Ensuring part quality and productivity through automation of integrated exposure calibrations

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Industrial users of metal AM are continuously pushing OEM's to find ways to increase productivity and ower part cost. In order to increase the material consolidation rate, the radiation energy exposing the powder bed must also increase. This is typically achieved by processing with higher laser power and/or using multiple lasers to sustain multiple melt pools. The use of multiple lasers working together on a single part requires good overlay accuracy between lasers. Even on a system where all lasers have full field capability and no stitching is necessary, laser to laser positioning overlay is vital for part quality.

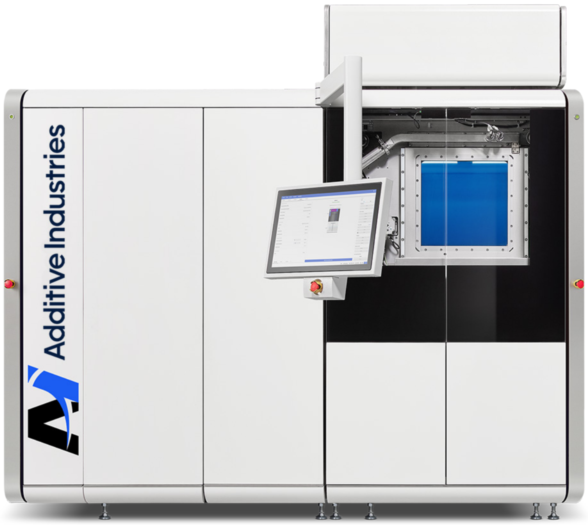
This paper describes how the integrated laser calibration and validation system in the MetalFab secures laser positioning accuracy. It explains the use of an integrated absolute position reference to which all laser scanners are calibrated and a method to align the laser focal plane positions with the powder bed.

Challenges with calibrating multi-laser scanners

With a Gaussian spot diameter of ~100 µm the MetalFab system has been designed to have a maximum laser to laser overlay error of ±50 µm over the full process area (420×420 mm2). This is to ensure full field laser operation, where lasers can work anywhere on the same part with no overlap regions. Meeting this specification by only producing a tightly tolerance opto-mechanical system is not possible in a cost-effective way. Even if this were possible the system would be susceptible to drift over time due to changing environmental conditions.

In multi- laser systems alignment of lasers relative to one another is critical in ensuring the quality of parts produced. In systems where a zonal approach is used, overlapping regions between zones are scanned twice and can produce undesirable changes in material microstructure locally in these areas. In the other extreme, where the overlay error is too large, unconsolidated areas can occur causing porosity and other quality issues within the part. Stitching lines and other visible defects are also clearly observed if inaccurate and unreliable methods of alignment are used.

It is common practice to use calibration methods to compensate for tolerances and external influences. Corrections can be made by mechanically adjusting the optical assembly or by applying corrections to the scanner control parameters. To ensure the produced parts have correct dimensions, the scanner positioning must be



It is common practice to use calibration methods to compensate for tolerances and external influences. Corrections can be made by mechanically adjusting the optical assembly or by applying corrections to the scanner control parameters. To ensure the produced parts have correct dimensions, the scanner positioning must be
related to an absolute dimensional reference. Note that for demanding markets such as aerospace full measurement traceability is also required.

In laboratory environments frequently used calibration methods require 'off-line' measurement and analysis of exposed calibration markers by means of a coordinate measuring machine. This method has the drawback of

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being both time consuming and costly. Also, it is inpractical to perform a validation of the executed calibration for obvious reasons. For high productivity systems the downtime required for calibrations must be minimized, but at the same time machine stability must be proven and if needed, frequently corrected for. For these applications, integrating a measuring and correction system inside the machine can strongly reduce downtime for calibration and validation runs. One of the challenges with this solution is that an accurate measuring device must be included in the processing chamber. This device is directly exposed to very high laser irradiation (focused laser beam during measurement) and metal powder contamination. Considering the typical high cost of a sufficiently accurate device and the likelihood of damaging it due to radiation or powder exposure, the implementation and realisation of such a concept is critical to success.

