Proceedings of the ASME 2021
International Mechanical Engineering Congress and Exposition
IMECE2021
November 1-5, 2021, Virtual, Online

IMECE2021-71737

GEOMETRIC PERFORMANCE TESTING OF DIRECTED ENERGY DEPOSITION ADDITIVE MANUFACTURING MACHINE USING STANDARD TESTS FOR MACHINE TOOLS

Shawn Moylan
National Institute of Standards and Technology
Gaithersburg, MD

Michael McGlauflin
National Institute of Standards and Technology
Gaithersburg, MD

Jared Tarr
National Institute of Standards and Technology
Gaithersburg, MD

M. Alkan Donmez
National Institute of Standards and Technology
Gaithersburg, MD

ABSTRACT

While performance testing of additive manufacturing machines is still nascent, standard tests for performance of machine tools used in metal cutting are well established. Our hypothesis is that because directed energy deposition (DED) additive manufacturing machines physically resemble typical vertical machining centers, standard geometric performance tests for machine tools will directly apply to DED machines. Standard tests of positioning error motions and circular motion were successfully conducted on a commercially-available DED system. With all tests providing reasonable and expected results, there is nothing to falsify our hypothesis. One additional consideration is the need for testing of the Z-axis on additive manufacturing machines using target positioning intervals on the order of a typical layer thickness at several positions along the axis.

Keywords: additive manufacturing; directed energy deposition; machine qualification; machine performance; geometric errors; standard test methods

1. INTRODUCTION

Performance testing is vital to optimal commerce and utilization of manufacturing equipment of all kinds. Standard tests allow vendors and customers to communicate capabilities in easily understood terms. Furthermore, using standard tests for acceptance of equipment at installation sets expectations for all parties involved in the purchase. Performance testing allows a user to fully understand the limitations of the equipment and periodic testing allows a user to track performance degradation, informing critical decisions about asset allocation and maintenance.

While this is equally true for additive manufacturing (AM) machines as for machine tools, performance testing of AM machines is still developing. AM machine geometric performance testing is not a high priority among recently released roadmaps [1], [2], and reviews [3], therefore limited research exists on this topic. One reason for this is the unknown or unestablished relationship between the machine geometric performance and the resulting part geometry in AM. On the contrary, such relationship is well established in conventional manufacturing.

Performance testing of in AM has focused largely on the parts more than machines. Geometric test artifacts comprise the vast majority of efforts in this area. This approach to performance testing bypasses the unknown relationship between the machine geometric performance and the resulting part geometry, attempting to answer geometric performance questions by measuring geometric accuracy of resulting parts fabricated on AM machines. Several review articles summarize the hundreds of artifacts detailed in literature [4],[5],[6],[7] and a recently published standard on the topic [8], [9]. Beyond test artifacts, performance testing is mostly limited to assessing limitations for geometric dimensioning and tolerancing, e.g., [10] and [11], and assessing minimum feature sizes, e.g., [12] and [13]. These methods do not provide valuable information about the sources of part inaccuracies. In order to establish the critical relationship between the machine geometric performance and the resulting part geometry in AM, we need to assess the machine geometric performance independent of the process and make the proper comparisons with the resulting part geometries.

Whereas precision engineering concepts are only recently proliferating in AM [14], machine tool performance measurement is based on years of research in precision machine design [14],[16],[17] and precision measurement [18],[19],[20]. This approach, building off of the known relationship between machine errors and part errors, advocates a deterministic approach to performance testing, where measurement of error motions in machine components allows users to determine the expected errors in parts produced by the machine. This strong

