Lasers in Manufacturing Conference 2015

Reliable Beam Positioning for Metal-based Additive Manufacturing by Means of Focal Shift Reduction

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Abstract

Metal-based additive manufacturing enables the production of even complex shaped parts that cannot be produced with conventional processes (e.g. milling). Taking advantage of the geometrical freedom in part production, an increasing number of industrial applications nowadays resort to these techniques. Hence, the additive manufacturing technology has currently passed the threshold from prototyping to mass production. This requires short processing times which are potentially reached by the adoption of multiple lasers with increasing output power. Typically, single mode lasers are used to reach customer demands, e.g. surface smoothness.
An optical setup of fibre beam delivery, collimation, focusing, and beam deflection is utilized to allow laser scan velocities of up to 1000 mm/s. For future applications of laser powers in the range of several kilowatts a critical level of absorbed power in these optical elements is likely to occur. The resulting thermally induced focal shift can lead to an undesirable beam defocussing and the corresponding increase of beam diameter will then lead to a loss of intensity in the powder bed interaction zone. To encounter this challenge for a future utilization of even higher laser powers, measures can be taken to reduce thermally induced focal shift. One possible approach comprises the insertion of additional optical glasses which compensate the focal shift by means of a converse thermal behaviour, i.e. negative refraction index gradient. Related to this topic, the measurement of absorption in optical components and the power dependent focal position are presented within this work. Laboratory measurements are complemented by the application of the corresponding results on an appropriate manufacturing system configuration. The investigations demonstrate that the desired reduction of thermally induced focal shift can be reached.

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Keywords: Metal-based Additive Manufacturing, Thermally Induced Focal Shift, Process Quality, Absorption Measurement, High Power Single Mode Lasers

1. Introduction

In recent years, developments in the field of IR high power solid-state lasers have made almost diffraction limited multi-kilowatt lasers commercially available and ready to use for industrial laser processing. However, the advantages of such laser systems are only deployable in conjunction with high-quality optics. Among other quality issues, it is of particular importance that the introduced amount of thermally induced wavefront aberrations is as small as possible. Otherwise, thermal effects must lead to decreasing beam quality and thermal lensing, resulting in poorer focusability und focal shifts.

To avoid these effects, the overall absorption of the beamline optics should be reduced to the smallest possible degree, by using high quality substrates and coatings at a high degree of cleanliness. For the handling of remaining thermal effects due to imperfection of the components there are two approaches. Firstly, active compensation of the thermal aberrations is possible. This approach comprises focus monitoring and feedback control systems using e. g. adaptive mirrors or actuators to adjust the position of elements in the beamline. Thus, a considerable amount of complexity is introduced into a laser system with this approach. This is why, secondly, a passive compensation scheme is worth considering, using optical materials with a negative thermal dispersion dn/dT.

Various attempts of passive compensation have been published so far, mostly focusing on intra-cavity compensation. Regarding extra-cavity optics compensation, an approach to a thermalisation with respect to the ambient temperature has been published by Scaggs et al. (2011) using CaF2 ($dn/dT < 0$) as compensating optical material. Piehler et al. (2012) have also demonstrated passive compensation of thermal lensing. To complement these, the following work depicts a passive compensation of focal shifts for high power laser optics in practice. As currently the selective laser melting process is mainly focusing on productivity increase and corresponding developments, the use of higher laser power and higher load on the optics is on the agenda. The handling of thermal effects in selective laser melting machines is therefore discussed in this paper.

2. Parameters in selective laser melting

As described before, controlling the focal position is of crucial importance for counteracting process instabilities caused by thermal effects. But it becomes apparent that this parameter is one of a large variety of different adjustable variables. Van Elsen (2007) has listed numerous main influence factors related to selective laser melting. Subsequently van Elsen et al. (2008) are demonstrating the possibility for simplifying the number of input parameters by using a dimensional analysis.

Eisen (2010) has considered 96 input parameters for the process of selective laser melting categorized in 5 groups by means of selective laser melting. According to his work, the derived categories are: operator, machine, environment, material and method. For his specific analysis he reduced the input parameters to the following: scan velocity v_s, hatch distance y_s, and laser beam diameter d_B. Whereas e. g. Kurzynowski et al. (2012) have focused on laser power P_L, layer thickness t_{La} and hatch distance y_s.

