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Towards dynamic shaping of high power laser beam intensity profile by means of a deformable mirror

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Abstract

In high power laser material processing, such as laser welding, laser transformation hardening and laser cladding, the material properties depend on laser-induced thermal cycles during the process. Traditionally, these thermal cycles are controlled by modulating laser power and beam velocity. However, the thermal cycle is also strongly affected by the laser beam intensity profile in terms of dimensions and shape. Adapting this intensity profile during processing allows to control and tailor the thermal cycles. Therefore, this work presents a dynamic beam shaping setup for high power laser applications. An optical setup, based on a deformable mirror, has been designed and implemented. The prototype of the setup is evaluated in a lab environment by measuring the laser intensity distribution with a CCD camera based beam profiler at low laser powers. Results show that the setup makes it possible to create various distinct laser intensity profiles dynamically and with a large design freedom.

Keywords: Laser material processing; Laser intensity profile; Dynamic beam shaping; Deformable Mirror

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1. Introduction

In various high power laser-material processing techniques , such as laser welding, laser cladding and laser transformation hardening, the final processing results, such as microstructure and thus mechanical properties, depend on the laser induced thermal cycles (Kwok et al. 2016; Thompson et al. 2015). These thermal cycles can be controlled by tuning the beam velocity, the laser power and (if applicable) the additional material feed rate.

Conventionally, these laser-material processing techniques use a Gaussian(-like) or a Top Hat laser intensity profile. However, various studies showed that the laser beam shape—i.e. the geometrical distribution of laser intensity within the laser spot on the surface, also strongly affects the final processing result. For example, in laser transformation hardening, Wellburn et al. 2014 used axisymmetric beams with various core-ring power ratios to show the effect on uniformity of the hardened layers. Rasch et al. 2019 employed points, line and ring shaped laser intensity profiles in heat conduction mode welding to study their effect of the profiles on the melt pool size, shape and dynamics. In our earlier work (Bremer, Luckabauer, and Römer 2023) we showed the effect of circular, square and annular laser intensity profiles on the thermal cycles and resulting microstructure of deposited tracks in Directed Energy Deposition (DED).

The above mentioned beam shapes are static beam shapes—i.e. the intensity profile is not changing during the process. Dynamically adapting the intensity profile, so in-situ, during processing allows to tailor the processing results, e.g. the material properties. An optical device allowing dynamic beam shaping is a Deformable Mirror (DM). Such a mirror has been employed, e.g. in laser conduction welding to create an elliptic beam (Mi et al. 2022). This paper provides a proof of principle for a DM based dynamic beam shaping setup with more flexibility and complexity in the beam shapes that can be created. In section 2 the optical layout of the setup and the measurement setup including the deformable mirror will be presented and discussed. Section 3 will present and discuss the experimental performance of the setup, showing the potential of beam shaping using a deformable mirror. Finally, section 4 will conclude this work.

2. Experimental setup

The experimental setup, which was designed and implemented as a proof-of-principle of beam shaping using a deformable mirror, is shown in Fig 1. Section 2.1 presents and discusses the optical layout of the focusing optics in more detail. In section 2.2 the measurement setup and procedure are described.

2.1. Laser source, optical transport fiber and focusing optics

The laser beam is generated by a Yb:YAG disk laser source (TruDisk 10001, TRUMPF SE + Co. KG, Germany), equipped with a 100/400 µm 2-in-1 optical transport fiber (Haug et al. 2019) of which only the core (100 µm) is used. The fiber is coupled to focusing optics (BEO D70, TRUMPF SE + Co. KG, Germany), of which the collimator has a focal length of 150 mm and the focusing lens a focal length of 600 mm. Both the collimator and focusing lens are disassembled from the original focusing head and mounted on an optical breadboard, as shown in Fig. 2. Between the collimator and the focusing lens the deformable mirror is mounted. This mirror (PDM30-37, Flexible Optical B.V., Netherlands) is actuated by 37 Piezoelectric actuators. To enlarge the diameter of the focal spot, a Galilean beam expander is implemented to reduce the diameter of the collimated beam. This beam expander consists of convex mirror with a focal length of -150 mm (87-681, Edmund Optics Ltd, UK) and a concave mirror with a focal length of 500 mm (CM254-500-P01, Thorlabs Inc., USA). In between these mirrors a flat mirror (PF10-03-P01, Thorlabs Inc., USA) is positioned to keep the optical layout compact. Furthermore a neutral-density (ND) filter (NG1 3mm, Schott AG, Germany) is applied to reduce the optical power of the laser beam to protect the deformable mirror, as the anti-absorption coating of the mirror is not (yet) optimized for the wavelength of the laser beam.