Integrated vision system and reference

The MetalFab system was designed with the capability of integrated calibrations as an important requirement. The system is equipped with up to 4 identical scanning modules. Each of these modules is equipped with a digital three-axis laser positioning system; two actuated mirrors for XY positioning and a third actuator for dynamic focus positioning.

A dichroic mirror is positioned such that an in-line camera system can observe the scanned area on the process plane with a field of view in the order of 10mm2 (figure 1). For reasons that will become clear in the next sections the mechanical stability between camera and collimator is critical for calibration performance. Proper thermal management in the scanning module is critical to secure the required overlay stability.

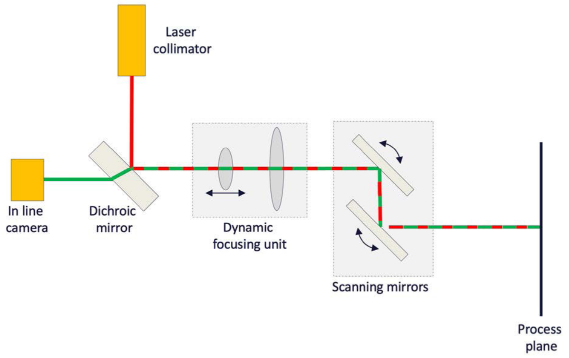


Figure 1 - Schematic representation of the optical path

The MetalFab scanning modules are all able to cover the full processing area of 420×420 mm2, i.e. 100% overlap in scanning field of view. This eliminates the need for stitching between separate laser regions, however for optimizing multi-laser assignment on a single part, laser interaction to avoid building in the condensate of another laser must be observed. Scanner timing synchronization and laser to laser overlay is vital to perform effective multi-laser assignment.

In order to achieve the required laser to laser overlay and absolute laser positioning accuracy a calibration element is placed in the process chamber. The calibration element consists of a glass plate with a chrome etched marker pattern that is thermally stable and supported by a plate which matches the process chamber build plate interface (figure 2). The absolute accuracy of the etched pattern is in the order of 20 µm over the full process plane with respect to a traceable reference. Local marker to marker deviations are also smaller than 5 µm. This plate can be loaded and unloaded automatically by the MetalFab robot build plate handling and storage system. The markers are set up such that they can be interpreted by the integrated vision system and are positioned exactly on the processing plane. This grid of markers forms the absolute reference of the MetalFab system and also if required, a factory of MetalFab systems to ensure absolute repeatability between them all.

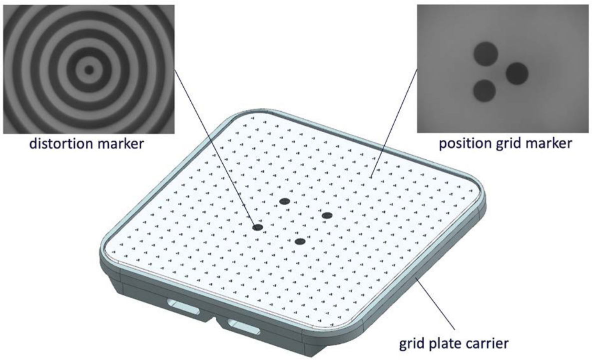


Figure 2 - MetalFab reference grid marker plate

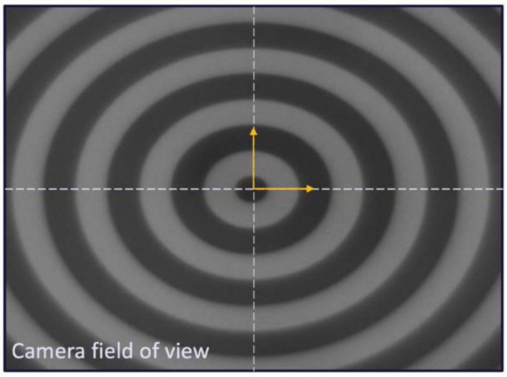
Vision as intermediate reference

Although the grid marker plate is relatively insensitive to powder contamination, exposing it to irradiation of a focused processing laser beam will cause permanent damage. The following sequence explains how the laser scanning positions are related to the grid plate marker positions by introducing the scanner vision system as an intermediate reference.

