Machine Health Verification Process for Laser Powder Bed Fusion

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Laser powder bed fusion (LPBF) machines are complex systems comprised of a number of interconnected subsystems which work in concert during the laser powder bed fusion process. The health, i.e. consistency in performance, of these complex systems must be monitored and verified to ensure consistency in the process during long-term production. If a system is 'unhealthy' the process becomes less controlled and can lead to decreased, unknown, or unverifiable part quality. To monitor and validate whether a machine is healthy, a number of tests were developed, which consist of: power monitoring, multi-laser alignment, laser position, laser caustic, gas flow, elevator accuracy, and machine condition. The methodology and efficacy of each test are discussed along with additional potential tests and next steps. This work was funded by The Department of Energy's Kansas City National Security Campus is operated and managed by Honeywell Federal Manufacturing & Technologies, LLC under contract number DE-NA0002839.

Background

As metal additive manufacturing (MAM) efforts mature, there is a growing need for monitoring the machine processes. There is a particular need for monitoring the long-term consistency in the performance of the process. To that end, industry standards have been published by SAE, ASTM, and ISO with regard to process qualification, verification, and other similar concepts [1-5]. Additionally, other groups have proposed various methods for monitoring machine performance, however, few have published a practical description of the methods and tests required to execute these practices [6]. Furthermore, there is little information available as to what subsystems need to be inspected, how often, or by what methods.

This paper is intended to describe the scope and purpose of one particular battery of tests which is intended to provide insight into the health of LPBF MAM machines. For the purposes of this discussion, the health of a machine is the machine's ability to maintain a consistent and acceptable level of performance over time. For example, if a machine is consistent but does not meet a set standard of performance the machine might be considered in poor health. Additionally, a machine might be considered in poor health if it always meets the required performance metrics but changes between the top and bottom ranges of those metrics frequently or suddenly with no clear explanation.

The primary goal of a machine health battery is not necessarily to calibrate a system but to verify that the various subsystems are performing in a consistent and stable manner. By testing the individual subsystems directly any future issues can be more readily attributed to the specific subsystem that may be causing the issue. Additionally, by quantifying the performance of the various subsystems it is possible to implement statistically based engineering controls such as control charts. As some tests have multiple sources of inherent error, such statistical controls can help to differientiate what is the noise and more accurately identify actual responses to the testing.

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Test methods and development

The series of tests described here consists of seven individual tests, with each attempting to characterize a primary variable of an LPBF machine. The tests are: laser power, multi-laser alignment, laser position, laser beam characterization, cover gas flow measurement, Z-axis verification, and machine condition inspection. An overview of the methodology and purpose for each test is discussed in the following sections.

Power Monitoring

Laser power monitoring is intended to determine the laser's ability to provide the requested input energy to the build plate, failing to do so can have detrimental effects on the build quality. For example, if the input parameters for the process require 300W but the system is unable to deliver that amount of energy, it can result in lack-of-fusion defect porosity forming within the final component. Additionally, if the test is set up to run as a standard build file without the addition of powder, the test can verify and monitor that the machine's calibrated power curve is still accurate. The machine's calibrated power curve being the curve used to translate between the laser generator's output values and the machine's input values.

Power monitoring is typically done by placing a beam power measurement sensor within the build plate area (usually directly underneath the laser window), and firing the laser upon it while the chamber is inert. , and the method used to input the amount of energy to be measured may depend on the abilities and limitations of the machine being interrogated. One of these methodsmethod is to set the test up as a build file and disable the machine's ability to dose powder during the process. For example, in an SLM280, the dosing and recoater mechanism can be removed and a pass-through placed between the powder feed hoper and the rear overflow port to prevent powder from entering the chamber during the power test. Using this method, allows the machine to handle all energy input requests in the same manner it would handle them for a typical build, thus providing an accurate representation of what energy will be delivered for each input during a build. Another method is to manually fire the laser through the laser generator's manual control mode. For this method, the power measurement sensor is placed in the build chamber the same way as with method one and the laser is fired upon it with minimal interaction of the machine's control software. This method can provide a more direct interrogation of the output from the laser generator. Running both methods and comparing any differences can assist in troubleshooting efforts if laser power is in poor health. Additional input methods may be available depending on the machine.

Regardless of which method is run, a machine's laser power is in good health when it is able to consistently deliver the requested energy to the build plate. It should be noted that most lasers found in LPBF machines have a certain degree of variation that is inherent to their generation and additional energy variation may occur as the laser moves through the optics train. Thus, when conducting laser power testing, it is prudent to know the amount of variation expected from the laser being measured. It may additionally be necessary to expand the allowable variation depending on the accuracy of the sensor used to make the measurement.