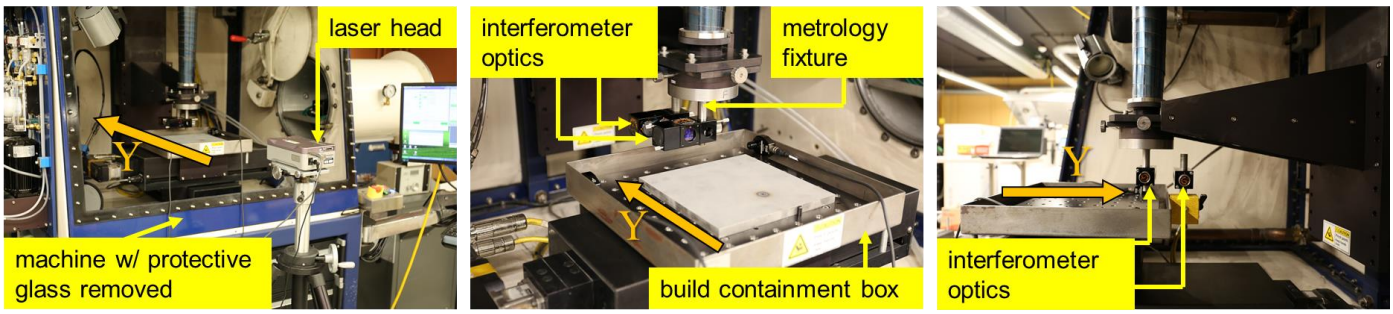

FIGURE 1: THREE VIEWS OF THE SETUP FOR MEASURING LINEAR DISPLACEMENT ERROR IN THE Y-AXIS. LEFT: WIDE VIEW; CENTER: CLOSE-UP OF BUILD AREA; RIGHT: SIDE VIEW.

foundation of research supports key standards on the topic [21],[22],[23],[24].A logical approach to shorten the learning curve in AM is to draw from proven work in other fields—machine tool metrology in this case. Indeed, some have taken this approach, for example in laser powder bed fusion machines [25],[26]. However, we are not aware of similar work on directed energy deposition (DED) machines. Our hypothesis is that because DED machines physically resemble typical vertical machining centers, standard geometric performance tests for machine tools will directly apply to DED machines.

2. EXPERIMENTAL SETUP

The machine, test equipment, setups and tests performed all use standards and devices that are commonly available commercial products.

2.1 Machine

The machine in this study was an Optomec LENS MR-7 DED machine. The machine uses a four-nozzle deposition head to blow metal powder into the laser beam focal spot. We call this point the functional point of the machine because we believe this is the best analogy to the functional point on a machine tool, which is where the cutting tool meets the workpiece.

The X- and Y-axes are stacked on the bed of the machine. This represents the workpiece side of a conventional machine tool. The deposition head is attached to the vertical Z-axis to create the layer-by-layer motion. This represents the tool side of a conventional machine tool.

The machine has a build volume of approximately 300 mm x 300 mm x 300 mm. However, limiting factor to the maximum workable distances is the lack of software-based travel limits on the individual axes. To avoid hitting hard stops at the ends, we used approximately 90 % of the travel range for each test.

2.2 Testing Equipment

ISO/TR 230-11 summarizes equipment used for testing machine tools [26]. Linear displacement error motions and angular error motions were measured using a laser displacement interferometer. Straightness error motions were measured using a reference straightness artifact (straightedge) and capacitance-based displacement sensors. A reversal technique was used to separate the straightness error motion from the straightness error in the artifact [21]. Circular tests were performed using a 100 mm long telescoping ball bar.

2.3 Test Setups

A special fixture was designed to mount tool-side components of measuring instruments at the functional point to reduce measurement uncertainty (see Figure 1). The deposition head was removed, and this fixture was attached in its place. Note that it is not a requirement to manufacture a special fixture head to accomplish these measurements. Other means of fixturing can be achieved while leaving the original deposition head in place. Users should take note that an offset between the measurement location and the functional point (Abbe offset) may contribute to measurement uncertainty [16].

2.3.1 Linear and Angular Displacement

Linear displacement tests and angular displacement tests are described in detail in [21], [22], and [23]. A laser interferometer uses a simple setup and provides measurement with low uncertainty. Tests were conducted on all three machine axes. Ten sets of bi-directional measurements were taken with 19 target positions in each direction. Target positions were selected in accordance with ASME B5.54 to eliminate equally spaced intervals corresponding to multiples of the pitch of the test axis lead screw [21]. For testing the X- and Y-axes, the Z-axis was lowered so the tool-side fixture was just above the build containment box and approximately centered above the build platform. Figure 1 illustrates the setup for the measurement of linear displacement error along the Y-axis. Measurement uncertainty on an individual displacement measurement was 1.54 µm, calculated according to ISO 230-2 [22].

