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ON THE INFLUENCE OF THERMAL LENSING DURING SELECTIVE LASER MELTING

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Abstract

Multi kilowatt single mode lasers are increasingly being used in Selective Laser Melting (SLM), typically with the aim of improving productivity. However, the high power densities present in the optical path lead to a thermally induced focal shift i.e. thermal lensing. Whilst thermal lensing has been studied for many processes, its impact on parts produced by SLM is currently unknown. Therefore this work discusses the characteristics of a thermally induced focal shift supplemented by a method for the compensation of this effect. In addition, SLM parts with and without thermal lensing compensation are compared in order to show the effect on final part quality.

Keywords: Thermal Lensing, Focal Shift, High Power Laser, Control, SLM

1. Introduction

In recent years, Selective Laser Melting (SLM) [1] has evolved from rapid prototyping toward rapid manufacturing. This has led to research efforts being directed toward increasing production rates and improving the quality of parts produced by SLM. One of the resulting trends is the transition toward high power lasers in the kilowatt (kW) range. The added benefit of these high power lasers is twofold. On the one hand, production rates can be scaled up significantly by increasing the laser spot size and subsequently the hatch spacing and/or layer thickness. On the other hand, the ever increasing materials palette is moving towards refractory metals, highly reflective metals and super alloys, which often require high laser power for processing/melting. This has led to the successful introduction and adoption of high power single mode laser systems by SLM equipment manufacturers on an industry wide scale. However, this shift also introduces the need for a better understanding and compensation of the thermally induced effects they cause, i.e. thermal lensing. As the power densities in the optical path increase, thermal effects/disturbances in this optical path become more important, having a direct impact on the power intensity being radiated upon the powder bed. This can detrimentally influence part properties and quality consistency during manufacturing cycles. While thermal lensing and the mechanics behind it are well-studied for more traditional laser based material processing techniques (welding, cutting, etc.) [2] [3] [4], not much is known on the impact it has during the SLM process. This paper will therefore describe the characteristics of the induced thermal shift, supplemented by a method for the compensation of this effect. In addition, SLM parts with and without thermal lensing compensation are compared in order to show the effect on final part quality.

2. Background

The mechanism behind thermal lensing in high power laser manufacturing processes is well known and considered to be well understood [5] [6] [7]. Thermal lensing occurs as a result of the absorption of laser emission in transmissive optical components. The absorbed emission in turn induces a temperature gradient within the optical material. This affects the optical propagation properties throughout the system by two mechanisms [5][6]. Firstly the temperature gradient induces a gradient in the refractive index. Secondly, the thermal gradient induces a mechanical stress which in turn leads to deformation of the optical surface, often referred to as bulging. Both mechanisms affect the system’s ability to maintain a diffraction limited focus i.e. the position of the focal point relative to the work plane changes together with the minimum achievable spot size. Both principles are demonstrated in Figure 1. When using a laser of the YAG wavelength (1064nm), the typical material to construct lenses, mirrors and other optical components is fused silica, which is characterized by a high $\partial n/\partial T$, and a comparatively low Coefficient of Thermal Expansion (CTE) with typical values of 10x10^{-6} K^{-1} and 0.5x10^{-6} K^{-1} respectively [8] . This leads to the conclusion that the change in refractive index is the predominant driver of thermal lensing in 1064nm based material processing techniques such as SLM.

