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Technical Communication

Investigation on Laser Scanner Synchronization via Advanced Beam Path Analysis in 3D Additive Manufacturing Systems

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In selective laser melting processes, the precise synchronization of mirror motion and laser illumination is one of the major influential factors, determining the quality of additively manufactured metal parts. Utilizing a novel laser beam diagnostic approach, we are able to determine timing errors on the scale of a few µs. Since the method does not involve the structuring of test specimens with certain processing windows, the analysis is applicable over a wide range of power levels, allowing the direct observation of power dependent laser switching delays, and their influence on the aspired shape accuracy. We present investigations of power dependent start/stop-point displacement over a variation of 400 W and devised a quick and convenient calibration procedure.

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1. Introduction

In recent years, the field of additive manufacturing (AM) has seen a tremendous development, influencing a wide field of scientific and industrial applications. Especially in metal processing like selective laser melting (SLM), the technology is changing the manufacturing landscape via its unique design and fabrication possibilities, allowing accelerated product development and complex, lightweight metal parts. However, in order to become a viable industrial production method, e.g. for small batch series, arises a demand for quality standards and repeatability. Especially industries with high security demands like aerospace, automotive or medicine require a high level of quality monitoring [1].

In terms of laser beam diagnostics, the special geometric constraints posed by the interior of an AM machine (like limited space and a high variety of possible beam incident angles), typically restricts the analysis to the center of the scanning field. Consequently, all investigations associated with the beam deflection system, like field distortion or flatness, rely on alternative methods, such as the writing of test patterns on a work piece and subsequent visual inspection. In addition, many of the parameters crucial for a solid understanding of all process relevant conditions exceed the possibilities of conventional beam diagnostic concepts, like e.g. the determination of the marking speed. Thus, a thorough characterization of the laser beam in the scanning field is only inadequately provided by state of the art beam diagnostic devices.

Our novel measuring concept [2,3] is adapted to the special framework conditions of an AM machine. It allows a compact measuring instrument capable of addressing a majority of the above-mentioned scanner specific measurement tasks, including quantities so far inaccessible to conventional beam profilers. Even the accurate stitching of two overlapping exposure schemes is feasible.

In this paper, we want to emphasize the possibilities this novel measuring technique holds for synchronization issues in a SLM machine: In order to precisely position a meltpool in the powder bed, it is crucial to accurately synchronize the scanner motion to the laser switching times. Delays between the deflecting unit and the laser programming can lead to tracking errors, and thus poor part quality [4,5]. Hence, the determination of these laser-switching delays is an essential calibration task.

Nowadays, common practice to determine such delays often involve the processing of a test specimen, and subsequent visual inspection with regard to the geometric accuracy of the written patterns. Since the specimens have specific operating points, which typically differ from the optimum parameters of the SLM process, a calibration at the actual process parameters is not possible. Consequently, effects like power-dependent temporal behavior of the laser cannot be accounted for via such methods. Moreover, as an iterative or trial-and-error process the calibration procedure can be cumbersome and time consuming.

We present an alternative approach, using a prototypical measurement device, based on our novel measuring concept - the ScanFieldMonitor (SFM). A special measurement sequence allows a direct determination of the laser switching delays with µs accuracy, within a measurement period of only a few seconds, and independent of the laser power.

2. Working principle of the ScanFieldMonitor

While conventional laser beam diagnostics probe stationary beams, the measuring concept of the SFM utilizes a moving beam, as depicted in Fig. 1 a). Since this movement is provided by the scanner itself, we hereby also characterizes the steering apparatus, in addition to the properties of the laser beam.