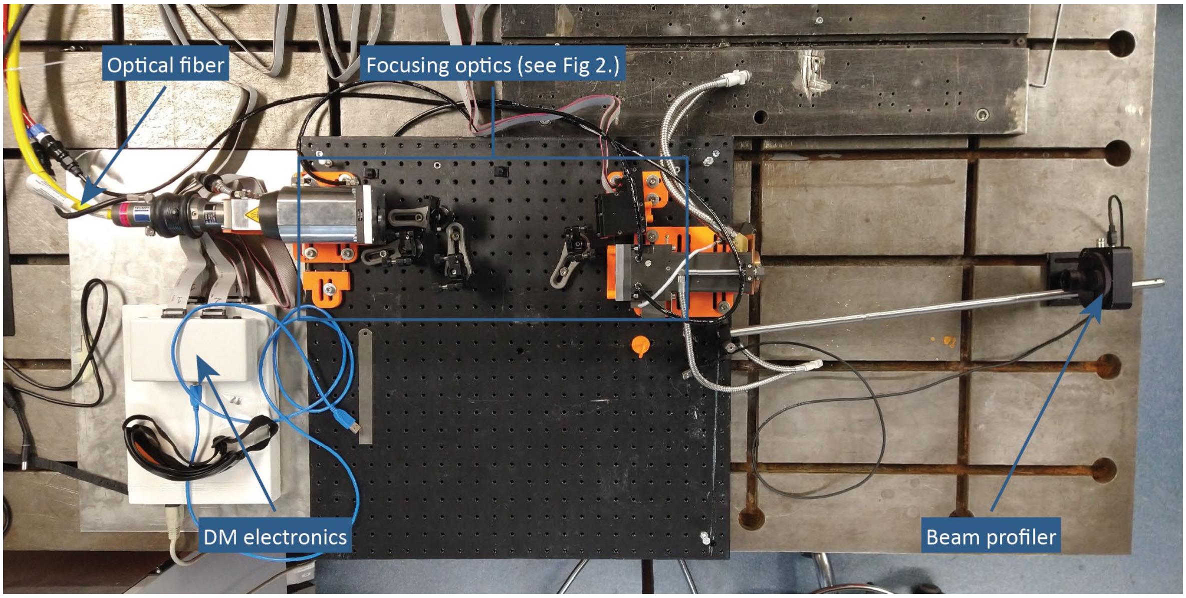

Fig. 1. Photograph (top view) showing an overview of the experimental setup. A detail of the optical layout of the setup is shown in Fig 2.

2.2. Measurement setup

The shaped laser intensity distributions, in the focal plane of the focusing lens, were measured using a laser beam profiler (BC106-VIS, Thorlabs Inc., USA), see Fig. 2. During the measurement, the power of the source was set to is minimum stable laser power of 200W and operated in the pulse mode. That is, the temporal pulse shape was set to a “square wave” with a pulse duration of 0.3 ms at a pulse repetition rate of 2 Hz. This results in an average laser power of 0.12 W. The ND filter (Fig. 2.) reduced this to 120 nW. This low power assures that the deformable mirror is not damaged, due to absorbed laser energy. Much higher laser powers, up to several kW, could be applied when the anti-absorption coating of the mirror is optimized. The low powers used in this paper suffice the demonstrate the feasibility and flexibility of beam shaping using a deformable mirror for laser material processing.

To avoid damage to the CCD sensor of the beam profiler, additional ND filters (NExxA-B series, Thorlabs Inc., USA) are mounted in the beam path depending on the maximal intensity of the measured beam profile. The exposure time of the beam profile is synchronized with the pulse rate of the laser beam, reading 500 ms.

