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Additive manufacturing machine tool qualification: Methods and insights

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Abstract
Machine tool qualification is an essential capability to ensure manufacturing process control and repeatability. Additive manufacturing (AM) machines, i.e., AM machine tools, are no exception to this principle. Critically, the performance and state of AM machine tools does not only impact workpiece geometry, but also material characteristics. Nonetheless, the current state of AM machine tool qualification can be summarized as relatively immature in terms of methodology, rigor, and coverage of the various subsystems within the typical AM machine. This work focuses on the laser powder bed fusion (PBF-LB) process – a metal AM process which uses a laser to selectively fuse feedstock metal powders into the desired workpiece geometry. A brief review of current machine tool qualification techniques for PBF-LB systems is provided, with current limitations and opportunities for development highlighted. Additionally, original work on a novel method for measuring laser focal plane error is presented. An artifact-based measurement method is proposed, where a coating is ablated with the PBF-LB system laser at varying stand-off distances and ablated track width is used to measure the focus position of the laser. The applications of this method to PBF-LB systems are then explored as an example of how machine tool qualification in AM can capture off-nominal machine performance.

Keywords: Laser powder bed fusion (LPFB/PBF-LB), machine tool qualification, laser focus, process qualification.

1. Introduction

The maturation of metal AM machine tools has seen their role evolve from rapid prototyping to production. This particularly applies to the laser powder bed fusion (PBF-LB) process, which has gained traction in areas such as the aerospace and medical sectors – applications that require minimal risk of manufacturing defects. As such, a great deal of research and development in PBF-LB has been focused on materials and process qualification [1]. The present work considers three classes of process qualification approaches: post-manufacture ex-situ, in-situ, and machine tool qualification. Ex-situ analysis includes a wide variety of techniques spanning both destructive materials characterization and non-destructive examination. While these techniques are indispensable, ex-situ approaches are limited in that they may not enable the straightforward diagnosis of the underlying cause of manufacturing defects. In-process or in-situ monitoring has largely been the community's answer to this problem [2], as these techniques move one step closer to capturing root-causes of manufacturing induced defects. Even so, both of these approaches focus on the workpieces being manufactured, not the AM machine tool itself. As such, neither directly addresses the likelihood of off-nominal performance in AM machine tools due to factors such as poor construction, performance drift, calibration error, or physical limitations.

This paper proposes that a third mode of AM process qualification is most suitable to address this gap: AM machine tool qualification. The use of the term "machine tool" in this context is intended to invoke longstanding qualification frameworks developed for machine tools in machining contexts. While the field of machine tool qualification/metrology as developed for machining processes has limited direct applications to AM machine tools, the overall mindset can be adapted to the AM process. That is to say, the use of machine tool qualification techniques in machining applications has long been employed to identify sources of systematic errors, compensate and/or correct them, and apply process control to achieve overall process improvement [3]. In many aspects, AM machine tools would benefit from a similar approach [4] if repeatable and in-control AM processes are to be achieved.

2. Analysis of the prototypical PBF-LB machine tool

Fundamentally, PBF-LB machine tool qualification aims to assess the error between the actual performance of the machine and its nominal behavior, where the nominal condition is defined by process variables whose levels are set by the user or machine tool manufacturer. Notably, unlike in conventional machine tools, these process variables and associated errors are not limited to geometrical performance, e.g., commanded vs. actual axis position, for example – they can be complex and more multi-physics in nature. As such, before considering which methods of PBF-LB machine tool qualification, it is prudent to consider a list of critical process variables. These are distilled into four groupings of closely connected variables here:

(1) Laser power, intensity distribution (spot size/shape)
(2) Laser scan speed, laser position, and scan path
(3) Layer thickness
(4) Build environment and carrier gas flow

These process variables have been chosen as they represent aspects that the AM machine tool is expected to systematically determine. As such, external variables not traceable to systematic machine performance, e.g., certain powder feedstock characteristics, are not included. Figure 1 provides a schematic of the prototypical PBF-LB machine tool with some of these process variables pictorially shown. For the remainder of this work, a PBF-LB machine that uses a blade recoater-style spreading device is analyzed.

