Dynamic High-Power Beam-Shaping for 3D Laser Polishing

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An optical design and setup for the shaping and dynamic adaptation of an application-adapted intensity distribution is presented. The optics allow for a free rotation of the distribution and a compression of the distribution along an arbitrary axis perpendicular to the optical axis. The compression enables the compensation for the distortion of the distribution on tilted or curved work surfaces.

1 Introduction

Laser polishing is an uprising candidate for a replacement for the time-consuming and error-prone manual polishing of complexly shaped steel tools and components [1]. Still, state of the art polishing rates of ~1 cm²/min with round beam shapes heavily limit the economic efficiency of this technology. Kumstel investigated the use of process adapted intensity distributions and was able to increase the area rate by a factor of 10 on flat work pieces [2]. On curved and/or tilted surfaces, however, the intensity distributions get distorted, resulting in a deterioration of the process results and/or a reduction of the area rate.

In this work, an optical design and setup for a high-throughput 3D laser polishing system is presented. The almost loss-free shaping of a 2 kW continuous wave (cw) laser beam into an application-optimized intensity distribution enables high area rates (~10 cm²/min). The optical system also allows for a free rotation and 3D-positioning of the intensity distribution on the work piece. To compensate the distortion of the distribution on curved/tilted surfaces, the distribution can be pre-compressed along an arbitrary axes perpendicular to the optical axis.

2 Optical Concept

The optical concept is depicted in Fig. 1.

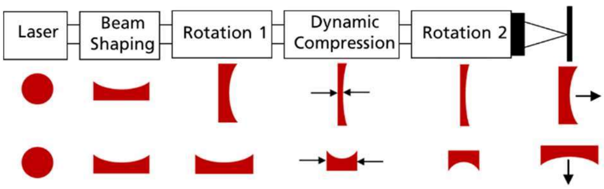

Fig. 1 *Concept for the 3D laser polishing optics with 2 exemplary beam shaping sequences.*

First, the raw laser beam is shaped into the desired intensity distribution. The beam is then rotated to be correctly orientated for the upcoming compression. Next, the intensity distribution is compressed to pre-compensate for the elongation of the distribution on tilted work piece surfaces (cf. Fig. 2). The compression factor can be dynamically varied based on the shape of the work piece and the current position on the work piece. The distribution is then rotated again to match the feed direction of the process. Finally, a 3D laser scanner and commercially available focusing lens are used to focus the beam onto the work piece.

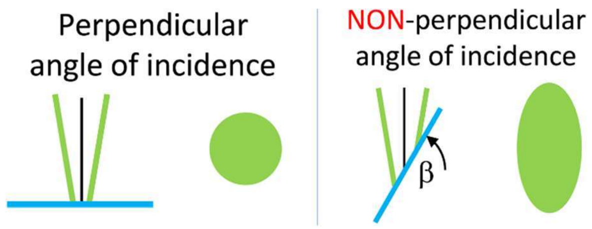

Fig. 2 *Influence of non-perpendicular angle of incidence on a (simplified) intensity distribution on the work piece.*

3 Initial Beam Shaping

The target intensity distribution was chosen based on the results in [2]: a rectangular flat-top with an outer size of 1500x400 µm² and a “cut-out” triangle in the middle (cf. Fig. 3). For the initial beam shaping, a custom made diffractive optical element (DOE) is used. The DOE changes the phase of the incoming single-mode laser beam. This leads to a basically loss-less reshaping of the beam into the desired distribution in the far field or in the focal plane of a focusing lens [3]. By rotating the DOE via a hollow shaft motor, the first rotation (cf. Fig. 1) is directly integrated in the initial beam shaping.

However, using a phase element for beam shaping at the beginning of the optical system introduces additional challenges for the optical design and setup. Any distortion of the beam phase, e.g. by diffraction at apertures or mirrors with insufficient flatness, directly affects the final intensity distribution. Furthermore, these effects cannot be simulated via standard ray-tracing but require wave propagation methods. Thus, each step of the conventional optical design via ray-tracing needs to be accompanied by physical optics simulations.