2.1. Considerations on the effect of thermal lensing on the SLM process

In SLM, fine metal particles are molten and fused together under the influence of laser emission [1]. Due to the high melting point of metals, the laser emission needs to be concentrated into a small area on the powder bed. This in order to achieve the required intensity to successfully melt and fuse the metal particles. The area irradiated by the laser emission determines the resulting intensity at the intersection with the work plane as follows:

$$\mathrm{I} = \frac{P}{A_{surf}} = \frac{P}{r^2\pi} \tag{1}$$

Where I is the intensity, P is the laser power and A_{surf} is the exposed surface area of the melt pool. As a material independent metric[1] for a circular Gaussian beam profile, the surface area can be approximated by that of a circle i.e. $A_{surf} = r^2\pi$. This implies that the intensity is inverse quadratic related to the radius of the beam caustic at the intersection plane. In turn implying that a small dynamic change in the beam radius due to thermal lensing invokes an instability in the processing intensity, resulting in an undesirably inhomogeneous intensity distribution on a spatial and temporal scale. As shown in figure 2, the relationship between the beam radius and the focal shift is determined by the innate propagation mode of a TEM00 laser. This relationship is non-linear by nature, however in an industrial setting it is commonly accepted that the Rayleigh range denotes the ‘in focus’ zone and beyond that threshold, ‘defocusing’ occurs [9]. The following section will quantify the extent to which a focal shift occurs and the time scales involved with respect to the SLM process.

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[1] The material/melt properties, e.g. wetting angle, viscosity,... determine the actual area that is being irradiated.

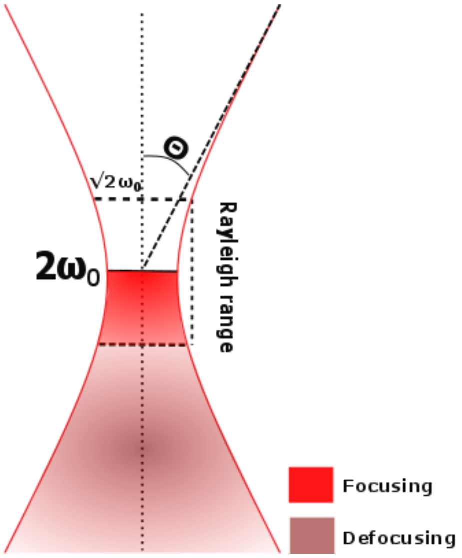

Figure 1 Cross section of a TEM00 beam caustic

3. Measurements & Methods

To quantify the effect of the focal shift due to thermal lensing, a dedicated test setup was developed. All experiments were carried out on the in-house developed SLM machine (LM-Q) at the Additive Manufacturing laboratory at KU Leuven. The LM-Q machine is equipped with a 1 kW fiber laser with a wavelength of 1080nm and a variable focusing unit together with process monitoring optics [10]. To measure the focal shift, the build module was removed and a beam caustic measurement device was placed in the working plane. In addition an OPHIR thermophile laser power meter was added to measure and dump the generated power output. The laser caustic measurements were carried out with an OPHIR BeamWatch® which is a Non-Contact Beam Profiler. The operating principle of this system is the measurement of Rayleigh scattering originating from the laser's beam waist, allowing for fast non-contact measurement of the beam caustic. By measuring the focal shift at the level of the working plane, the lensing of all the optical components in the optical path is combined and included in the measurement, i.e. intra- and extra-cavity lensing is measured simultaneously. By combining and synchronizing the measurement data of both sensors, the relationship between laser power output and the thermally induced focal shift is determined.

3.1.Measured response & system identification

To assess the relationship between the laser power output and the resulting shift of the focal point, a set of measurements were carried out at different laser power set points. Figure 3 shows the steady state values for the focal shift in function of the laser power output, plotted against the Rayleigh length of the system. The focal shift was measured over a range of 400 to 900 Watt in increments of 100 Watt, and with a measurement time of 60 seconds per laser power setpoint. Figure 3 shows that the focal shift is linearly dependent on the laser power, which is in accordance with previous findings reported by Thiel et al. [11]. A least squares fit is applied to extrapolate the values for the focal shift over the entire laser power range. Note that the performed measurements reflect the static focal shift, i.e. the beam is deflected toward one point in the working plane. These measurements do not accurately represent the working conditions during processing, they do however show that the effects of thermal lensing are not negligible and can have a large influence on the focal position and subsequently the processing intensity. As an example, consider a laser power setpoint of 600 Watt with the initial focal plane aligned with the working plane. From the measurement results it is derived that the steady state focal shift in this case amounts to ~100 % of the systems Rayleigh length, i.e. the spot radius is doubled and the incident power intensity is only a fourth of the intended value.

