Powder Bed Fusion Machine Performance Testing

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INTRODUCTION

Although additive manufacturing (AM) is often referred to as a "disruptive technology," there are many ways an AM process is similar to conventional processing methods. Raw material is prepared for the processes: casting, forging, forming, powder creation, etc. Then the process is performed by a machine on the prepared material: turning, milling, grinding, electrical discharge machining (EDM), laser drilling, powder bed fusion, etc. Finally, the processed part is typically post-processed—heat treatment, deburring, polishing, etc.—to obtain desired material properties, surface condition, etc.

Independent of the processing path, there are four basic categories of quality for all processed parts: dimensions, form, surface finish, and material properties. One approach to understanding the contributions of the machine performance to the overall part quality is to begin with a list of independent error motions of the machine components. For a traditional machine tool, these are the well-known parametric and geometric errors of the axes, but AM machines require more thought and study.

GEOMETRIC ERRORS IN MACHINE TOOLS

The accuracy of the positioning of a conventional linear machine axis depends on the accuracy of the scale (or other position feedback device) together with two angular errors, each paired with an offset distance. The two angular error motions are typically called pitch and yaw. The lateral offsets are from the scale position to the point where the workpiece and cutting tool intersect in a plane perpendicular to the nominal motion. Straightness is the lateral deviation from the nominal axis direction, which is also dependent on the position of the functional point and two angular error motions. In this case, the angular errors are roll and either pitch or yaw. However, an offset of the functional point perpendicular to the motion in the direction of the straightness deviation is typically assumed to not affect straightness.

Typical 3-axis machine tools generally consist of a combination of stacked linear axes. As such, with a known tool location and point of contact with the workpiece, the systematic portion of the errors can be predicted from the measured data of 21 well defined tests: 3 linear accuracy tests (1 for each axis), 6 straightness tests (2 for each axis in perpendicular directions to motion), 9 angular error motions (3 for each axis), and 3 squareness tests (YX, ZX, and ZY) [1]. Note that many of these tests can be performed simultaneously.

PBF MACHINES ARE MORE CHALLENGING

Laser-based powder bed fusion (PBF) additive manufacturing machines also follow the concepts of axes for motion and positioning [2], but the concept of the functional point and the method of actuating that point are different. In these processes, thermal energy from a laser beam selectively fuses regions of a powder bed. Figure 1 shows a two-dimensional (2D) schematic of the process. A computer model of the part's geometry is virtually sliced into discrete layers. The laser traces the geometry of an individual layer onto the top surface of a bed of powder material. After an individual layer is completed, the build platform (and therefore the entire powder bed) is lowered by the prescribed layer thickness, and a new layer of powder is swept over the powder bed, filling the resulting gap. The top surface of the powder bed is created by the recoating blade as it drags powder from the dispenser bin onto the powder bed. The laser then traces the geometry of the next layer to be built.

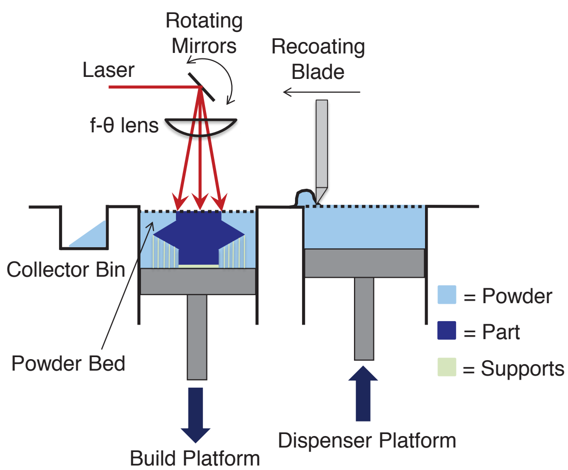


FIGURE 1. TWO-DIMENSIONAL SCHEMATIC OF A LASER-BASED POWDER BED FUSION ADDITIVE MANUFACTURING SYSTEM.

The functional point for PBF processes (i.e., the point where the part is being formed) is the point where the laser beam meets the top surface of the powder bed. Laser-based systems typically deflect the laser beam off two mirrors and through some optics (often an f-θ lens) to focus the beam on the top surface of the powder bed. The beam spot is moved by a galvanometer system that rotates the deflecting mirrors (see Figure 2).