In addition to the variety of parameters also the resulting process and part properties should be regarded. Users of the selective laser melting technology can select between different target figures. Concerning this matter Krol et al. (2013) have mentioned density, surface quality, residual stresses, dimensional accuracy, strength, hardness, production time and material requirements. They have developed a finite element model for revealing most influencing parameters dependent on the used target figure. Hence, this procedure leads also to less variable parameters.

It becomes evident, that for receiving a manageable design space only the most influencing factors should be selected whereas other variable parameters should be kept constant. To consider this aspect, this investigation is focusing on one factor which can be difficult to stabilize due to thermal aberrations. As discussed in the previous chapter it is the stability of focal position, i. e. reduction of focal shift. This parameter is indeed crucial as it defines the laser beam diameter utilized at the material interaction zone within the selective laser melting process. It is assumed that this zone has to be the plane of the powder surface.

The beam diameter on the powder surface d_B and the laser power P_L define the laser intensity in the process. The diameter of the laser beam d_B is a result of beam parameters and of positioning in beam propagation direction. Laser intensity drops with the square of the distance of the smallest beam diameter (beam caustic) from the powder surface and is a critical factor for melting metal powders as well as the formation and resolidification of melt. Therefore it will influence the material density and the surface quality of a selective laser melting manufactured part.

As an example for the decreasing part quality during selective laser melting when working at changed positioning of the laser beam caustic Δz, the results of density measurement of parts made of stainless steel 1.4404 and with a 400W single mode laser are shown in figure 1. The parts are built with varying focal positions. The distance of the beam caustic from the powder surface is called focal position. It is given as a ratio of the Rayleigh length which describes the distance where the beam cross-sectional area has doubled. Positive values designate a focal position above the powder surface. Negative values indicate a caustic position inside the powder.

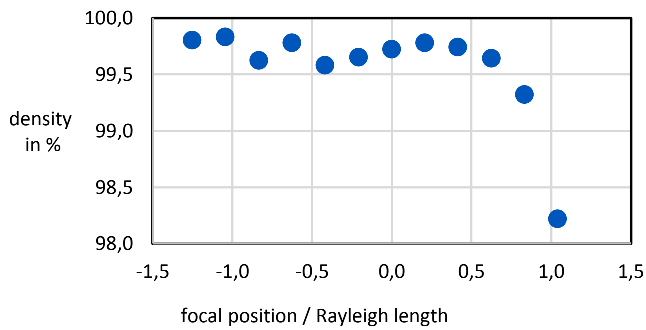

Fig. 1. Exemplary result of part density (1.4404) measurement achieved with different focal positions during the selective laser melting process.

According to the measurement results given in figure 1, the density is stable over a large range of focal positions, but dramatically decreases, once a threshold is reached.

Surface quality values, i. e. average roughness on the top side of the built part are given in figure 2. Roughness rises above R_a = 20 µm when the focal position is shifted above one Rayleigh length. This imples that roughness is fairly stable over a large range of parameters, but clearly depends on focal positioning when the parameter field of focal positions is wide.

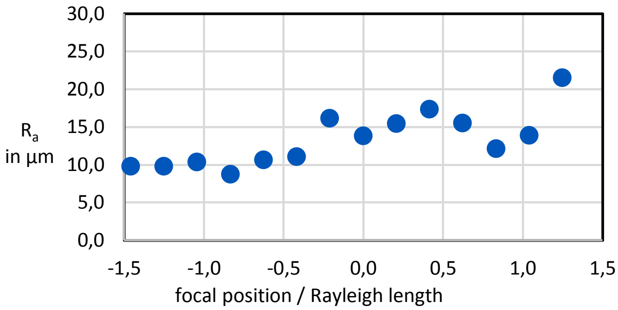

Fig. 2. Exemplary result of measurement of roughness on the top side of parts made of 1.4404. The parts were manufactured applying different focal positions during the selective laser melting process. Standard volume hatch parameters were used without surface finishing.