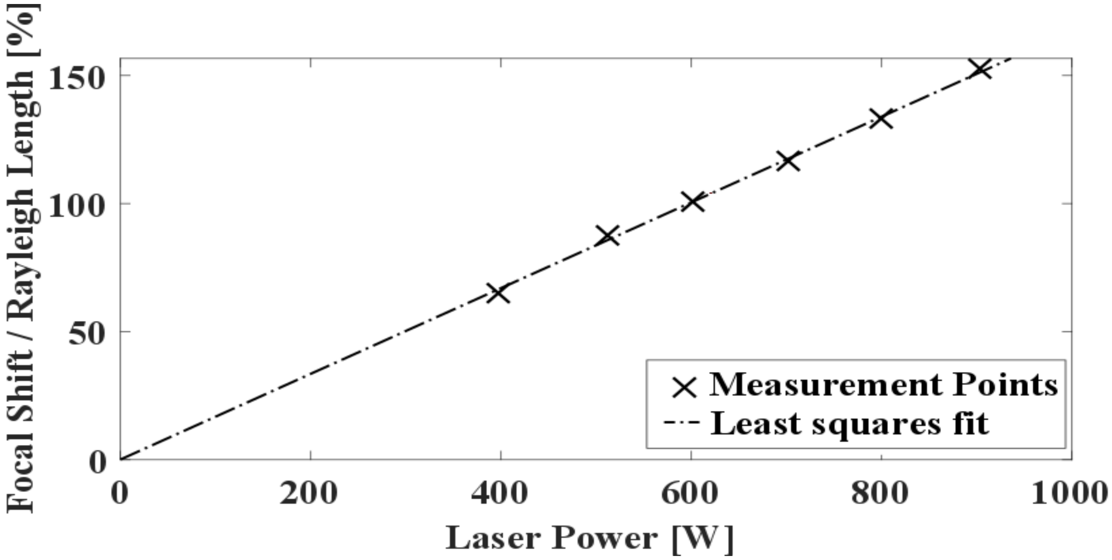

Figure 2 Measured focal shift ranging from 400 to 900 W

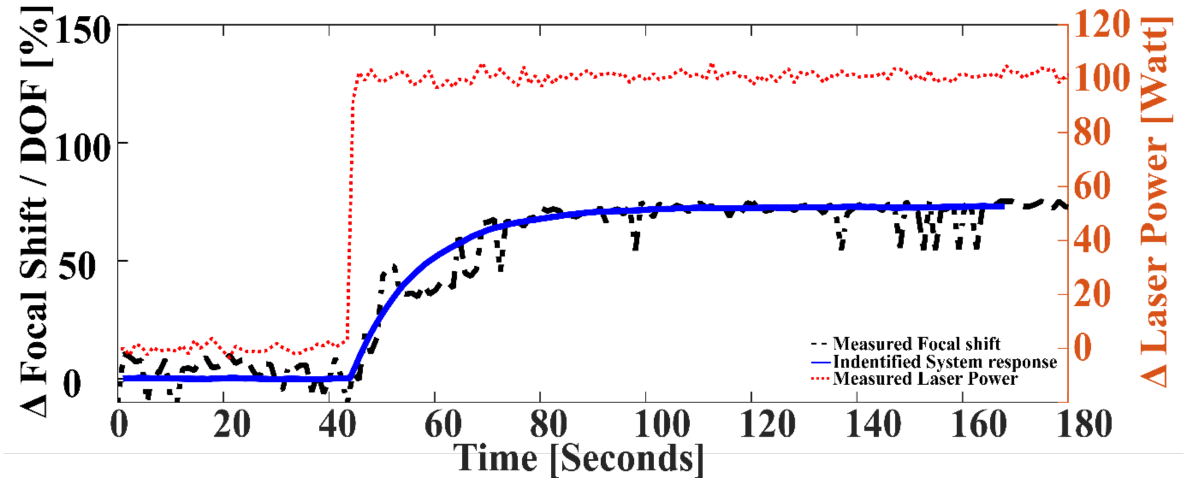

Figure 3 Measured step response and identified system model

In addition to the steady state values of the focal shift, the transient behavior was investigated. In order to do so, a step response measurement was carried out and shown in Figure 4. The measurement was performed for a 100 W step increase in laser power after steady state was reached. The measurement shows that the main dynamics of the induced focal shift are that of a Linear Time-Invariant (LTI) system of first order. The model equation of which, is given in equation (2). To further quantify the system behavior in the time domain, a system identification was employed. The system was excited using square steps (staircase) with a laser power amplitude ranging from 500 to 1000 W in increments of 100 W and with a holding time of 120 seconds for each step, during which the thermally induced focal shift was measured at a sampling frequency of 2 Hz. The systems transfer model was identified using MATLAB together with a 'non-linear least squares' system estimator. From this, the following LTI system transfer function was identified together with its characteristic time constant τ (4) (also shown in Figure 4):