Laser Caustic

Laser caustic and profile measurements provide various information about the shape and energy distribution of the laser's beam. This information can be valuable in running simulations on the performance of the machine and can be used to troubleshoot issues involving the laser system. ISO standards 11146-1 and 11146-2 discuss the various methods for measuring and calculating the various parameters involved with measuring the laser beam [7, 8]. Though most of these methods generally require a special piece of equipment.

The laser beam can typically be considered healthy if the focal height is close to the build plane, if the beam has an acceptable energy distribution, and if the diameter of the beam at its waist is close to the intended size and shape of the laser. Focal height being close to the build plane is generally desirable as it indicates that the beam is in focus and provides all of the input energy at the build plane as intended. The energy distribution of the beam as reported by the M^2 value indicates that the input energy of the laser is being evenly distributed around the area of the beam. For example, an M2 value of ~1 indicates a circular Gaussian distribution of energy [9]. Each machine and laser should have a known and reported beam size which is assumed for the purposes of process parameter development. Laser caustic measurements allow for this value to be verified.

Should the laser have poor focus, it may be delivering less power than intended. This then can lead to a at the melt pool. A poor energy distribution and an increased defect generation as it will affect a number of factors around the formation of the meltpools. For example, if the beam has a doughnut distribution of energy, the meltpool may separate into twoseparate beads as a majority of the energy is focused away from the center of the beam's area. Such deviations may not be detected by power testing as power testing measures the entire area of the beam and is minimally affected by focus or distribution. While laser caustic is a valuable tool for simulations, troubleshooting, and process development; the high cost of the specialized equipment and in-depth technical knowledge required can make it difficult to use the information effectively.

Multi-Laser Alignment

Multi-laser alignment is the process by which two or more lasers are brought into spatial alignment in the build zones where they interact, also referred to as a stich zone. This is done to ensure that when two lasers are working on the same component, the spatial offset from one beam to the other is small enough that it minimizes the risk of defects. If two lasers are trying to draw the same vector, they should be aligned such that the final result is a single track, not two tracks slightly offset from each other. Figure 1 clarifies the difference between a vector and a track.

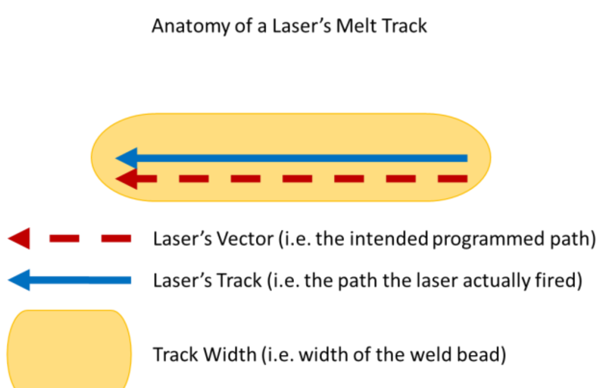

Figure 1: Graphic to Explain Laser Terminology

The process for verifying and correcting multi-laser alignment can and should vary depending on the number of lasers and their relative positions to one another. However, the process as a whole can generally be reduced to 3 steps: create a pattern requiring the lasers to align in multiple orientations (usually build area X and Y), measure, and adjust [10, 11]. Any pattern can be used as long as it allows for differentiating measurements and all lasers involved to interact in at least 2 perpendicular axes. The more axes that are verified the more confidence that there is alignment of the lasers along every movement direction. Regardless of the number of axes, there are at least two ways to determine alignment. First is deliberate misalignment and second is end-to-end alignment. Both methods are recommended though depending on need, one may be more critical to the intended task than the other. In deliberate misalignment, a vector for each laser are set specific and known distances from one another. Each vector is then fired by the lasers and the difference between the track's actual position and the vector's intended offset is measured. The difference between the actual offset and the intended offset is the amount of misalignment. Care must be taken to account for variations in track width when making these measurements. It is recommended to try and establish the centerline of each track width and measure the offset of those lines. In end-to-end alignment the lasers are commanded to form a track such that the vectors will meet end-to-end. Any measured variation in the resulting laser tracks is the amount of misalignment. Again it is recommended that the difference in the position using the center line of the lasers' tracks be measured for each axis while also ensuring that the widths of the tracks are comparable. Though the exact value of acceptable misalignment will vary based on the desired track width, a value less than half the nominal track width is usually accepted as the maxrecommended. Additional work could be down to determine an optimal amount of acceptable margin. Significantmisalignment. Also, significant differences in track width can lead to defects that may look similar to lateral misalignment of the lasers.