The measurement of geometric errors and the ability to predict systematic errors is different in PBF machines than for machine tools. Accuracy of positioning the beam spot or straightness of the path of the beam spot could theoretically be measured along a nominal axis direction of the machine. However, these accuracy and straightness measurements do not provide information to predict the accuracy or straightness along any other line, or, given two orthogonal lines of measurement, at any arbitrary point. The systematic errors in the position of the laser spot in the x-y plane arise from inaccuracies in the positioning of the galvanometer mirrors, the geometric quality of the optical system alignments, the quality of the mirrors, imperfections of the f-θ lens, and the profile of the laser beam.

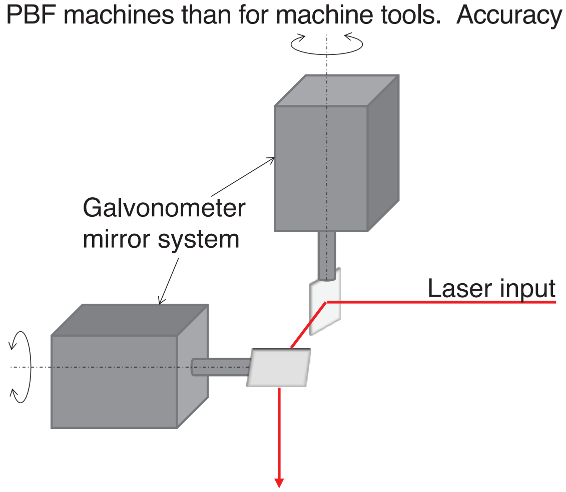


FIGURE 2. SCHEMATIC DEPICTING THE GALVANOMETER AND MIRROR SYSTEM USED TO MOVE AND POSITION THE LASER BEAM SPOT ON A TYPICAL POWDER BED FUSION MACHINE.

A complete characterization of laser spot accuracy in the 2D plane of the top surface of the powder bed could theoretically be done with an accurate representation of the machine component geometry along with detailed mapping of optical surfaces and measurement of mirror axis rotational accuracy. However, in general, this approach is impractical, requiring possible disassembly/reassembly of the machine's optical system and specialized optical test equipment. An alternate approach is to test point positioning accuracy using a workpiece or testpiece that has a sufficiently dense grid covering the entire workzone. Since the grid cannot practically be infinitely dense and because such a grid is often used to create a lookup table or parametric error representation for real-time correction, a different pattern must be used to test the resulting performance of the machine in the x-y plane.

When a test grid is generated to establish the accuracy in x and y, there are many error components which are not easy to resolve: scale errors from galvanometers, uncertainty in the kinematic geometry, and optical aberrations. While it is not necessary to measure all error components independently, it is desirable to quantify the systematic and non-systematic portions of the X-Y error so that corrections can be applied for the systematic errors and the non-systematic portion of the error can be used to establish expected performance.

DESIRED MEASUREMENTS

The non-systematic error is mainly related to thermal effects and 6 degree-of-freedom relative motion of the optical system relative to the part x-y plane. This suggests a drift test of optics to the recoating blade may be appropriate, although the test setup is difficult to imagine compared to conventional metrology methods.

The build platform, moving in the machine's z-direction, most closely resembles a traditional machine tool axis, leading one to consider the standard axis performance tests. However, while the linear accuracy of positioning through the Z-axis range relates to dimensions of finished parts or features with dimensions in the z-direction, variation in positioning accuracy over shorter distances relates to variation in layer thickness. This could have important consequences in the process performance, causing balling or incomplete melting, which lead to porosity or line/area defects. For example, in a conventional linear accuracy test [3-5] a maximum error at any point of 10 μm yields a test result of 10 μm for the axis. The axis could fluctuate between +5 μm and -5 μm at very high spatial frequency and still the axis result would be 10 μm. On a powder bed fusion machine, if the platform motion contained errors of +5 μm and –5 μm at a high spatial frequency, this could represent a 50% variation in layer thickness from the nominal programmed value, leading to possible defects throughout the entire thickness of the part. As such, both long range and short range measurement of the Z-axis is desired.

While it is true that the build platform moves the entire powder bed, the positioning of the build platform does not set the top surface of the powder bed; the movement of the recoating blade defines the top powder surface. In most machines, the recoating blade moves in the machine's x-direction. The error motions causing deviation in the top powder surface are the straightness in the z-direction along with the roll of the recoating blade. Note that non-flatness of the powder surface leads to inconsistencies in the layer thickness, as described in the previous paragraph, and small position deviations in the x-y plane as well, as illustrated in Figure 3.