AM machines differ from machine tools in that Z-axis motion is predominantly short moves corresponding to layer thickness of the builds. We believe the error motions at this scale are highly important to an AM machine's performance due to the resulting variations in layer thickness during the builds. We performed additional "layer-thickness" positioning error tests on the Z-axis with target positions spaced by 0.3 mm (0.012"), a typical part layer thickness, over a travel range of 6.7 mm. Four randomly-chosen regions within the total travel range were selected for testing. Ten bi-directional runs were performed at each region using 22 target positions.

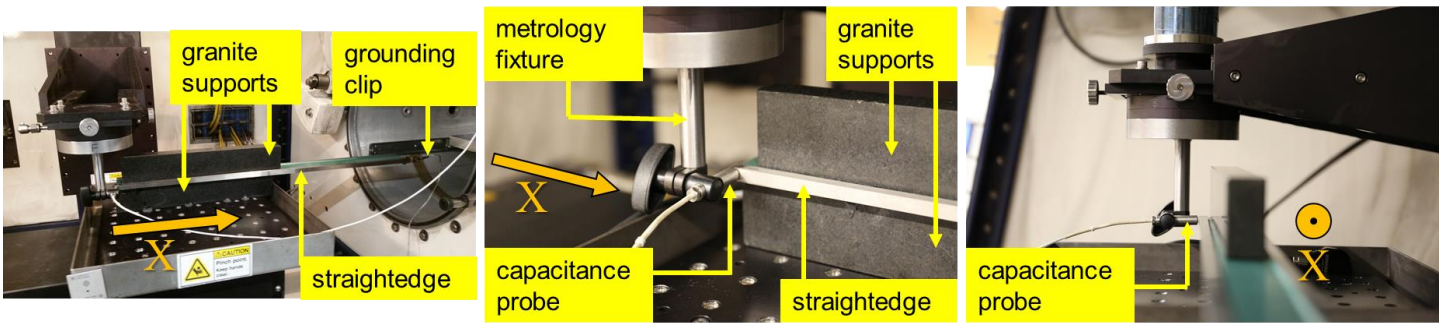

FIGURE 2: THREE VIEWS OF THE SETUP FOR MEASUREING X-AXIS STRAIGHTNESS ERROR IN THE Y-DIRECTION. LEFT: WIDE VIEW; CENTER: CLOSE-UP OF SENSOR AND STRAIGHTEDGE; RIGHT: SIDE VIEW.

2.3.2 Straightness Tests

Straightness tests are described in detail in [21] and [22]. We chose to use a straightedge because of the simplicity of the setup [21]. Straightness tests were conducted only on the X- and Y-axes. Figure 2 illustrates the setup measuring X-axis straightness in the Y-direction. The straightedge was on the workpiece side, aligned to the axis of motion, and capacitance-based displacement sensors, mounted on the tool side, measured the lateral motion in the two directions orthogonal to the direction of motion with uncertainty approximately 0.5 µm. Ten runs for both directions were conducted on each axis.

2.3.3 Circular Test with Telescoping Ball Bar

A ball bar test measures the ability of a machine to generate a circular path by coordinating two or more axis motions [24],[27]. This type of test is quick to set up and execute; characterizing a wide range of geometric errors such as: positioning accuracy, reversal error, backlash, straightness, and squareness of the test axes. For the purposes of this research, 360-degree tests were performed in the XY-plane (setup showing in Figure 3), and 180-degree tests were performed in YZ- and ZX-planes due to interference from the laser head support structure. Note that 360-degree tests are feasible with additional support fixtures. The worktable-mounted sphere was at the nominal center of the XY work area. The expanded uncertainty (k = 2) with this setup was approximately 1.1 µm.

3. RESULTS

No effort was made to calibrate or compensate the machine prior to testing. These results simply indicate the viability of testing procedures; the systematic components of these errors can easily be compensated via machine controller.