When the tracks meet end-to-end it becomes possible to determine if the lasers' tracks are interacting in an unacceptable manner or not. For example, an ideal end-to-end contact for the lasers' tracks would be to have that point be entirely indistinguishable from the rest of the track of either laser. An unacceptable end-to-end contact would be distinguished by either a gap of unmelted material indicating the lasers did not meet correctly, or as a substantially wider spot in the track indicating that one or both lasers passed too far into the other's track, creating a higher energy concentration (see Figure 2) . These misaligned modes can result in multiple forms of defects, ranging from visual defects on the surfaces of parts to increased porosity from lack-of-fusion (not enough energy) or key-holing (too much energy). Laser position could potentially be measured more directly with appropriate in-situ monitoring equipment, which is able to potentially eliminate the need for ex-situ measurement.

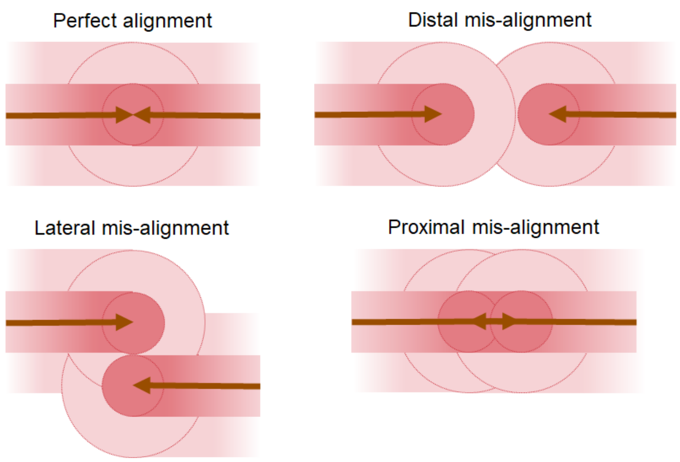

Figure 2: Examples of Misalignment [12]

Laser Position

Laser position testing is conducted to ensure that each laser individually is moving to the commanded positions. This is tested in a manner similar to multi-laser alignment in that it generally requires a pattern which is then measured and compared to the intended pattern. If the system is able to reproduce the pattern with minimal spatial deviation, at each position on the plate it would be considered to pass. The amount of deviation acceptable will vary by machine and laser but it is recommended to be approximately less than one laser track width off.or on the order of tens of microns or less not hundreds of microns. If the system reproduces the pattern with unacceptable deviation it has a greater risk of generating geometric or dimensional defects and/or failing to construct a build. This increased risk arises from lack of control in spatial position which may result in generating the oversized or undersized geometry.

Gas Flow

Gas flow testing, or more specifically, cover gas flow testing is conducted performed to ensure that the inert gas travels across the build area with an appropriate flow velocity and distribution. There is a variety of equipment that can be used to measure the flow velocity of the cover gas but it is recommended that the flow be measured at multiple points both across the build chamber and at a position near the laser windows. By measuring the flow at the build plate, one can determine the amount of flow that the laser plume and any generated spatter or debris will be subjected to, in addition to the variation in convection cooling rates for the meltpools. Measuring the flow near the laser windows provides information on the amount of gas flow used to prevent debris from contacting the window and potentially obscuring the laser.

Before this test can be run, a baseline needs to be established. It is recommended that a number of builds be conducted to verify that the machine is producing acceptable parts across the plate, with multiple independent measurements of the flow in similar positions to correlate results. Once the baseline is established, a machine is determined healthy when its flow measurements are consistent to the baseline measurements with an acceptable amount of variation. It is recommended that each position in the chamber be compared independently for maximum flow consistency. For example, if a baseline measurement is taken in the back left corner of the plate it should only be compared to other measurements taken in that position.

If the flow is lower than the baseline measurements, there is an increased risk of depositing detrimental debris on the downstream build surfaces [12]. If the flow is higher than base line there may be an increased risk of denuding the powder around the meltpool thus increasing the risk of defect generation. Both of these scenarios also effect the cooling rates of the meltpools, which in turn can also increase defect generation [12, 13]. There isThere is an opportunity for future work to develop a method for monitoring the gas flow during the build process as well as for determining the optimal flow velocity to minimize the risk of defect generation.