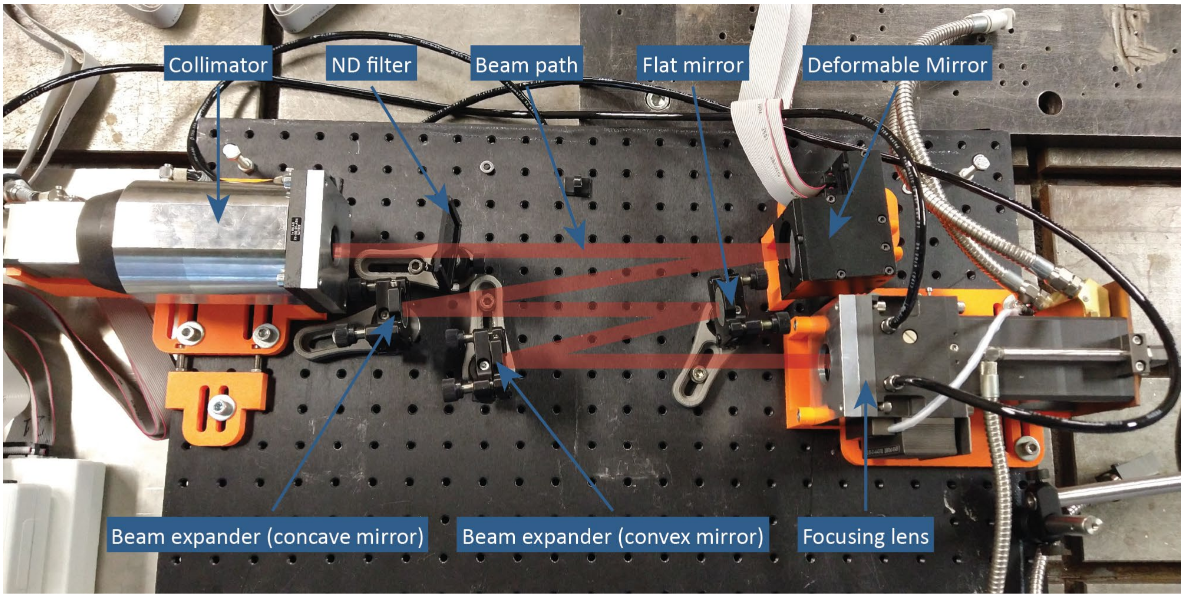

Fig. 2. Prototype focusing optics suitable for dynamic beam shaping. Red line indicates the beam path.

2.3. Experimental approach

For this proof-of-principle, three beam shapes are targeted, namely an annular, a square and a horseshoe shaped laser beam in the focal plane of the laser beam. These beam shapes will be generated by proper actuation of the 37 piezo-actuators of the deformable mirror. These piezoelectric actuators deform the mirror (shape) to create a curvature of the mirror surface corresponding to the desired beam profile where the local gradient (curvature) of the mirror surface determines the deflection of beamlets reflected at that specific local position on the mirror. In other words, the distribution of surface gradients determines the distribution of laser intensity in the focal spot. The deformable mirror can be actuated while exposed to laser irradiation. This allows to change the laser intensity profile during laser- material processing.

3. Experimental results and discussions

In this section the experimental results are presented and discussed. That is, section 3.1 presents some results without out beam shaping—i.e. that is without actuation of the deformable mirror, implying a flat mirror. In section 3.2 the measurement results are presented and discussed when targeting the annular, horseshoe and square shaped beam.

3.1. Preliminary results, unshaped beam

When the mirror surface is flat, the deformable mirror does not affect the laser intensity profile as emitted from the optical transport fiber. This is a Gaussian-like profile, due to the fact that the core diameter of the transport fiber is small (100 µm). The corresponding measured intensity profile is shown in Fig. 3. As can be concluded form this graph, the Gaussian-like intensity profile shows a diameter of about 1.35 mm, which is close to the theoretical value of 1.33 mm following from fiber diameter (100 µm), and the ratio of the focal lengths of the focusing lens and the collimator, as well as the ratio of the focal lengths of the beam expander.

The intensity distribution within the focal spot corresponds with distributions found in literature for the core of a 2-in-1 fiber (Haug et al. 2019).