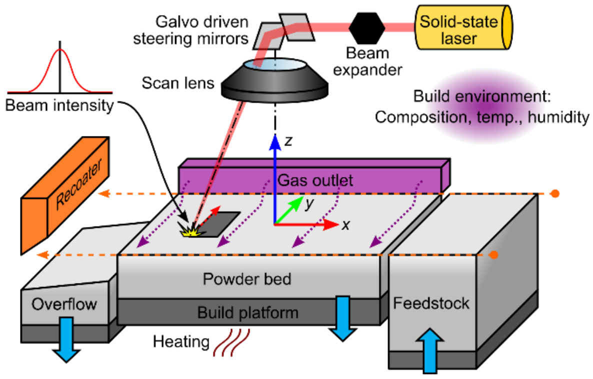

Figure 1 Pictorial representation of a prototypical PBF-LB machine tool.

An approach to PBF-LB machine tool qualification should assess aspects of machine performance that can unduly affect these variables. Figure 2 presents a such a root-cause analysis via a fishbone diagram. Here, root causes are separated into several first level categories corresponding to the earlier delineated process variables. The complexity of the PBF-LB process is evident, and it is likely that there are interrelationships and further root causes not fully captured by this high-level diagram. Nonetheless, the analysis can be utilized to identify subsystems and behaviours of the machine tool that should be qualified. For example, consider that layer thickness is not merely the result of build platform positioning, as a simpler examination might conclude, but several additional factors needing individual attention. For many factors on this diagram, it is likely that a further level of refinement is possible – this will be demonstrated for "focal plane error" later in this work.

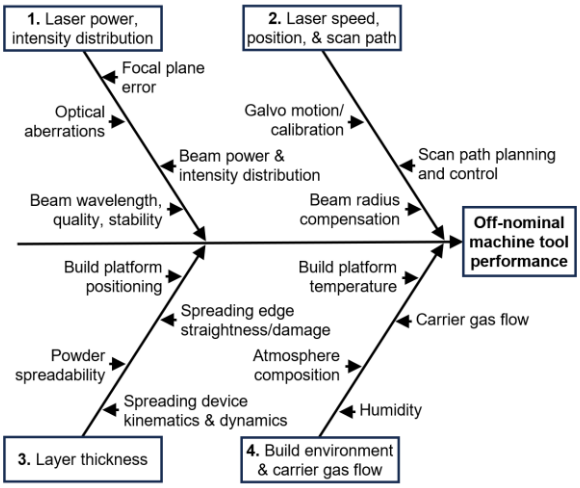

Figure 2 Fishbone diagram of PBF-LB machine tool performance.

3. Review of current AM machine tool qualification methods

Qualification approaches designed to assess root causes for systematic off-nominal PBF-LB machine performance have been proposed across both scientific literature and industrial standards. Likely, industrial practitioners have also developed other unpublicized practices as well. As the ensuing will demonstrate, while some PBF-LB subsystems have benefited from greater study than others, in general, the state of AM machine tool qualification is still developing. The following review is not comprehensive but intended to present some notable and relevant efforts.

3.1. Literature review

Multiple authors have presented analyses of build platform positioning [4,5] using conventional approaches, such as laser interferometry, finding errors with most likely minor effects on the process. Complimentary efforts have studied actual as-spread layer topography in the powder bed [6–9], revealing likely significant variability in the effective thickness of the powder layer – this area is a focus of active research. Laser positioning has also been investigated, most often through the inspection of etched patterns on artifacts [5,10]. Several varieties of in-situ camera-based laser positioning qualification have also been explored [11,12]. Gross positioning error and dynamic position error are likely prevalent under certain process conditions. The carrier gas flow subsystem has been qualified via gas anemometry [13,14], finding significant variability in flow velocity over the build space.