MEASUREMENT METHODS

The high powers of the lasers used in PBF machines make measuring the positioning of the beam spot rather challenging. If the laser power could be sufficiently lowered, one could envision the beam spot being projected down onto a large position sensitive device (PSD, using photodiode surface resistance) that would measure the position of the focused beam relative to an established datum on the PSD. However, most PSD systems cannot handle more than a few milliwatts of laser power, let alone the tens or hundreds of watts from PBF lasers.

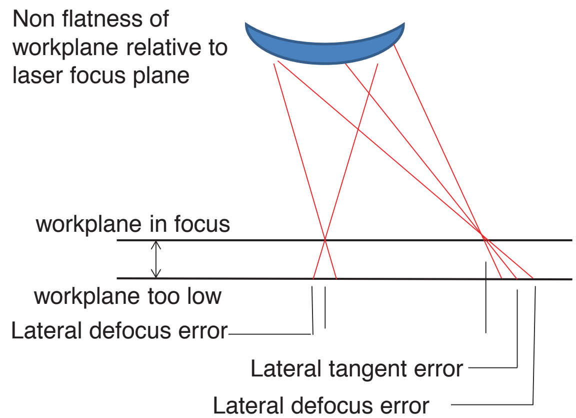
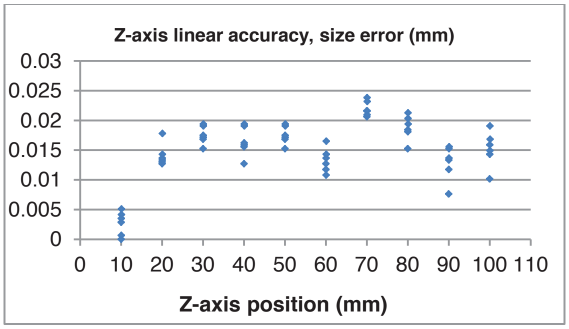


FIGURE 3. RAY DIAGRAM SHOWING SMALL LATERAL DEVIATIONS RESULTING FROM IMPROPER HEIGHT OF THE TOP POWDER SURFACE.

Absent a direct method of measurement, test artifacts can provide a viable measurement. The likely test artifact in this case would be a 2D planer artifact. A temporary building platform can be inserted into the machine and brought into the focal plane of the laser. The machine can then be programmed to burn only one layer of a test part with geometry suitable to test the performance of laser spot positioning. The temporary platform can be removed and evidence of the laser path can be inspected for geometry. The specific geometry and the method of measurement are still under development.

The measurement of positioning of the build platform can follow traditional approaches using either laser interferometer or gage blocks with dial indicators. The measurement should be conducted between the build platform and the recoating arm. Most PBF machines position only in one direction—when moving down, the build platform travels past its target position, stops, and then moves upward to the target position. As such, only uni-directional measurement is necessary. A series of a long movement (on the order of 10 mm) followed by several very short movements (on the order of 20 μm or a typical layer thickness) is likely most appropriate. The results should be split into long and short positioning accuracies. Figure 4 shows measurement data in this format.



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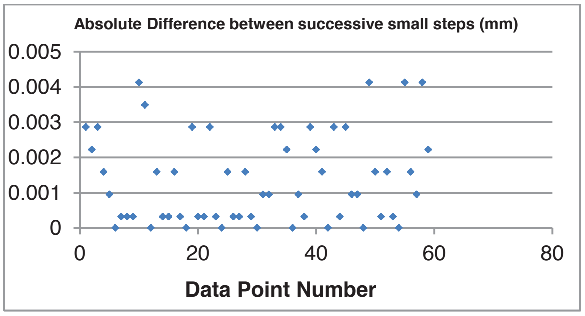

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FIGURE 4: RESULTS FROM POSITIONING ERROR TEST OF Z-AXIS. A: SIZE ERROR IS DIFFERENCE BETWEEN ACTUAL AND PROGRAMMED POSITION. B: LAYER ERROR IS ABSOLUTE DIFFERENCE BETWEEN ACTUAL AND PROGRAMMED POSITION FOR SUCCESSIVE NOMINAL MOVES OF 20 μm.

CONCLUSION

Unlike conventional machining where there is a near 1:1 correspondence of machine performance to the geometry of the workpiece, the accuracy of the machine components is only one of the contributors to the quality of a finished AM part. Rather, there is interaction with other process variations such as quality of the powder, stability of the laser electronics, etc. that affects all aspects of product quality related to dimensions, form, surface finish, and properties of the finished components. It is important to understand these relationships and the role of the mechanical accuracy.

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[5] ISO 230-2:2006, Test Code for Machine Tools – Part 2: Determination of Accuracy and Repeatability of Positioning Numerically Controlled Axes

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