Also a high significance is given to surface roughness on the sides of the parts. When measuring these a stable field of R_a = 9 µm to 12 µm is reached at focal positions of plus and minus one Rayleigh length. Then a rise up to R_a = 18 at 1.5 Rayleigh length is observed.

Focal positioning can be intentionally used in laser processes to create a desired laser intensity I_L. In addition, an undesired focal shift may occur due to occurrences in the beam path which consists of several passes of the laser beam through lenses and substrates to shape the beam caustic and position the beam.

3. Focal shift in laser processing optics

The absorption of an intense circular laser beam (radius r_b) propagating in z-direction through a cylindrical optical sample (length L, radius r_0, refractive index n_0) leads to a stationary temperature change $\delta T(r,z)$, giving rise to a wavefront distortion δw.

Considering a thermal expansion ΔL and changes of the refractive index with temperature Δn_T and induced stress Δn_σ, the distortion is given by

$$\begin{aligned}\delta w_{r,\varphi}(r) &= \int_0^L \left[(n_0 - 1)\frac{\Delta L}{L} + \Delta n_T + \Delta n_\sigma \right] dz \\ &= \int_0^L \left[(n_0 - 1)\varepsilon_{zz}(r,z) + \frac{dn}{dT}\delta T(r,z) - \frac{n_0^{\,3}}{2}(\boldsymbol{B\sigma})_{r,\varphi} \right] dz\end{aligned} \tag{1}$$

with dn/dT denoting the temperature variation of the refractive index, ε_{zz} the strain component in z-direction, $\boldsymbol{\sigma}$ the temperature induced stresses, $\boldsymbol{B}$ the photo-elastic tensor and the subscripts r, φ signifying the test beam polarization (Schäfer et al. 2009).

In a first order approach, $\delta w(r)$ may be approximated by its parabolic fraction, leading to an optical power $1/f$. After z-integration and averaging over the polarization states Eq. (1) yields in the plane stress ($r_b >> L$) or plane strain ($r_b << L$) approximation, respectively

$$\frac{1}{f} = -K \cdot L \frac{d^2}{dr^2}\delta T(r)_{|r=0} \tag{2}$$

(Stubenvoll et al. 2014) with the thermo-optical parameter K:

$$K_{pl,stress} = \frac{dn}{dT} + (n_0 - 1)\alpha(1+\nu) + \frac{n_0^3}{4}\left(B_{\parallel} + B_{\perp}\right)\alpha E$$
$$K_{pl.strain} = \frac{dn}{dT} + \frac{n_0^3}{4}\left(B_{\parallel} + (1+2\nu)B_{\perp}\right)\alpha E \quad (3).$$

In Eq. (3) α is the coefficient of linear expansion, E Young's modulus, ν the Poisson ratio and $B_{||}$, $B_{\perp}$ the stress optic coefficient for polarization parallel or perpendicular to the applied stress. From the parabolic part of the temperature profile near the axis one obtains:

$$\frac{1}{f} = K \cdot L \frac{c_S \mu P}{2\lambda\pi r_b^2} \quad (4).$$

In Eq. (4) P and λ are the average power of the heating laser and the heat conductivity, respectively. μ is an effective absorption coefficient, containing bulk and surface contributions i. e., $\mu = \mu_{bulk} + 2\beta/L$, with β the single surface absorption. c_s is a coefficient depending on the beam shape (e. g. c_s = 1 for a flat top and c_s = 2 for a Gaussian beam).

In order to compensate the thermal lens generated in an optical element I with a second plane element II placed closely in front of or behind I, Eq. (4) yields for the thickness of element II (parameters indexed by I and II, respectively) (Stubenvoll et al. 2014):

$$L_{II} = -L_I \frac{\mu_I \lambda_{II}}{\mu_{II} \lambda_I} \frac{K_I}{K_{II}} \quad (5).$$

Due to the fact that in isotropic materials $\Delta L/L$ and Δn_σ are always positive, the compensation of a $dn/dT > 0$ element requires $K_{II} < 0$, i. e. at least $dn/dT < -n_0^3\alpha E(B_{||} + (1+2\nu) B_{\perp})/4$. Schott®'s N-PK51 complies with this condition. The table shows the values of dn/dT and the parameter K/λ for N-PK51.