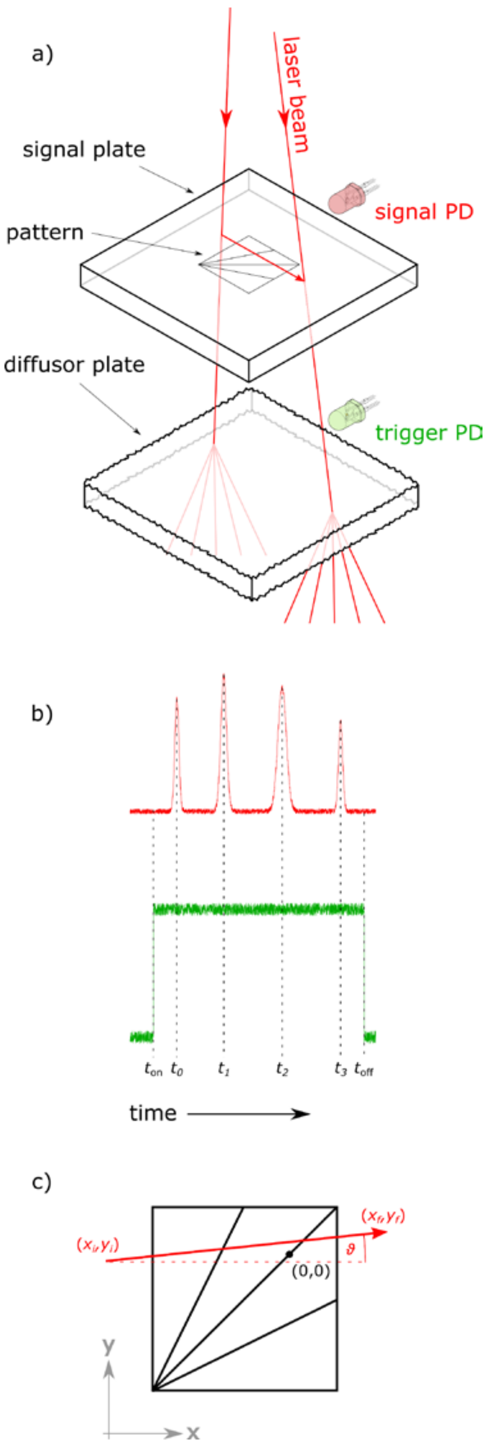

Fig. 1 Working principle of the SFM. a) A photo diode (signal PD) monitors scattered light form the laser beam crossing an in-glass pattern. Stray light from a diffuser (for beam expansion) serves as a trigger via a second photo diode (trigger PD). b) Time resolved signal of signal (red) and trigger PD (green). c) Vector coordinates in relation to signal pattern.

The underlying concept is based on the detection of scattered light from an in-glass measuring pattern. While scanning the laser in a straight line across said pattern we record the time resolved stray light signal with a photodiode (signal PD), as well as the laser illumination times (trigger PD). The transmitted beam is expanded via a diffuser plate, to reduce the power density to a noncritical level on the baseplate below. From the relative spacing and width of the PD signals (see Fig. 1 b), we on the one hand are able to deduce the beam size and an 1D integrated beam profile. On the other hand we can calculate the marking speed, and perform a complete reconstruction of the written vector (more specifically start- and end-point coordinates and hence vector length and direction) with respect to the measuring pattern is possible, as indicated in Fig. 1 c).

2.1 Timing and synchronization

Inaccurate synchronization of the beam steering apparatus to the laser illumination can originate from different sources within the machine, including inertia of the mechanical components, signal transduction, or delayed electronic responses. Via a comparison of the original trigger signal from the scanner programming to the actual laser emission, one could learn about the latter. However, this presumes access to the corresponding signals, which measurement equipment typically lacks. And it doesn't fully assess the problem, since the mechanical response of the mirrors is not included.

Comparing the programmed position to the actual written one would be an appropriate figure of merit, but this requires an absolute knowledge of the position. While the SFM in principle can provide these measurands with an appropriate calibration, we devised an alternative measuring sequence providing access to the timing information. The basic idea is to investigate the velocity dependency of the length or more specifically the start- and end-point of a vector. This is explained in more detail with the aid of Fig. 2: It shows two vectors of the same length L at two different velocities v_1 and $v_2 > v_1$. Consequently for the illumination times t_1 and t_2 holds the relation $t_1 > t_2$. In the chosen representation of a distance-velocity-graph, these times are given by the slope of the dashed lines.