Elevator Accuracy

Elevator accuracy testing is conducted to ensure that the elevator is moving at the correct commanded distance and there is no accumulation of error movement. To carry out the test, an independent measurement system with at least a +/-1um accuracy should be usedset up to measure the elevator's z-axis movements at multiple locations though the full range of the elevator. At each of these locations the elevator should be repeatedly commanded to move a fixed distance approximately equal to layer thickness used.

Passing the elevator accuracy test indicates that when the elevator is commanded to move a fixed distance during a build it is able to move that distance precisely. If a machine is unable to pass the elevator accuracy test, it likely means that the elevator mechanism is in need of service or repair. If the degree of unacceptable movement is severe or is accumulating as substantial over or under movement it could potentially builds, dimensionally or with an increase in internal defects,affect builds and should be addressed immediately.

It is important to note that minor deviations in elevator motion are unlikely to affect builds directly. This is because the elevator is covered with a bed of powder which does not pack down perfectly, and thus, does not rely solely on the elevator to determine the height of each layer [14-17]. Developing a method for monitoring the height of the powder layer directly and ensuring that it is the desired height could be a potential area for future investigation.

Machine Condition

Machine condition is a visual inspection of the machine's overall physical condition. This can include things like checking for dents or inspecting seals and valves. This is conducted to ensure that the less complex components of the system are still in good condition and operating in an acceptable manner. If the machine is in good working order then all the seals, valves, panels, and other non-automated or non-mechanical components are functioning as intended. In addition to this, the machine must demonstrate its ability to inert to the acceptable process oxygen percent ranges and pressures. A machine might fail this if there is a torn vacuum seal or it is leaking powder from a hopper or pipe. While it is a good practice to conduct a rapid visual inspection of the machine prior to each build, the machine condition test is intended to be a more thorough inspection. For example, a pre-build inspection may examine the area around a transfer pipe for any leaked powder while an inspection during the machine condition test might take the pipe off and check for any excess wear on the seals or pipe.

Discussion

The suite of machine health tests are meant to quantify the operating parameters of a system such that the performance can be monitored over time. This is intendedto indicate when events such as service, calibration, or repair might be required. Such a testing process can also potentially provide the ability to predict the acceptable lifespan of an LPBF system as a whole or a specific subsystem.

There are a few subsystems that are not monitored by thethe particular set of tests outlined in this document.discussed. Specifically, the cross-plate focusing system for the laser, the build plate heating system, the powder transfer system, the recoater assembly, and dosing mechanisms. Some of these systems are not monitored though the outlined machine health testing suite because they are not considered to have as large of an influence on part quality as the others identified here. However, machine health testing takes up valuable machine time that could otherwise be used for manufacturing parts, so it is vital to keep these tests short and only monitor the ones of most importance. Furthermore, although the laser caustic measurements and elevator test provide valuable information, they only indirectly influence the building process. There are additional external factors that can influence long-term machine performance that may need to be monitored in some way. While it is impractical to list all possible external conditions, a few specific important ones are environmental moisture levels or static charge conditions. These factors are external in that no specific system within an LPBF machine controls them, however, they should be measured within the build chamber and if possible, monitored for any changes over time or during a build process.

To maintain machine availability for production purposes, it is often prudent to run a battery of machine health tests all together on a repeating schedule rather than prior to every build. As such, the addition of a witness coupon or test artifact built in the same place and with the same parameters on every build can provide performance consistency data between each round of testing. Such data is unlikely to replace an in-depth battery of tests but rather provide complementary data for the periods between machine health testing.

Summary

LPBF machines are comprised of a number of interconnected subsystems which need to work together in a cohesive manner during the build process. In order to monitor the consistency in long-term performance, i.e., health of LPBF machines, an example battery of tests was outlined. The tests discussed comprised of: power monitoring, multi-laser alignment, laser position, laser caustic, gas flow, elevator accuracy, and machine condition. Should the system not pass any of these tests it would be 'unhealthy' indicating the process is less consistent and at risk of decreased part quality. Recommendations on methodology, equipment, and efficacy for each test were reviewed as well as potential future work or improvements. Of all the tests discussed, the tests the authors have found most impactful on build performance are: power monitoring multi-laser alignment, laser position, and gas flow. Thus these are the tests most strongly recommended for future work and development. This work was funded by The Department of Energy's Kansas City National Security Campus is operated and managed by Honeywell Federal Manufacturing & Technologies, LLC under contract number DE-NA0002839.

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