Figure 4 shows the results of a positioning error test for Y-axis (E_{YY}) per ASME B5.54, where B is the reversal error, R is bidirectional repeatability, E is the bidirectional systematic positioning error, and A is the bidirectional accuracy of positioning [21]. Table 1 summarizes the results for the X- and Y-axes:

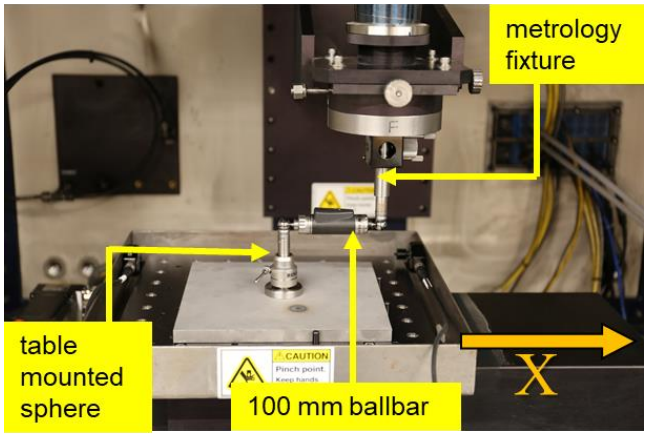

FIGURE 3: SETUP FOR CIRCULAR TEST IN XY-PLANE.

TABLE 1: SUMMARY RESULTS FOR POSITIONING ERROR TESTS

Error	X-axis	Y-axis
B	10.8 µm	31.5 µm
R	2.6 µm	39.6 µm
E	48.1 µm	112.9 µm
A	54.2 µm	113.3 µm

Positioning error test results of the total Z-axis travel are shown in Figures 5 and 6. A coiled spring steel cover protects the machine's processing laser beam along the Z-axis. This cover was not functioning properly on our machine. Poor engagement of the sections of the axis cover led to excessive rubbing when traveling upward, causing a large, non-repeating force on the support bracket holding the laser head in place. The effects of these on the machine's motion can be seen in the results for positive motion of the Z-axis, shown in Figure 5. As the axis moved in the negative direction, disengagement of the sections of the axis cover did not produce the same rubbing and a more linear, systematic error motion is observed. The results of these tests brought the malfunction to our attention. Once we removed the axis cover and conducted the same tests, performance improved, as seen in Figure 6, demonstrating that the performance tests are effective at identifying error motions.

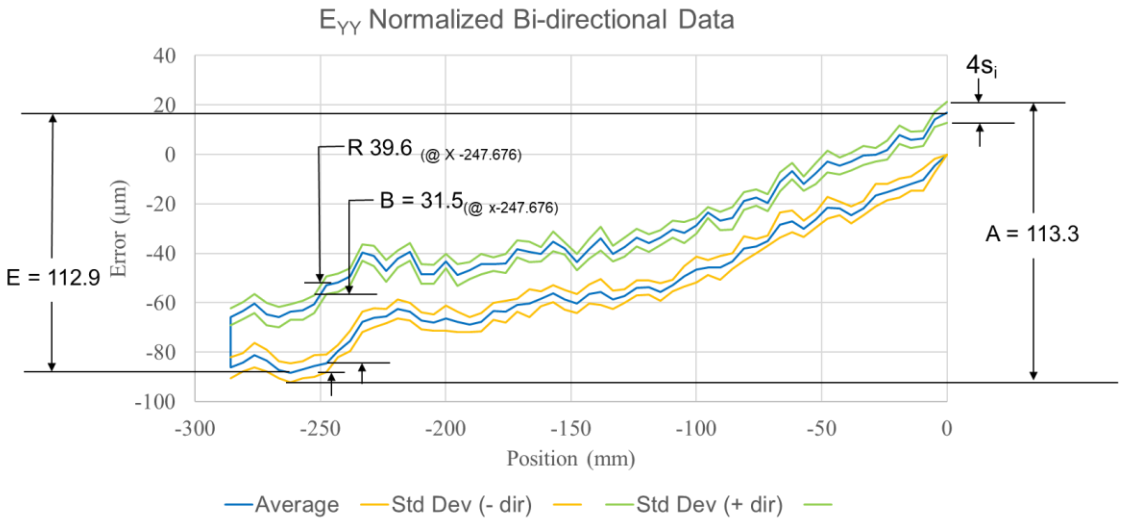

FIGURE 4: RESULTS OF LINEAR DISPLACEMENT ERROR MEASUREMENT ON Y-AXIS. NOTE THE SIMILARITIES BETWEEN THIS PLOT AND PLOTS IN ISO 230-2 and ASME B5.54. s_i = STANDARD DEVIATION