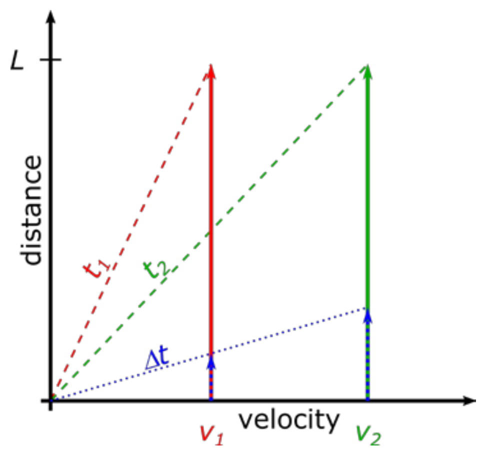

Fig. 2 Representation of two vectors of identical length, written with different marking speeds, and the influence of timing error in a distance-velocity-graph.

If we now assume a switch-on delay Δt, which is represented by a single slope (blue dotted line) in Fig. 2, this constant timing error will with higher velocity manifest as an increasing length error (blue dotted vectors). Thus, we can identify delay times by measuring the identical programmed vector with different marking speeds.

3. Experimental work

Our experimental scanner setup uses a continuous wave transverse single mode fiber laser (IPG YLR-400-WC), with a maximal output power of 400 W at a wavelength of 1070 nm as laser source. The scanning unit consists of a ScanLab intelliSCAN 20 and a fused silica *fθ*-objective with a nominal focal length of f = 420 mm. This results in a processing beam with a focal radius of w_0 = 35.7 µm, a full divergence angle of 2θ = 21.3 mrad, and a beam quality factor of M^2 = 1.12, measured in the scanner zero-point position with one of our camera-based devices (PRIMES MicroSpotMonitor). The corresponding Rayleigh length amounts to z_R = 3.36 mm. The 5x5 mm² measuring pattern of the SFM is composed of scattering lines of 10 µm width, and can withstand power densities of > 200 MW/cm² without alteration.

3.1 Delay time calibration

In order to perform a delay time calibration using the SFM, we measure a sequence of identical vectors with different marking speeds ranging from 0.1 m/s to 8 m/s. The vectors were written using ScanLab's laser processing software LaserDESK. For all markings, Skywriting was enabled. With a tenfold repetition, the complete data acquisition time takes about 1.8 seconds. The calibration was performed at 20 W of laser output power. The results are displayed as a distance-velocity-graph in Fig. 3. For the sequence with default values (red), the displacement of the vector's start- (triangles) and endpoints (circles) with respect to the lowest velocity in the writing direction show the linear behavior with increasing marking speed, which is expected for uncalibrated delay times.

The determined timing errors correspond to the slope of the linear regression fitted to the data (dashed lines). Repeating the measurement, taking into account the correction values, yields the green data set in Fig. 3, which does not show any significant dependency from the marking speed.

Hence, without any further iterations, and within a few seconds of measuring time, a delay time compensation of laser switch-on and switch-off times with µs accuracy can be performed. Since the determination of the velocity is independent of the orientation of beam path and measuring pattern (variations of ± 10° shown in [2]), the spot size, or the absolute position, setup time and device alignment for a valid delay-time measurement are considerably modest.

3.2 Power dependent timing behavior

One of the big advantages of using the SFM for delay time determination over conventional methods like marking of test specimens is the possibility to measure the relevant timing delays independent of the applied power level (power levels ranging from 20 W to 1 kW have already been tested). This allows to calibrate a SLM machine at the actual process conditions and ensures that e.g. power dependent timing behavior of the laser source can be compensated for.

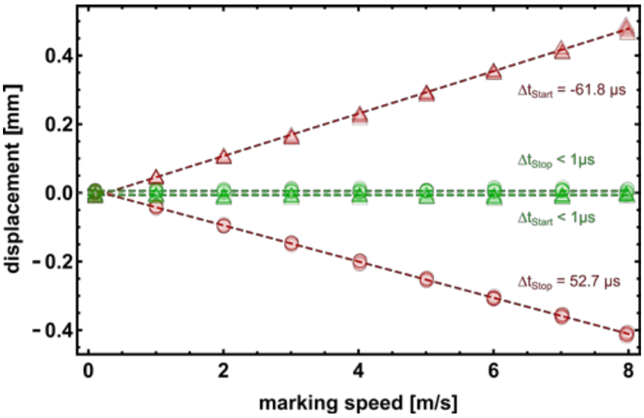

Fig. 3 Velocity-dependent start- (triangles) and endpoint (circles) variation for two delay time settings. red: uncalibrated, green: calibrated.