1. Determine camera distortion

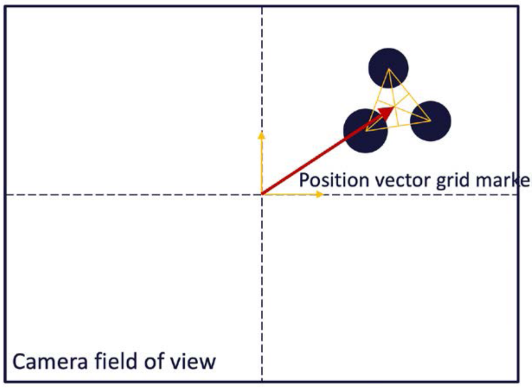
First step of the calibration sequence is to determine the distortion of the camera view. For this purpose 4 distortion makers are included on the grid marker plate. One directly below each vertical down scanning position.

The distortion marker consists of a set of high contrast concentric rings with well-defined dimensions. The in-line camera image is processed, and parameters are stored to convert the camera pixel coordinates to metric dimensions on the process area.



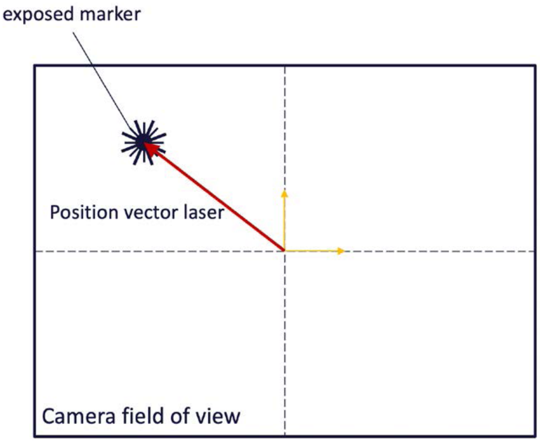
2. Determine marker position

The second step consists of moving the scanner to the first marker nominal position and using the in-line camera system to image the grid marker plate. The calibration application processes the image and determines the actual position of the centre of the marker with respect to the centre of the camera field of view. This process is repeated for all marker positions in the grid and a list of position vectors is stored.



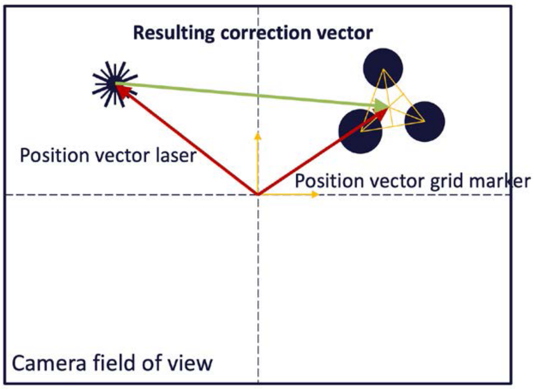
3. Determine laser position

During the third step of the sequence the high-power laser is fired. To this end a dedicated exposure plate is automatically loaded in the process chamber and the grid marker plate is stored in a secure location in the system. A predefined marker pattern is exposed on the plate and subsequently imaged by the in-line camera system. In similar fashion as in step 2, the actual positions of the exposed markers with respect to the centre of the camera field of view are determined and stored. Note that because of good stability between laser collimator and in-line camera only



4. Determine correction vector

Using the information from the previous steps a correction vector is determined to align the laser actual position with the reference marker position. This is repeated for each grid marker position, the results are interpolated, and existing correction look up tables are updated (See section Scanner positioning basics). Described steps can be iterated to validate the effect of previously applied correction and to further converge to the required positioning and overlay accuracy. Note that due to minimal variation in camera image distortion and laser position vector it is sufficient to iterate only steps 2 and 4 to achieve required accuracy.



Laser focus calibration

Besides laser to laser xy-overlay, the focal plane position is critical in achieving required part quality. As explained (See section Scanner positioning basics) the dynamic focus actuator is used to flatten the focal plane based on a nominal correction look up table. In similar fashion as with the XY corrections the focal plane position can be adjusted to compensate for scanner specific focal plane deviations.