Perhaps the greatest effort has been focused on test artifact-based methods where test pieces are manufactured via the PBF-LB process, then dimensionally inspected. Several reviews have covered the topic [15,16]. While much work in this area has been presented as performance benchmarking, some has focused on ascertaining the underlying causes of geometrical errors, for example, due to beam positioning or offset error [17,18]. While manufactured test artifacts are an important aspect of machine tool qualification, the insights gained do not always lend to decoupling root causes.

3.2. Standardization efforts

A variety of standardization efforts have been undertaken by several organizations within the last several years. ISO and ASTM International have been the most active in this field, with ISO's Technical Committee-261 and subcommittees of ASTM Committee F42 issuing a small number of standards relevant to AM machine tool qualification. These are listed in Table 1.

Table 1 Standards relevant to AM machine tool qualification

Standard name	Authoring org.
ISO/ASTM52902-19 Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems	ASTM F42.01 Subcmte. on test methods/ ISO TC-261
ISO/ASTM 52930-21 Additive manufacturing — Qualification principles — Installation, operation and performance (IQ/OQ/PQ) of PBF-LB equipment	ASTM F42.05 Subcmte. onmaterials and processes/ ISO TC-261
ISO/ASTM 52941-20 Additive manufacturing — System performance and reliability — Acceptance tests for laser metal powder-bed fusion machines for metallic materials for aerospace application	ASTM F42.07 Subcmte. on Applications/ ISO TC-261
ASTM F3522-22 Standard Guide for Additive Manufacturing of Metals — Feedstock Materials — Assessment of Powder Spreadability	ASTM F42.01 Subcmte. on test methods)/ ISO TC-261

Several standards contain test methods or content of note. ISO/ASTM 52902 presents a fairly prescriptive test artifact design but minimal guidance on applying inspection results to the analysis of machine tool performance. ISO/ASTM 52941 requires testing for machine subsystems, e.g., "laser beam tests" and "mechanical function tests," but in most cases provides sparse information on the accompanying measurement methods. ISO/ASTM 52930 emphasizes the application of machine performance monitoring for a significant list of subsystems, but is similarly broad in scope with little-to-no enabling guidance. Overall, while each of these documents represents important progress in PBF-LB machine tool qualification, these efforts reflect the maturing nature of industrial standardization, with very few prescriptive tests and inference methods established.

4. Case study: Laser focal plane error measurement

It is conducive to discuss a particular example of research into AM machine tool qualification to investigate the value of such an approach. Consider the optomechanical system of the prototypical PBF-LB machine: a columnated solid state continuous wave laser is directed by steering mirrors through an F-theta scan lens, which focuses the beam onto a *focal plane* that exists in relation to the *build plane*. Here, the build plane is defined as a the top surface of the powder bed as formed by the spreading mechanism. Proper processing of the powder feedstock layer is dependent on a known energy intensity input at the interaction point of the laser and material. As such, the actual intersection between the converging-diverging beam and build plane is a critical characteristic that affects process variables such as laser spot size and intensity distribution. Under nominal conditions, the focal plane is ideally flat, parallel to the build plane, and at a controlled position relative to the build plane. Off nominal conditions lead to focal error, also known as "defocus" or "focus offset." Here, the phenomenon of focal error over the build plane is referred to as *focal plane error*.

To illustrate how the root cause analysis of Figure 2 may be further refined, consider Figure 3, which does the same for "focal plane error," previously depicted as an individual root cause in Figure 2. Factors under category (1) describe how the performance of the F-theta lens might drive focal plane error, for example due to field sag, which describes the tendency of these optics to display field curvature towards the scan field edges. Category (2) captures the quality of optical element alignment relative to the build plane. Category (3) captures factors that may either generate non-flat powder beds or simply obfuscate operator ability to determine the build plane location. Although a full investigation is out-of-scope for this paper, it is the authors' opinion that the contribution of factors in category (3) are likely negligible.