To emphasize to what extent these effects can influence the accurate positioning during a 3D printing process, we investigated this issue via a direct observation of the laser emission times, and the SFM, respectively.

For this purpose, we characterized the power dependency of our laser source with the following experimental setup: The laser emission was triggered by means of a 5 ms rectangular pulse from an arbitrary waveform generator. The time resolved laser emission was monitored via the transmitted beam behind an HR mirror with a fast photodiode. Trigger and emission signal were simultaneously recorded with a 1Gs oscilloscope and are depicted in Fig. 4 for different power levels.

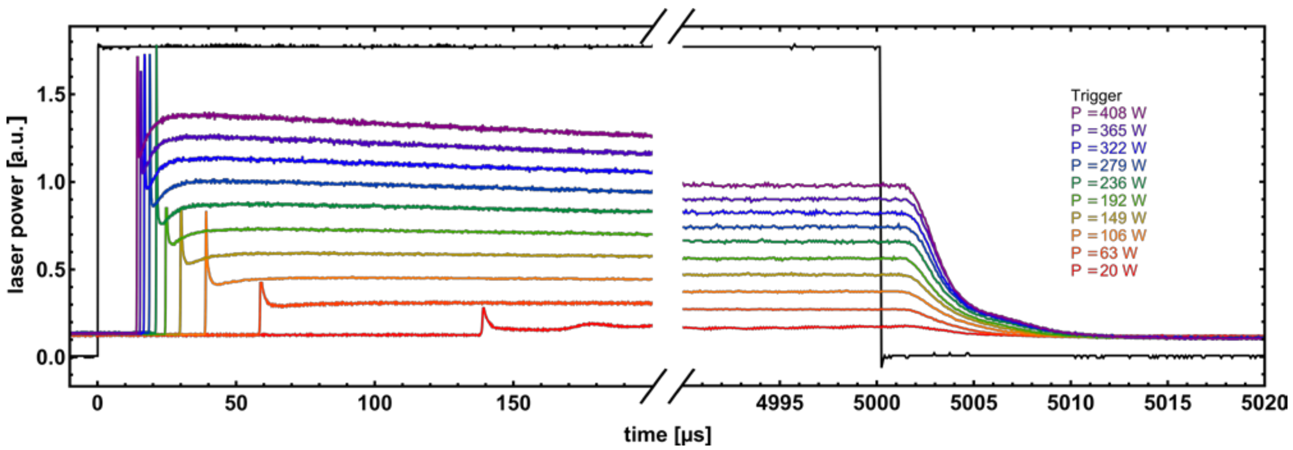

Fig. 4 Time resolved laser emission for different power levels monitored via a PD, in comparison to the external trigger signal (black).

The laser switch-on features a prominent overshoot on a few µs scale and then approaches its equilibrium value for t > 2 ms (not displayed). Obvious is the power-dependent delay of the rising edge compared to the trigger signal (black), which decreases almost exponentially from about 140 µs to 14 µs with increasing laser power. The switch-off shows a less pronounced dependency. There is a constant delay of about 2 µs with respect to the trigger edge, followed by a decrease of the laser power. When defining the switch-off time as the point where the power falls below a certain (e.g. process) threshold value, this ring down time can lead to an additional power dependent delay of a few µs.

Keep in mind that the observed offsets only feature the electronic delays in signal transmission and processing, and do not incorporate mechanical influences.

For the investigation with the SFM, we use the same delay time settings for all power levels, which were optimized for a laser power of 20 W (see Fig. 3). Repeating the measurements in the way described in section 3.1, yields the results displayed in a distance-velocity-graph in Fig. 5. As expected by the previous observations, we see an influence of the set power level on start- as well as the end-point variation.