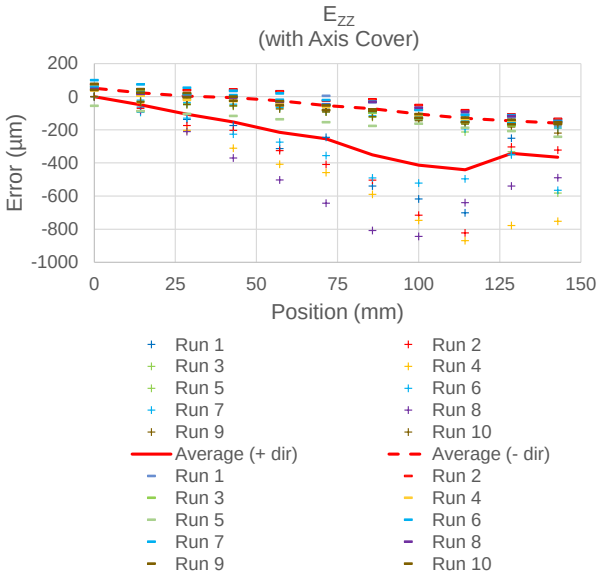

FIGURE 5: RESULTS OF MEASUREMENT OF Z-AXIS LINEAR DISPLACEMENT ERROR, Ezz, WITH COVER IN PLACE CREATING LARGE ERRORS AND REQUIRING PARTIAL AXIS TRAVEL.

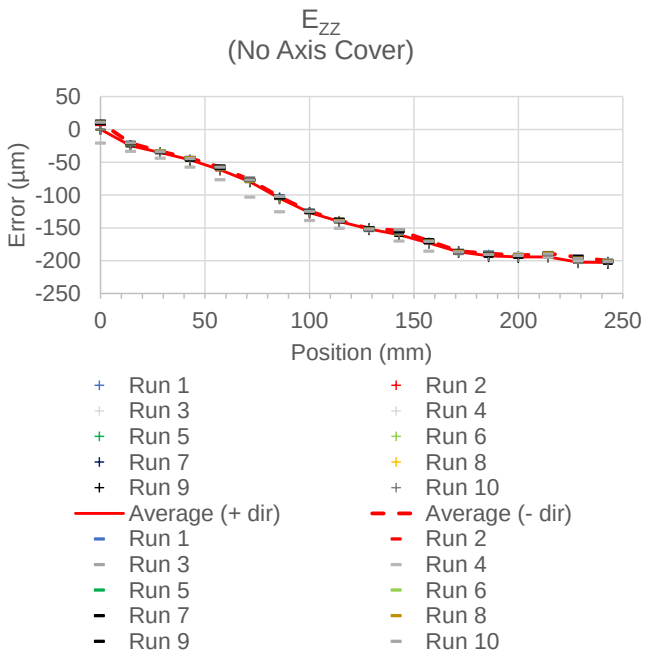

FIGURE 6: RESULTS OF MEASUREMENT OF Z-AXIS LINEAR DISPLACEMENT ERROR, Ezz, WITH COVER REMOVED. NOTE THE DIFFERENT SCALE ON THE ORDINATE AXIS FROM FIGURE 5.

Figure 7 shows results of layer-thickness tests at four random regions. Here, the small spreads in data at each measurement position demonstrate that these errors are largely systematic. However, it may be impractical to compensate at every layer position. We note that the maximum extent of deviation over the entire bi-directional motion, analogous to A in the full axis test, were 26.4 µm, 14.7 µm, 14.0 µm, and 12.7 µm for the tests conducted at Z = 0.0 mm, Z = 85.55 mm, Z = 127.74 mm and Z = 217.14 mm, respectively. We also note that the maximum deviation from one target to the next (of the averaged position over the ten bi-directional runs), i.e., the largest deviation from the expected layer thickness, was -4.3 µm, 4.1 µm, -2.9 µm, and 2.5 µm in each test region. If one value were to be reported for each of these, we believe that the maximum values should be reported to inform a user of the largest expected deviation.