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For measuring the required focal plane correction again the inline camera system is used. For each laser one or multiple focus patterns are exposed on an exposure plate. Multiple markers can be used to correct for local focal plane deviations or for laser power dependent focus shift. The marker can consist of several hatches that are exposed with a range of focus settings (figure 7). The exposed marker(s) are analysed using the in-line vision system. Depending on how well the spot was in focus on the exposure plate the hatch lines will be sharp (in focus) or more blurred (out of focus). For each hatch with a defined focus offset the average grey value within a defined are of the marker is determined. This is done using some image filtering steps.

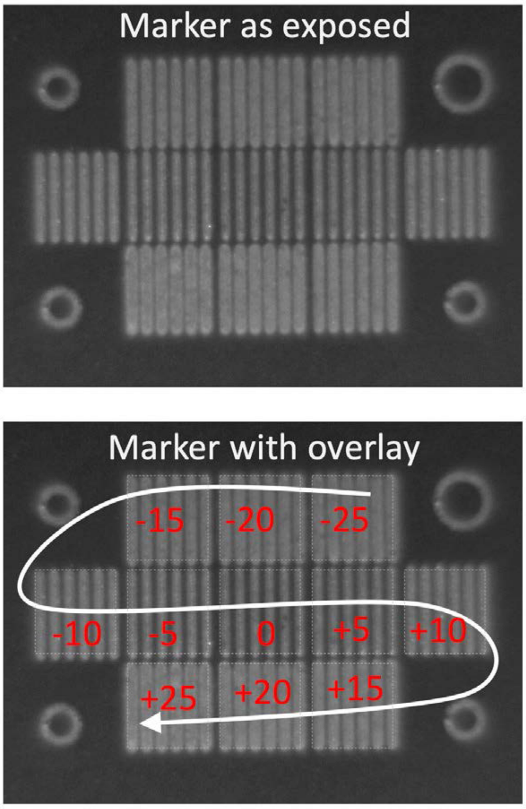

Figure 7 - Exposed and imaged focus marker

For each marker, the average grey value is plotted against the focus setting used during exposure. A curve is fitted through these values and the optimum of this curve can be determined to be the focus offset where the laser was best in focus (figure 8). A global or local correction can be applied to the focus correction look up table.

Typical accuracies that can be achieved using this method are in the order of less than 5% of the Rayleigh length.

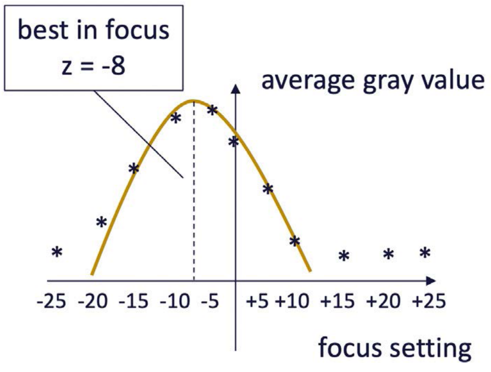

Figure 8 - Schematic focus marker interpretation

Scanner positioning basics

For positioning a laser beam on a process area typically a 2-mirror deflection system is used. Each mirror controls the positioning along 1 axis of the process area (i.e. x or y direction). Figure 9 shows a simplified representation of a single axis scanning mirror. In order to steer the laser beam to requested set point position the scanner proportional controller commands the actuated mirror to make an angle:

$$\theta_{setpoint} = K_x \cdot x_{setpoint}$$

Where Kx is a proportional gain [mrad/mm]. Resulting laser spot actual position will deviate from the requested set point due to projection of the laser onto the flat process area. The non-linear positioning error increases with increasing scanner angle as shown in Figure 9.