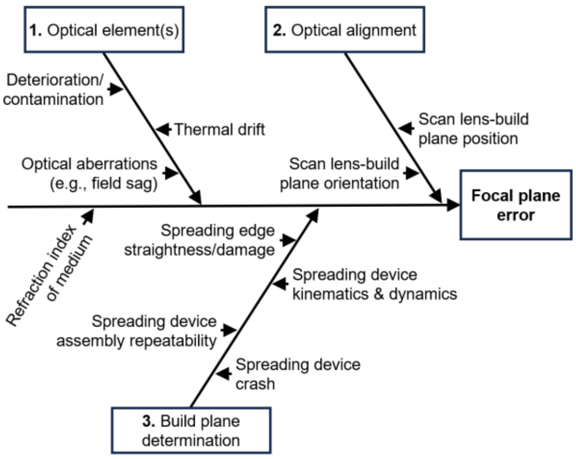

Figure 3 Fishbone diagram of focal plane error.

Factors in categories (1) and (2) require a machine tool qualification approach to address. While field sag can be readily determined for a given lens by optical element manufacturers, its impact when coupled with a PBF-LB machine architecture is not well understood. Similarly, optical alignment is exclusively inherent to the scan lens as installed on the PBF-LB machine. Notably, current instruments for measuring beam focus error (derived from measurements of the beam caustic, i.e., the converging-diverging beam profile) are not ideally suited for on-machine implementation. Camera-based beam profiling instruments may have high uncertainty in beam travel distance, obfuscating the ability to determine the relative position of the beam waist. These instruments also struggle with off-axis beam measurement, preventing inspection at nonzero beam incidence angles. Current diffraction-based instruments offer an alternative and can measure the beam off-axis. That said, in all these cases, the experimental effort to determine focal error at one (x, y) position can be significant, not to mention doing so at many (x, y) positions can be laborious or altogether inhibited by the bulky nature of these instruments, given the available space in the AM machine tool.

4.1. Focal plane error measurement methodology

A novel approach to focal plane error measurement, designed to address current shortcomings, is presented herein. In this artifact-based method the laser beam is used to ablate the coating of anodized aluminum coupons at varying offsets (in the z direction) from the build plane. The widths of these ablated tracks are expected to approximately reflect the beam diameter as a function of z, thereby enabling an indirect determination of the beam caustic and thus, focal error. The benefits of this approach are chiefly in its (1) affordability, (2) ease of integration into existing PBF-LB workflows – only standard machine programming techniques are required, (3) ability to measure focal error nearly up to the build space limits, and (4) efficient and high-throughput nature enabling a high density of focal error measurement over the (x, y) field.

This novel method was employed on an EOS M280 commercial PBF-LB machine tool to gain further insight. This machine used a 400 W Yb-fiber laser (λ = 1064 nm) with a single-mode gaussian power intensity distribution. The F-theta scan lens employed had a focal distance of f = 410 mm and focused the beam over a 250 X 250 mm build area. To conduct the focal plane error measurement, the build platform was made coincident with the build plane as defined by the spreading device, establishing a static coordinate system with z = 0 being the build plane. Coupons were 19 x 19 mm pieces of black anodized (type II) 6061 aluminium, as per MIL-A-8625. 6.35±0.05 mm thick. Tracks were ablated on the coupons using a laser power of 150 W and a scan speed of 2000 mm/s. Ablated tracks were inspected under a bright field illumination on a digital microscope at 500X. Computer vision techniques, e.g., thresholding and binarization, were used to conduct track width measurements at each pixel along the imaged track length for all tracks ablated at differing z offsets. Figure 4 shows track width measurements from a single coupon located at (x, y) = (0, 0).