$$\mathrm{H}(s)=\frac{\mathrm{A}}{\tau s+1} \tag{2}$$

$$H(s) = \frac{0.0026}{s + 0.07861} \tag{3}$$

When the time constant of the focal shift is compared to the typical scanning time found in SLM (order of magnitude of seconds), it is clear that most if not all of the scanning is occurring in the transient region of the induced focal shift, i.e. when the scanning time is shorter than 38 seconds (3τ) (5), all of the processing takes place in the transient region. This leads to a gradient and inhomogeneity in the applied intensity throughout one layer as shown in section 2. Figure 5 shows a simulated focal shift during the successive scanning of 2 layers for the production of 10 cubes (10x10x10 mm). The simulated response also shows that thermal lensing not only affects one layer as a whole, but also the intensity distribution of a single cube. Despite the fact that the identified model overestimates the impact due to its static nature, it provides a good insight in the spatial and temporal behavior of thermal lensing.

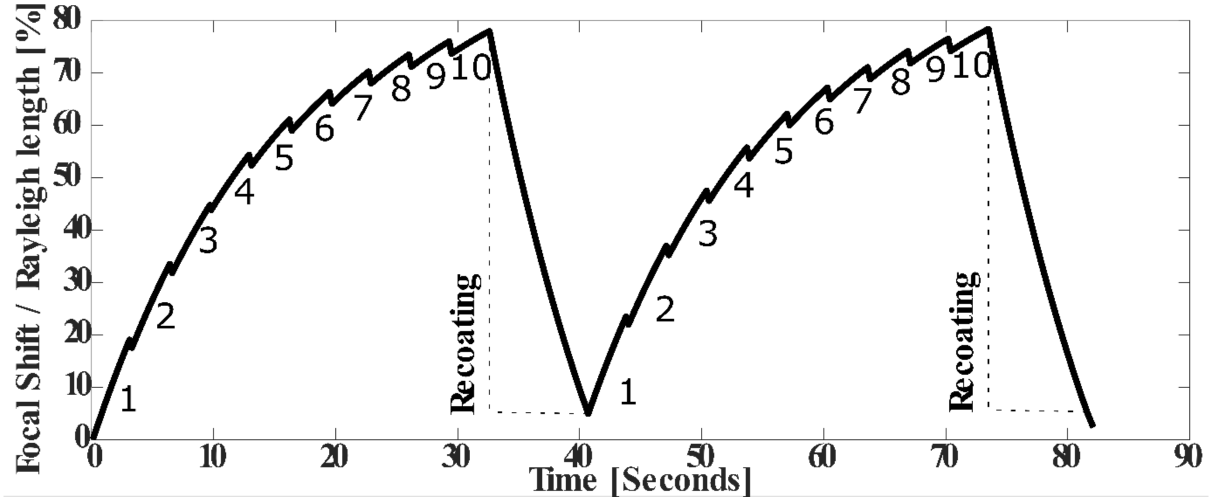

Figure 4 Simulated focal shift for two successive slices (10 cubes) with the scan speed set at 500 mm/s, laser power set at 500 W and a recoating time of 8 seconds