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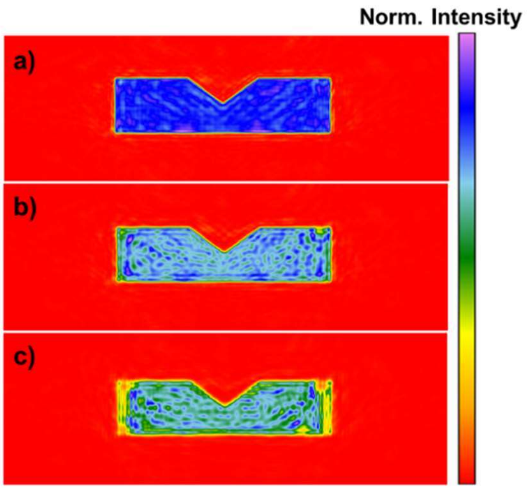

Fig. 3 *Influence of the diffraction at apertures on the final intensity distribution. Aperture sizes: a) ≥ 2x beam diameter, b) 1.5x beam diameter, c) 1.25x beam diameter*

For example, Fig. 3 shows the simulated impact of insufficient large apertures (smaller than 2 times the beam diameter) on the final intensity distribution as a result of the diffraction at the edges of the aperture. Due to the high laser power of 2 kW, the optical system must be optimized for a beam that is neither vignetted at apertures nor damaging optical components due to a small beam size.

The DOE also leads to an additional divergence of the laser beam of ~0.3° at 10 mm beam diameter ($1/e^2$ intensity). This corresponds to around 60 times the natural beam divergence and needs to be taken into account for the design of beam expanders/reducers and zoom telescopes in the optical system.

4 Dynamic Compression

The dynamic compression is performed with an anamorphic four element zoom lens that increases the beam size in one axis by a factor between 1 and 2. This decreases the size of the intensity distribution on the work piece by the same factor along the chosen axis. The two movable lenses are positioned via a high dynamic linear axis to dynamically compensate local tilts of the work piece of up to 60° during the process.

5 Beam Rotation

The second beam rotation is realized via a mirror based Abbe-König prism (cf. Fig. 4). As a result of the uneven number of reflections, the beam is inverted after the prism. A rotation of the prism of $\boldsymbol{\alpha}$ leads to a rotation of the beam of $\mathbf{2}\boldsymbol{\alpha}$. Due to the size of the beam at that point in the optical system, the prism is designed with a clear aperture of 30 mm diameter. A second hollow shaft motor is used to hold and rotate the prism.

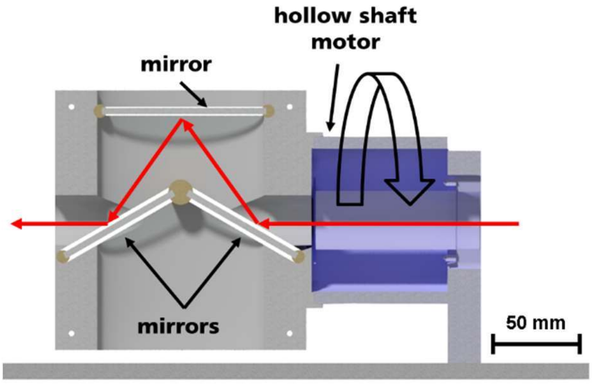

Fig. 4 *Half section of the mechanical design for the Abbe-König prism. The prism is held and rotated via a hollow shaft motor.*

6 Beam Positioning and Focusing

To freely position the laser beam on a 3D work piece, a focus shifter together with a standard 2D galvanometer based laser scanner is used. Commercially available focus shifters for laser scanners use a two lens system and are optimized for an incoming collimated laser beam. With the additional divergence introduced by the DOE (see sec. 3), such a two lens system (with spherical lenses) is not sufficient as it would distort the intensity distribution on the work piece. Therefore, a *Newson Elevathor* focus shifter was modified to hold a three lens system.

7 Outlook

All parts of the optical system were designed, manufactured and were individually tested. The next step is the integration of all parts into the optical system.

The optics will then be integrated into an existing machine tool for laser polishing at the *Fraunhofer ILT*. The machine tool has 5 mechanical axes to freely position and rotate the work piece. Together with the 3 optical axes from the laser scanner and the additional 3 degrees of freedom for the intensity distribution (rotation, compression, direction of compression), the machine tool offers 11 axes to control and optimize the laser polishing process.

References

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