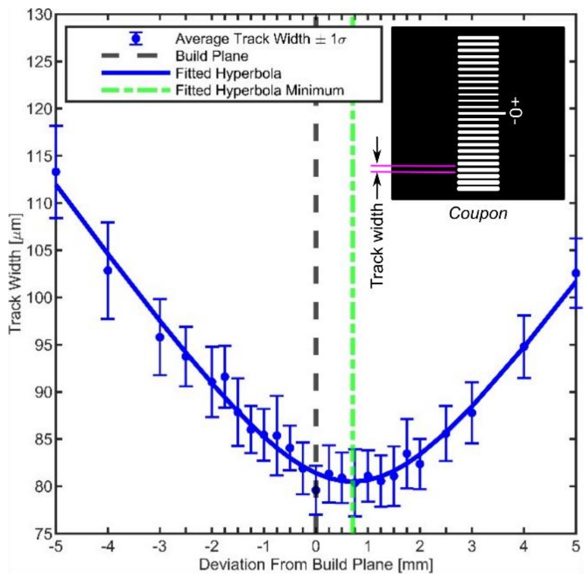

Figure 4 Track width measurements a one coupon at (x, y) = (0, 0). Inset: Depiction of coupon and tracks – not to scale.

The converging-diverging nature of the beam is prevalent, with the minimum thickness of 82 µm being reasonably close to the d4σ spot size, nominally 70-80 µm. The minimum of a fitted hyperbola is located at z = 0.75 mm, which represents the focal error at the (x, y) = (0, 0) position.

4.2. Focal plane error measurement results and discussion

Through a similar analysis of many coupons that had been placed over the build area at 50 mm intervals, focal plane error was measured. Figure 5 shows the focal error at each coupon (x, y) position plotted as red circular markers with linearly interpolated mesh in between. The red grid represents the least-squares plane of best fit to the data.

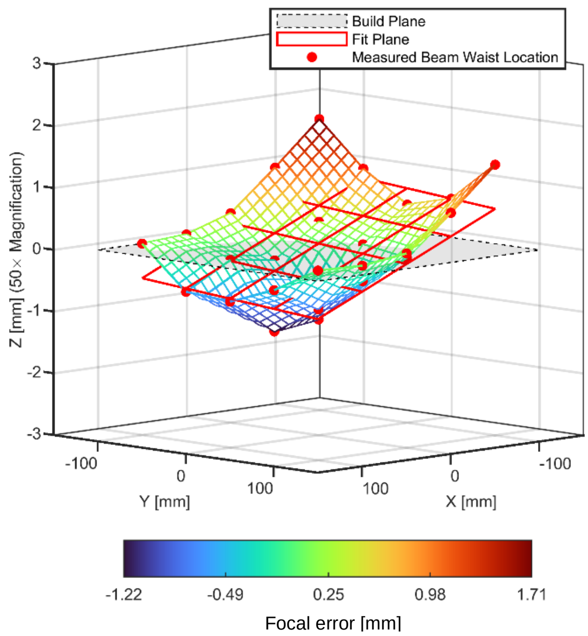

Figure 5 Focal plane error measurement.

The focal plane appears to display multiple components of error: poor flatness, poor parallelism, and some amount of positional error relative to the build plane. Each of these components may be associated with a root cause as was presented in Figure 3. Form error most likely originates from field sag, resulting in a convex bowl-shaped focal plane. Parallelism error results from poor alignment of the scan lens to build plane. Finally, there appears to be relatively little error in the relative position of the scan lens, with the focal plane somewhat evenly distributed around the build plane. The net result of these superimposed errors is a range of -1.21 to +1.71 mm of measured focal error – this is expected to lead to a variance in effective spot size of up to approximately a 15 µm. This represents a potentially significant change in energy intensity of the beam at the process zone. Consider that the build space was measured to within 25 mm of its edges and error most likely increases towards these limits. Finally, note that an intentional optical misalignment was introduced prior to this test to demonstrate the effect of such a root cause.

5. Conclusions

Plainly, machine tool qualification for AM systems, such as the novel approach presented, can provide significant insight into the underlying causes of off-nominal performance in a PBF-LB machine tool. Further development of this method and others should focus on establishing uncertainty in measurement methods, developing guidance for corrective actions, and studying the correlation between specific performance errors and the manufacturing process outcomes. This would enable control limits to be applied to subsystems of the AM machine, leading to more deterministic process control.

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