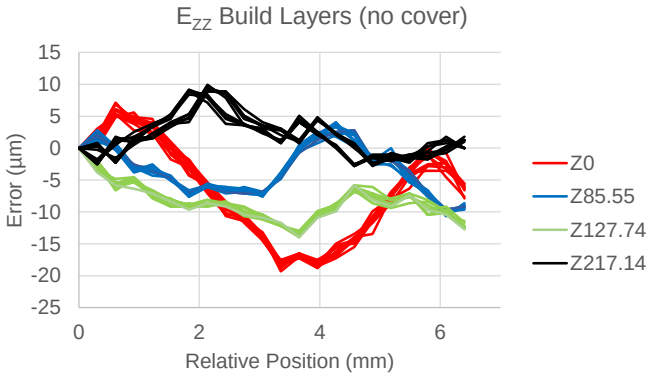

FIGURE 7: RESULTS OF MEASUREMENT OF Z-AXIS LINEAR DISPLACEMENT ERROR, E_{ZZ}, WITH TARGET INTERVALS CORRESPONDING TO BUILD LAYER THICKNESSES. TEN BI-DIRECTIONAL RUNS AT EACH OF FOUR RANDOMLY SELECTED REGIONS ARE OVERLAYED ON THE PLOT.

Figure 8 shows the measured angular error motions. Figure 9 illustrates the straightness error motions after separating the straightedge straightness [21].

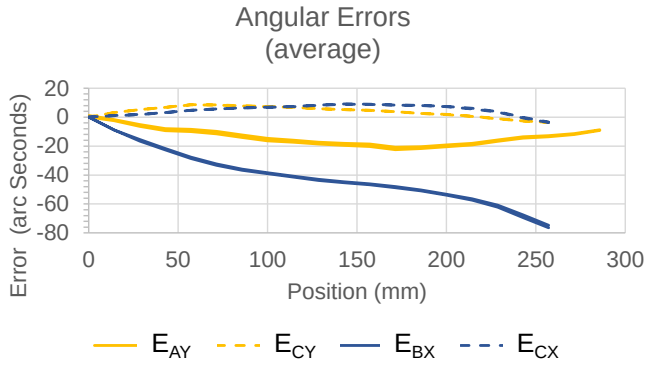

FIGURE 8: RESULTS OF MEASUREMENT OF ANGULAR ERROR MOTIONS IN X- AND Y-AXES.

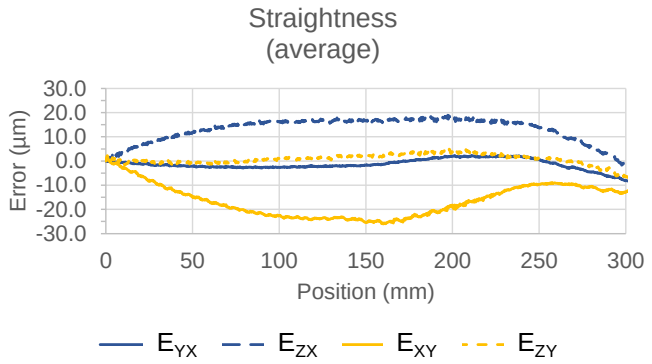

FIGURE 9: RESULTS OF MEASUREMENT OF STRAIGHTNESS ERROR MOTIONS IN X- AND Y-AXES.

Results for Circular Deviation in the ball bar tests were:

- XY-plane: 76.5 µm in the clockwise (CW) direction and 105.1 µm in the counterclockwise (CCW) direction;
- YZ-plane: 70.6 µm (CW) and 46.9 µm (CCW); and
- ZX-plane: 154.7 µm (CW) and 158.7 µm (CCW).