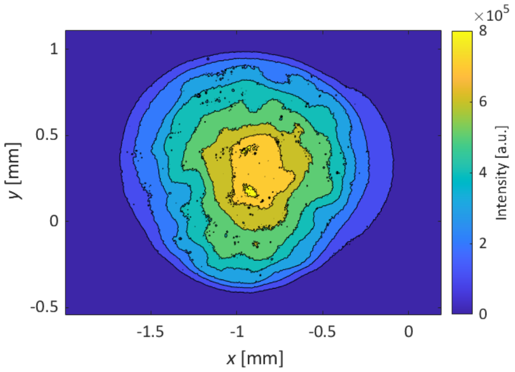

Fig. 3. Contour plot of the measured laser intensity profile of the unshaped laser beam, in the case the deformable mirror is not actuated (flat).

3.2. Targeted beam shapes

The annular beam shape is an intensity distribution where the laser intensity is distributed in a ring. As the gradients of the mirror surface should also be distributed as a ring, the deformable mirror is shaped as a cone, see Fig. 4a. This mirror shape is used as input for the piezo-actuator and the intensity profile in the focal plane is measured. The laser intensity profile of Fig. 4b. is obtained. This beam shape indeed resembles the desired annular beam shape. However, the measured intensity profile is not completely uniform in tangential direction, but shows some "peak" intensities in the upper-left quadrant. These small irregularities are attributed to small misalignment of the laser beam with respect to the center axis normal to the surface of the deformable mirror or by differences between the desired and actual mirror shape.

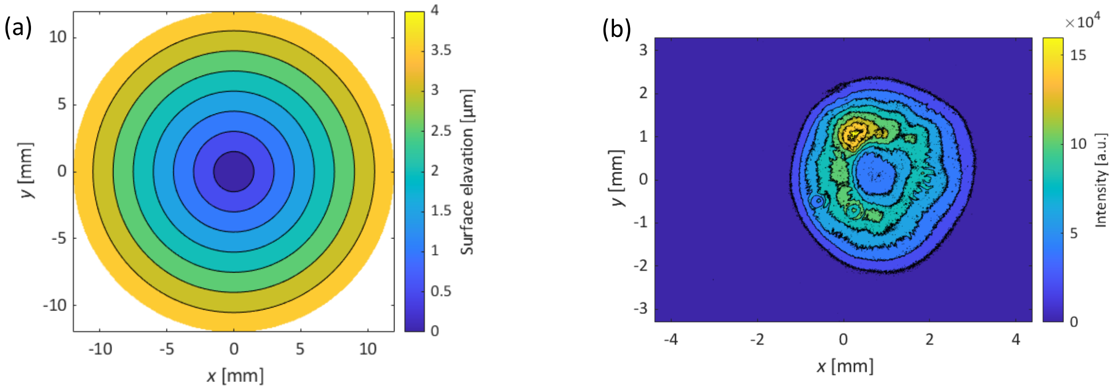

Fig. 4. (a) Contour plot of the conical shape of the deformable mirror to form a annular intensity profile and (b) contour plot of the measured laser intensity profile when the conical mirror shape is used.

A horseshoe shaped intensity profile consists of a semi-circle and two straight ”legs”, with a 50:50 power division between the legs and the half ring. To shape the intensity profile into a half ring, the right half of the deformable mirror should be shaped like a cone, see Fig. 5a. The left half of the mirror shapes the legs of the beam profile. As there are two legs, this left half of the mirror consists of two quadrants, where each quadrant is responsible for one of the legs. For each leg of the profile, the laser irradiation is to be spread over a horizontal line. Therefore the y-component of the gradient is constant for the corresponding mirror quadrant and the x-component of the gradient of this mirror quadrant is decreasing (so becoming steeper) when going in negative x-direction, see Fig 5a. When applied as an input to the piezo-actuators, this mirror shape results in measured laser intensity profile in the focal plane as shown in Fig 5b. When comparing this measured profile to the measured profile in the annular beam shape (Fig. 4b), the left half of the horseshoe profile is indeed—as it should— similar to the left half of the annular beam shape. Also here some “peak” intensities occur in the upper-left quadrant.