Table 1. Material Parameters (Schott® 2013)

Schott® N-PK51	
dn/dt * 10^6 [1/K]	-8.4
$K_{pl.stress}/\lambda$ * 10^6 [m/W]	2.8
$K_{pl.strain}/\lambda$ * 10^6 [m/W]	-10

In this paper the focus is put on the power dependent focal shift which is, according to equation (4) subject to linear dependency. The effect of increased absorption by different qualities of optical components is not subject of this paper. Transient effects will occur due to the accumulation of absorbed energy in the components and is subject of one of the measurement setups presented.

4. Measurement of focal shift

In order to quantify the suitability of N-PK51 as a compensating material for high-power laser optics, a measurement was set up as outlined in figure 2. The high-power beam is propagating through the compensating element and the focusing objective. The beam waist position at different laser powers is determined directly via caustic measurements. For this purpose the beam has to be strongly attenuated without introducing additional thermal aberrations. This is achieved by using the reflected beam from high-quality fused silica wedges in combination with additional filters.

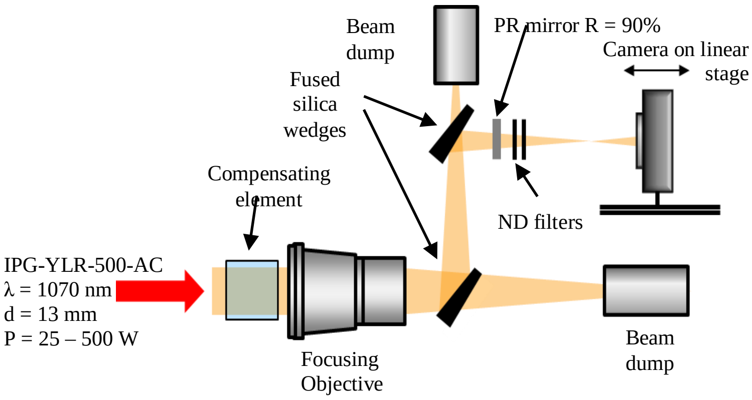

Fig. 3. Setup for focal shift measurement in the laboratory.

A second setup was used inside a selective laser melting machine (SLM®280) to measure the focal shift resulting from the complete beam path inside the machine. The compensating element was introduced into the beam path at a beam diameter of about 9 mm. For this setup the metal powder was removed from the built platform and the measurement device, including attenuators and a camera was put on the platform.

5. Experimental results

In the laboratory setup the focal position (caustic position) was measured at different laser powers and the transient behavior of the beam diameter was measured at working distance. Figure 4 contains the results of a beam caustic position measurement. The maximum shift of the focal position occurring between 25 W and 460 W laser power was normalized to 100% relative focal shift.

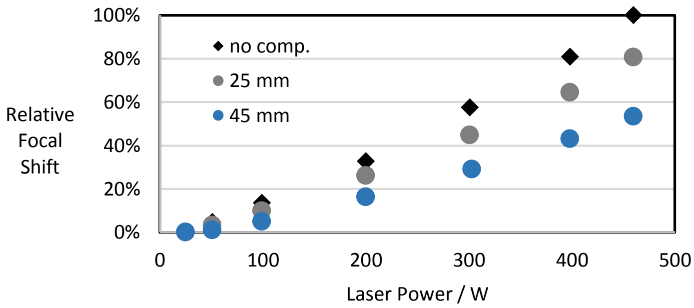

Fig. 4. Measurement results of focal position shift relative to the maximum focal shift between 10% and 100% in laboratory setup.

As can be derived from equation (4), the focal shift depends linearly on the laser power. Using two compensation elements of different lengths, both reduce the measured focal shift. A reduction by a factor of 2 was successfully demonstrated.

As mentioned at the end of chapter 3 the transient behavior caused by the accumulation of energy inside the optics are another subject of investigation. Figure 5 illustrates the build-up of a focal shift over a few seconds as a result of the time-dependent power absorption and, consequently, the formation of a radial temperature gradient in the lenses.