Completing 360-degree tests in the XY-plane allowed for additional results from the analysis software, as seen in Figure 10. For example, squareness error, the angular misalignment of the Y-on-X-stacked slides, was 612.7 µm/m. Other results confirmed earlier testing, albeit with a simpler setup and quicker tests. For example, straightness error in X was 10.8 µm and 23.3 µm in Y were very similar to straightness results obtained using the straightedge.

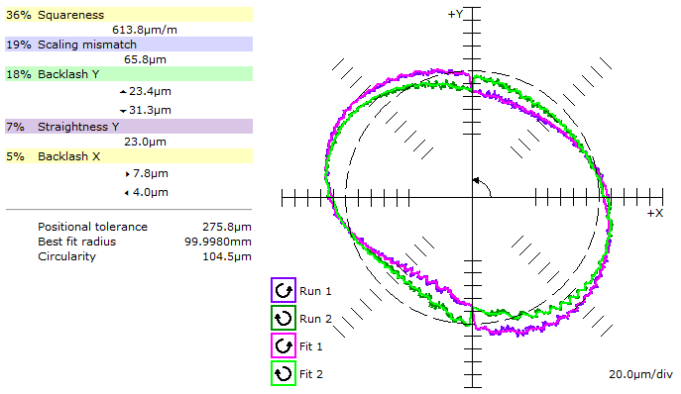

FIGURE 10: RESULTS OF CIRCULAR TEST IN XY-PLANE USING A TELESCOPING BALLBAR.

4. CONCLUSION AND FUTURE WORK

With all tests providing reasonable and expected results, there is nothing to falsify our hypothesis. Indeed, the importance of machine performance testing to identify and rectify sources of unexpected errors for improved performance was demonstrated in this work with the unexpected observation regarding the machine Z-axis cover and the improved results with the axis cover removed. Extrapolating, we believe that other standard

tests, such as diagonal displacement testing [28], and other measuring instruments, such as laser tracers for larger machines [27], in the ISO 230 series would also apply to DED machines.

We can envision a DED-specific or AM-specific standard for performance evaluation that largely references existing standards for machine tool metrology and adds some specific guidance. One additional consideration is the need for testing of the Z-axis using target positioning intervals on the order of a typical layer thickness at several positions along the axis. Furthermore, additional guidance on the functional point for DED and its implication on test setups is likely warranted.

A next step for research in performance evaluation is to compare results from these standard tests with results from a test artifact. Because the tests described here isolate errors resulting from machine components whereas a test artifact compounds variations from machine components and process physics, we expect to see differences. Large differences between results from these approaches would indicate that a significant amount of geometric errors in parts may result from the stochastic nature of the process physics. In this case, compensation of geometric errors may have limited impact compared to improvements in control of the process.

DISCLAIMER

This is an official contribution of the National Institute of Standards and Technology; not subject to copyright in the United States. Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by NIST, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

REFERENCES

[1] Joint Defense Manufacturing Council. 2021, *Department of Defense Additive Manufacturing Strategy*. https://www.cto.mil/wp-content/uploads/2021/01/dod-additive-manufacturing-strategy.pdf (last accessed June 28, 2021).

[2] America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMCS). 2018. Standardization Roadmap for Additive Manufacturing. https://www.ansi.org/standards-coordination/collaboratives-activities/additive-manufacturing-collaborative (last accessed June 28, 2021).

[3] R. K. Leach, D. Bourell, S. Carmignato, A. Donmez, N. Senin, and W. Dewulf. 2019. Geometrical metrology for metal additive manufacturing. *CIRP Ann.*, 68(2). 1–24.

[4] Moylan, S., Cooke, A., Jurrens, K., Slotwinski, J., Donmez, M.A. 2012. A review of test artifacts for additive manufacturing. *NISTIR 7858*. National Institute of Standards and Technology.

[5] Rebaioli, L., Fassi, I. 2017. A review on benchmark artifacts for evaluating the geometrical performance of additive manufacturing processes. *International Journal of Advanced Manufacturing Technology*, 93(5-8):2571-2598.

[6] Toguem, S.-C., Rupal, B., Mehdi-Souzani, C., Qureshi, A.J., Anwar, N. 2018. A review of AM artefact design methods. *Proceeding of ASPE and EUSPEN*. 69: 132-137.