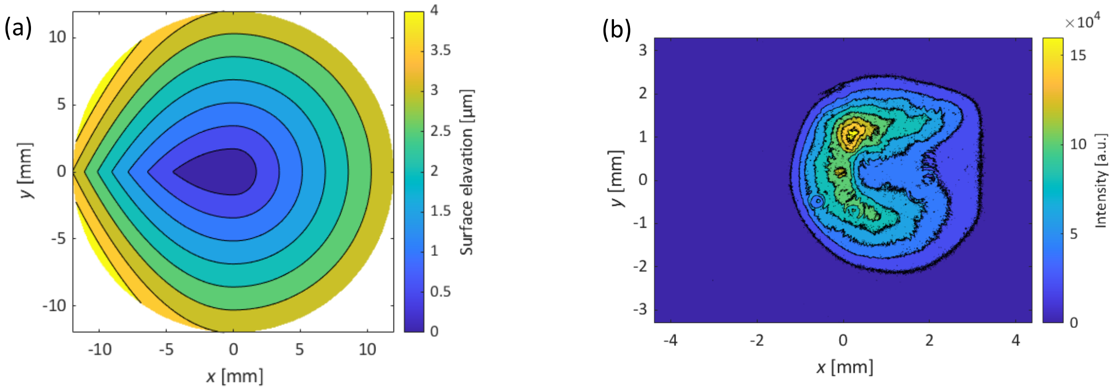

Fig. 5. (a) Contour plot of the shape of the deformable mirror to form a “horseshoe” profile and (b) contour plot of the measured induced intensity profile of the horseshoe profile.

The mirror shape to obtain a square uniform intensity profile is not trivial. Therefore, inspired by the equiaxial mapping of a disk to a square, the x- and y-components of the gradient of the mirror shape was determined. When using these gradients the mirror surface of Fig 6a. is found. However, a mirror surface matching both components of the gradient with the desired ones over the entire mirror surface could not be found. Therefore the resulting laser intensity profile of Fig 6b. deviates from a perfect square intensity distribution.

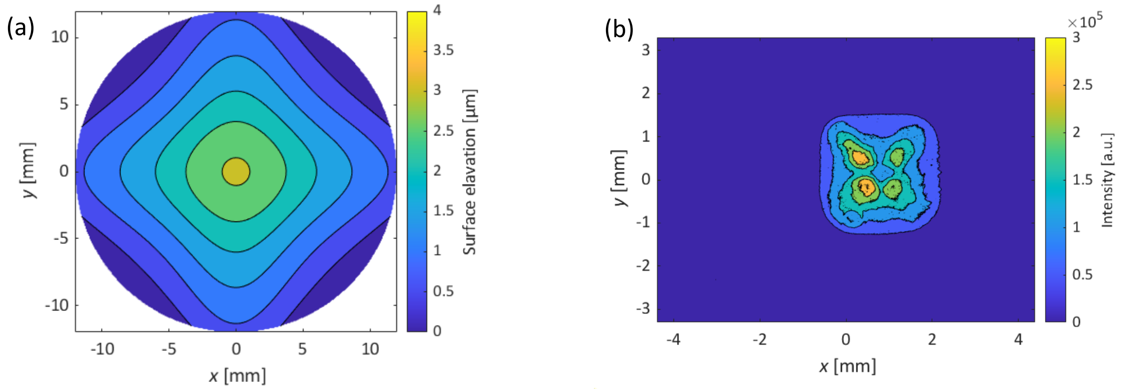

Fig. 6 (a) Contour plot of the shape of the deformable mirror to form a square uniform profile and (b) contour plot of the measured induced intensity profile of the square uniform profile.

4. Conclusion

A setup to study the feasibility of in-situ and dynamic shaping of the intensity profile of a laser beam was designed and implemented. The required shapes (local gradients) of the mirror surface to generate annular, horseshoe and square shaped intensity profiles were determined and realized with the deformable mirror. The experimental results of measured intensity profiles in the focal plane showed that the setup is capable of generating a wide variation of laser intensity profiles. As the mirror shape and therefore also the laser intensity profile can be adapted on-the-fly, this optical design and implementation paves the path for dynamic beam shaping in laser beam processing. Future, research will include designing and assembling a dust-proof setup with High Reflective (HR) coated optical components and high power testing of the designed setup.

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