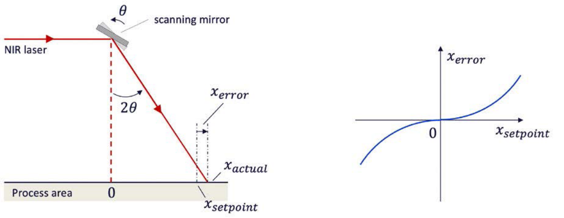

Figure 9 - Schematic representation of single axis scanning mirror

This effect is normally solved by adding a position dependent correction value taken from a lookup table:

$$\theta_x = K_x \cdot x + dX(x, y) \quad \text{and}$$

$$\theta_y = K_y \cdot y + dY(x, y)$$

The nominal shape of look up tables dX and dY is determined by system geometry and typically has a shape as in Figure 10.

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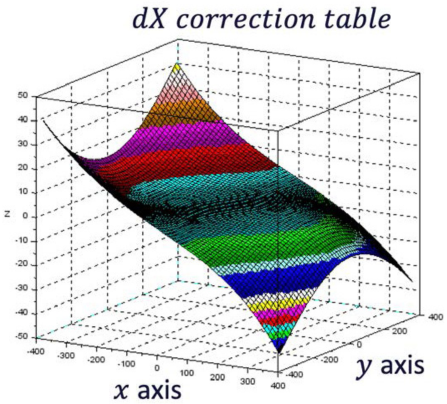


Figure 10 - Typical shape of a scanner correction table. Z-axis show applied X-correction as function of x and y build plate position

Besides nominal corrections the lookup tables can also be used to apply scanner dependent and xy-position dependent corrections.

Due to the changing optical path length of the deflected laser beam the projection on the process area will be out of focus quickly when moving away from vertical down position (Figure 11). Focus field flatting uses an xy-position dependent look up table dZ with corrections for the z-setpoint in similar fashion as the dX and dY tables.

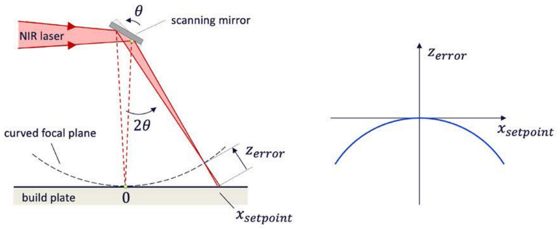
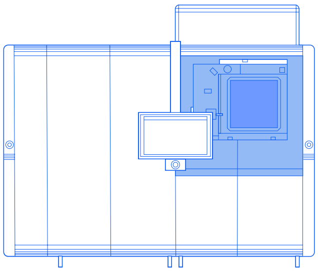
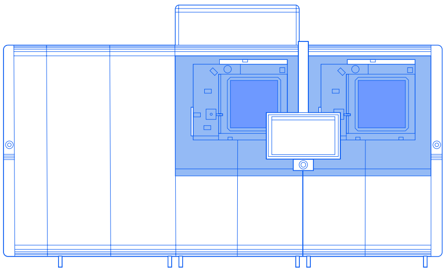


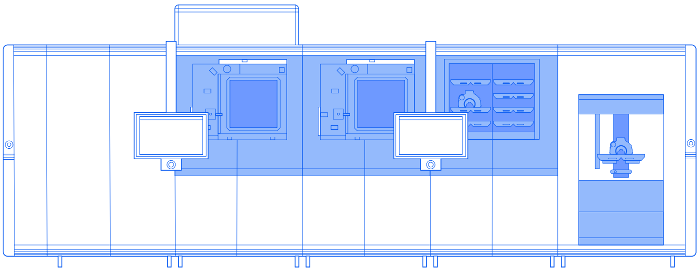
Figure 11 - Schematic representation of focus error due to increased working distance when scanning

Conclusion

The described system and calibration method result in a system performance that meets the set requirements for laser positioning and overlay. Laser positioning accuracy better than 50 µm is achieved. Focal plane deviations can be calibrated to less than 5% of the Rayleigh length, which relates to spot diameter variation far smaller than 1% when processing around the beam waist. Furthermore, full automation allows the customer to schedule calibrations when impact on machine availability is minimal. The calibration method and apparatus described are unique to the MetalFab and covered through a series of patents.







White paper.

At Additive Industries, our objective is the success of our customers in achieving the lowest cost per part at market leading quality.

We pride ourselves on our flexibility to work with our MetalFab users in achieving their industrial goals.

To find out more, contact us at:
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