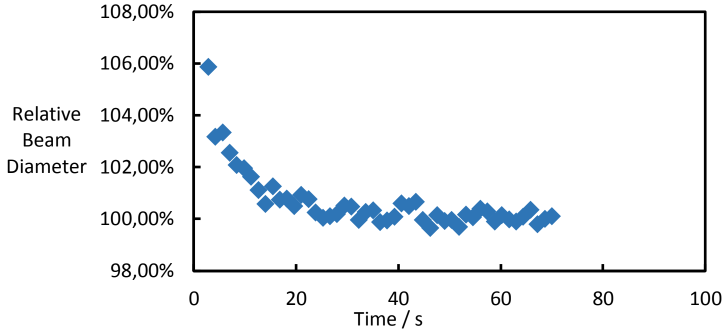

Fig. 5. Course of relative beam diameter over time in the plane of powder surface without compensation element.

The measuring plane is at working distance. The desired beam diameter, i. e. maximum intensity is only reached after some seconds. Nevertheless, the measured starting value of the beam diameter is only 6 % above the intended diameter. In the future it will be necessary to further investigate the behavior within the first 2 seconds which is the typical laser on-time during fast scanning applications. The measurement setup must be adapted accordingly to get reliable results. A good compensation of focal shift should include the transient behavior.

Measurements in the selective laser melting machine show a very similar behavior compared to the results from the laboratory (figure 4). A reduction of the focal shift by the factor of 1.8 is reached at all power levels when using the 45 mm compensation element.
In figure 6 setups using compensation elements of different lengths are compared. As described in chapter 3 the length of the compensation element should match the diameter of the laser beam when passing through the glass. Here the focal shift is normalized to the maximum shift occurring at the specific setup. The highest value at 100% was Δz = 0.9 times the Rayleigh length.

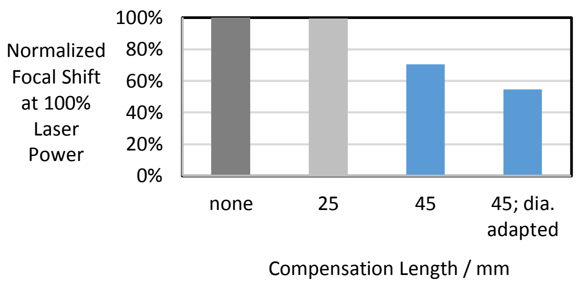

Fig. 6. Reduction of the focal shift according to the grade of adapting the compensation element to the beam diameter.

Although the simple expressions given in eq. 3 for the edge cases of plane stress and plane strain, the thermo-optical parameter K is dependent on r_{beam}/L as well as on laser and material parameters in a complex manner. The thermal behavior of such systems can therefore only be determined by a numerical thermo-elastic approach. Stubenvoll et al. (2014) have shown that a particular length of the compensating element is necessary for mere self-compensation. Whereas the effects of thermal expansion (i. e. the bulging of entry and exit surfaces) saturate with increasing sample length, the negative dn/dT contribution is accumulated along the beam path. Hence, the compensating property of such an element can only come into effect at a specific length, depending on a set of laser and material parameters. With this in mind, it is apparent that in figure 6 the 25 mm long element is just at the point of self-compensation for the given parameters and can thus make no contribution towards reducing focal shift. For longer elements and/or smaller beam diameters the compensation starts to take effect. No limits in compensation have been found so far, so that a full compensation of focal shift with a longer glass block should be possible in future.

6. Conclusion

Focal shift is an issue to be discussed in every high power laser machine and/or process. The approach discussed in this paper is a compensation for focal shift by using an optical element with corresponding glass characteristics. That procedure was successfully tested and a reduction of focal shift in a selective laser melting machine by the factor of 1.8 was shown. It proved to be necessary to choose a distinct layout of the geometry of the compensation element according to the beam path setup. The advantage of this approach is that the compensation element is subject to thermal load for the same time as the other components in the beam path and will therefore compensate most of the transient distortions. The investigation results provide a tool to handle focal shift when it reaches a critical dimension e. g. at higher thermal load in future. The range of focal positions that exhibit good density and surface quality values of parts manufactured using selective laser melting can more easily be reached when using a passive compensation element.

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