[7] M.-A. de Pastre, S.-C. Toguem Tagne, and N. Answer. 2020. Test artefacts for additive manufacturing: A design methodology review. *CIRP J. Manuf. Sci. Technol.* 31, 14–24.

[8] ISO/ASTM 52902:2019. Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems. International Organization for Standardization. Geneva, Switzerland.

[9] J. Berez, M. Praniewicz, C. Saldana. 2021. Assessing laser powder bed fusion system geometric errors through artifact-based methods. *Procedia Manufacturing*, to appear.

[10] Al-Ahmari, A., Ashfaq, M., Mian, S.H., Ameen, W. 2019. Evaluation of additive manufacturing technologies for dimensional and geometric accuracy. *International Journal of Materials and Product Technology*. 58(2-3). 129-154.

[11] Rupal, B.S., Answer. N., Secanell, M., Qureshi, A.J. 2020. Geometric tolerance and manufacturing assemblability estimation of metal additive manufacturing (AM) processes. *Materials and Design*. 194.

[12] Geng, H., Li, J., Xiong, J., Lin, X., Zhang, F. 2017. Geometric Limitation and Tensile Properties of Wire and Arc Additive Manufacturing 5A06 Aluminum Alloy Parts. *Journal of Materials Engineering and Performance*. 26(2). 621-629.

[13] Kim, M.J., Saldana, C. 2020. Thin wall deposition of IN625 using directed energy deposition. *Journal of Manufacturing Processes*. 56, 1366-1373.

[14] Leach, R., Carmignato, S. (ed). 2021. *Precision Metal Additive Manufacturing*. CRC Press. Boca Raton, FL.

[15] Donmez, M.A., Blomquist, D.S., Hocken, R.J., Liu, C.R., Barash, M.M. 1986. A General Methodology for Machine Tool Accuracy Enhancement by Error Compensation. *Precision Engineering*. 8(4):187–196.

[16] Slocum, A.H., 1992, *Precision Machine Design*, Society of Manufacturing Engineers, Detroit, Michigan.

[17] Schellekens, P. and Rosielle, N., 1998, "Design for precision: current status and trends," CIRP Annals, v47, no2, pp 557-586.

[18] Sartori, S. and Zhang, G.X., 1995, Geometric Error Compensation of Machines, *CIRP Annals*, 44(2), 599-609.

[19] Schwenke, H. Knapp, W., Haitjema, H., Weckenmann, A., Schmitt, R., and Delbressine, F., 2008, Geometric Error Compensation of Machines – An Update, *CIRP Annals*, 57(2), 660-675.

[20] Smith, G., 2016, *Machine Tool Metrology: An Industrial Handbook*, Springer.

[21] ASME B5.54-2005. Methods for performance evaluation of computer numerically controlled machining centers. American Society of Mechanical Engineers. New York, New York.

[22] ISO 230-1:2012. Test code for machine tools - part 1: geometric accuracy of machines operating under no-load or quasi-static conditions. International Organization for Standardization. Geneva, Switzerland.

[23] ISO 230-2:2014. Test code for machine tools - part 2: determination of accuracy and repeatability of positioning of numerically controlled axes. International Organization for Standardization. Geneva, Switzerland.

[24] ISO 230-4:2005. Test code for machine tools - part 4: circular tests for numerically controlled machine tools. International Organization for Standardization. Geneva, Switzerland.

[25] Moylan, S., Drescher, J., Donmez, M.A. 2014. Powder bed fusion machine performance testing. *Proceedings of ASPE*. April. Berkeley: 57:123-126.

[26] Lu, Y., Badarinath, R., Lehtihet, E.A., De Meter, E.C., Simpson, T.W. 2018. Experimental sampling of the Z-axis error and laser positioning error of an EOSINT M280 DMLS machine. *Additive Manufacturing* 21: 201-216.

[27] ISO/TR 230-11. Test code for machine tools — Part 11: Measuring instruments suitable for machine tool geometry tests. International Organization for Standardization. Geneva, Switzerland.

[28] ISO 230-6:2002. Test code for machine tools - part 6: determination of positioning accuracy on body and face diagonals (diagonal displacement tests). International Organization for Standardization.