$$\tau = \frac{1}{0.07861} = 12.72[s] \;\; (67\% \, Steady \, state) \tag{4}$$

$$3\tau = 38.16[s] \; (95\% \, Steady \, state) \tag{5}$$

3.2.Model based compensation of thermal lensing for SLM

In this section a feed-forward system for dynamically compensating the thermally induced focal shift is introduced. This system consists of two principal components: an actuator that is able to move the focal point relative to the work plane and an altered system model based on the identified system model that is able to link the required actuator effort with the induced focal shift. In the optical path implemented on the LM-Q machine, a variable focusing unit is installed. This allows the position of the focal plane to be changed by translating a diverging optic relative to a focusing lens, thus shifting the focal position relative to the working plane. Figure 6 sketches the working principle of the variable focusing unit. By changing the relative distance between the two lenses, the divergence of the outgoing beam is altered. Changing the beam divergence allows a shift of the focal plane with a minimal effect on the spot's intensity distribution. As mentioned in section 2, the main effect of thermal lensing using fused silica optics is a shift of the focal plane. By synchronizing the thermally induced focal shift with the output of the variable focussing unit, the effect and its transients can be eliminated. Since this control scheme is feed forward, the results attained depend strongly on the accuracy of the model used. The following section will show some experimental results obtained with and without compensation of the thermally induced focal shift.

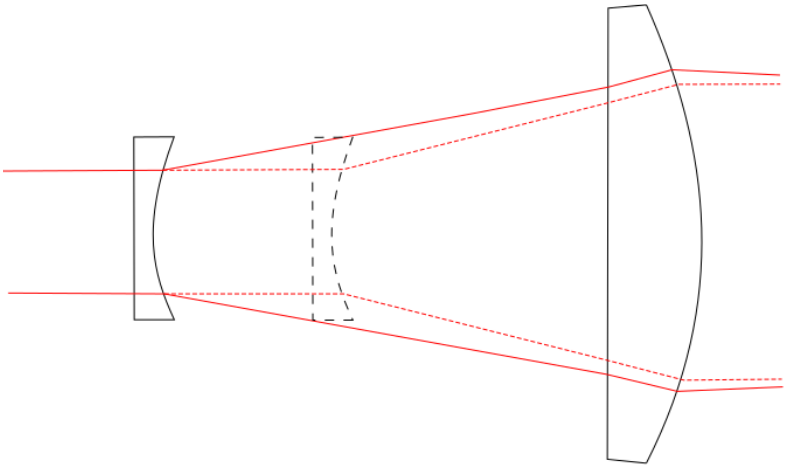

Figure 5 Principle of operation for a variable focusing unit

4. Results and Discussion

To assess the impact of thermal lensing on SLM of metals, several samples were built with and without active compensation for thermal lensing. The material used to build the specimens is a Cu alloy consisting of 99.95% Cu with a narrow processing window. The optimal processing parameters require a laser power that exceeds 800W and a scanning speed that is below 500mm/s to achieve near dense parts. The hatch spacing and layer thickness are respectively 0.07mm and 0.03mm. Under these processing conditions, the effect of thermal lensing can clearly be identified as shown in Figure 7. This figure shows top views of six specimen's cross sections, which are built in a serial fashion from left to right with identical processing parameters. Visually it is observed that the porosity level increases from left to right, with a defect morphology that suggests lack of fusion due to insufficient power input. This is in accordance with what is to be expected from the identified system model and the simulated response (Figure 5). It shows that the processing impact of thermal lensing can have an effect on final part quality.