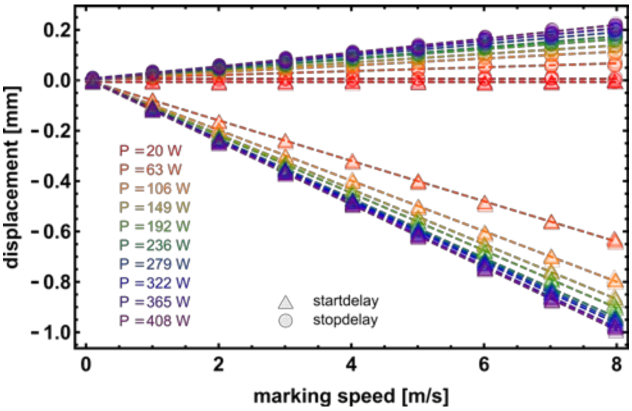

Fig. 5 Delay time measurements with the SFM at different power levels.

Also in this measurement, the effect is more pronounced for the onset point and shows a similar convergence for high power levels. The negative slope of the corresponding curves is in accordance with the fact that the delay shortens with rising output power. The weak dependency of the end-point can be associated with the discussed laser ring down time and a fixed threshold as implemented in the SFM.

While the actual threshold level in this definition can have a certain influence on the measured switch-off time, the sharp rising edge of the onset gives an unambiguous signal. A comparison of the determined onset delays and their power-dependency for the two different measuring methods is presented in Fig. 6. The direct approach via the photo diode measurement (red triangles) only includes electronic signal transduction and not the mechanical response of the system. Moreover, as the scanner settings were calibrated to the 20 W measurement, for comparability the vertical axis is shifted about a constant value of 138.7 µs against the ordinate of the SFM data (green triangles), but has the same spacing.

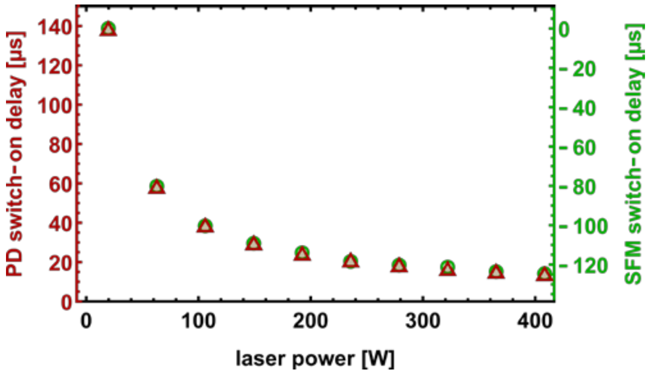

Fig. 6 Comparison of the determined switch-on delays, from PD (red triangles) and SFM measurement (green circles). The vertical axes have the same scale and are shifted by 138.7 µs.

The excellent agreement of the two data sets is evident. The standard deviation of the differences over the complete power range amounts to only ± 0.4 µs. Keep in mind that this comparison is between two vastly different measuring approaches, with different preconditions: An absolute quantification of the timing error with respect to a known trigger signal, versus a relative measuring technique with no a priori system information.

4. Conclusion

We presented a thorough investigation of the possibilities our new measuring approach for laser scanner systems holds in terms of timing and synchronization calibration. The working principle is based on a time resolved measurement of scattered light, when a laser beam is scanned across a measuring pattern. By reconstructing the beam path over a said pattern, we are able to precisely locate the start- and end-point of the written vector. An investigation of the velocity-dependency of these points allows a direct calibration of the synchronization times, without an a priori knowledge of the applied trigger signals.

In addition, we used the system to observe and quantify the power dependency of these delays, due to the electronic response of the laser source at different output levels. In our experimental setup, the differences in response time can exceed 100 µs over a range of 400 W, what even at moderate marking speeds of 1 m/s would lead to a tracking error of > 100 µm. This is already significantly larger than the aspired accuracy of < 60 µm for aerospace applications [1].

Hence, we see several advantages compared to alternative techniques for timing calibration, which typically rely on the marking of test patterns and subsequent visual inspection. This includes the possibility to measure at arbitrary laser powers to calibrate the system at the actual process parameters and is not restricted to the operating point of a special test specimen. Moreover, the modest measuring time of a few seconds in combination with the fact that the correction values are directly accessible via this kind of measurement and do not need a successive approximation to the optimal parameter set, can constitute a significant saving in time when calibrating or inspecting scanner systems.

Acknowledgments

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