.54-2005, “Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers”

[4] ISO 230-3:2012, Test Code for Machine Tools – Part 3: “Determination of Thermal Effects”

[5] Moylan, S., Drescher, J., Donmez, M.A., 2014, “Powder Bed Fusion Performance Testing,” ASPE 2014 Spring Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing.

[6] ISO/ASTM 52921-13 “Standard terminology for additive manufacturing -- Coordinate systems and test methodologies”