It is to be expected that for larger parts, for a large amount of parts (longer scanning times), or for materials with narrow processing windows, the inhomogeneity in intensity can lead to unstable processing conditions. This in part, might explain why processing parameters optimized for comparatively small test samples do not always scale for larger or multiple sets of parts.

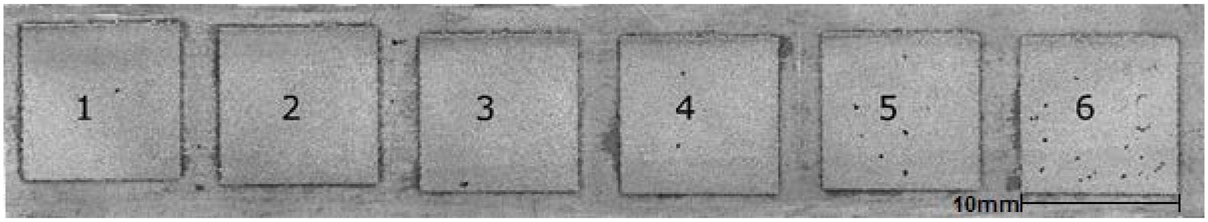

Figure 6 Top view of cross-sections of six consecutive scanned samples (left to right) produced without compensation for thermal lensing

In a next step, the same specimens were built under the same processing conditions but with active compensation of the focal shift (Figure 8). These specimens show no gradient in porosity from left to right as opposed to the specimens built without compensation. This shows that the thermally induced focal shift is the cause for the gradient in porosity in the samples without compensation and that by using a model based active compensation approach, the effect can nearly be eliminated.

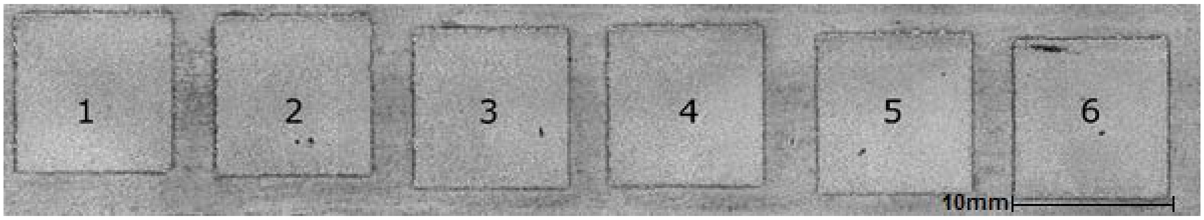

Figure 7 Top view of cross-sections of six consecutive scanned samples (left to right) produced with active compensation for thermal lensing

Conclusions

While high power single mode lasers are employed in SLM machines to scale up productivity and to expand the materials palette, their influence on the SLM process and on the quality of metal SLM parts largely remains to be investigated. One important effect that typically occurs at high laser powers is thermal lensing, i.e. a thermally induced focal shift during processing. This work focused on the effect and controllability of this thermal lensing phenomenon on Cu alloy parts produced by SLM.

Initial results indicate that a thermally induced focal shift can have a large impact on the temporal and spatial distribution of the laser's incident intensity. It was shown that for the measured SLM system, the 95% steady state time constant was 38s, implying that a significant portion of SLM processing (scanning a layer) is done in the transient region. This was examined further by building six cubical parts, always in the same consecutive order, with a constant high laser power to successively increase the thermal effects in the optical path. It was found that, due to the increasing gradients of temperature in the optical path, the porosity of the specimens processed last was larger than in the specimens processed first, even though identical processing parameters were used. In a final step, a model based feed forward approach was successfully implemented to compensate this thermally induced focus shift by means of a variable focusing unit, showing uniform density throughout all specimens.

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