Lasers in Eng., Vol. 46, pp. 305–312
Reprints available directly from the publisher
Photocopying permitted by license only

Piezo-based Beam Shaping for High Dynamic Three-dimensional (3-D) Laser Material Processing – PISTOL

L. DEVARAJ NAIR[1], C. GOPPOLD[2], P. BÖTTNER[3], D. STOFFEL[1], A. JAHN[2], C. JOLLIFFE[1] AND M. BACH[1,*]

[1]*Physik Instrumente (PI) GmbH & Co. KG, Auf der Römerstrasse 1, 76228 Karlsruhe, Germany*
[2]*Fraunhofer Institute Material and Beam Technology IWS, Winterbergstrasse 28, 01277 Dresden, Germany*
[3]*Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Albert-Einstein-Strasse 7, 07745 Jena, Germany*

Laser machining processes get more and more relevant for a vast number of industrial applications such as cutting, welding, ablation and surface treatment. These processes can be enhanced through high-speed active vertical shift of the beam energy within the workpiece. A piezo-driven dynamic focus shifter provides the opportunity to the vertical oscillation frequency in a robust and reliable manner. Up to a drive frequency of approximately 2.7 kHz, safe operation of the stack using the integrated cooling system was proven both by simulation as well as by experiments. For cutting plates out of stainless steel with a thickness of 10 mm an increase of the cutting speed by 60% was achieved compared to conventional processes at unchanged cut edge quality. The great importance of laser machining processes and the need of further improvement of these applications has been considered through development of the presented highly dynamic focus shifting module.

Keywords: Laser beam, piezo, shaping, thermal control, optics, full-stroke, focal plane

1 INTRODUCTION

Laser machining processes get more and more relevant for a vast number of industrial applications such as cutting, welding, ablation and surface treatment. These processes can be significantly enhanced through high-frequency

*Corresponding author: E-mail: m.bach@pi.de

oscillation of the laser beam in *X-Y* plane [1, 2]. New requirements in industry are demanding for not only fast in-plane motion but for high-speed active vertical shift of the beam energy within the workpiece. But the vertical oscillation is still limited by low frequency oscillation of the beam focus [3]. For laser beam cutting of thick plates an improved cut edge quality is expected [4-6]. In terms of laser beam welding of aluminium die cast material a significant enhancement of the process stability as well as of the weld seam quality is aimed. A piezo-driven dynamic focus shifter provides the opportunity to increase the vertical oscillation frequency.

This article presents an efficient heat management system for piezo-driven actuator assemblies that act as a beam forming module in laser machining. The actuator's performance at working frequencies above 2.5 kHz is a challenge due to self-heating triggered by dielectric losses of piezoelectric ceramics [7]. This work aims to find a solution to subdue the limitation of reduced operating frequencies by controlling the temperature using an air cooling system. A thermal simulation model depicts the influence of air on the heated actuator. Different flow rates of the air, flow regimes (laminar/turbulent) and flow mediums are examined to find the most advisable approach. Experimental results validate the suitability of the approach.

Additional application-oriented experimental investigations are presented, proving the functional capability and showing interrelations between high-speed vertical oscillation and process behavior.

2 PIEZO-BASED LASER BEAM FORMING MODULE

Laser material processing using a highly dynamic deformable mirror that instantly adapts the focus of the laser system enables both (i) an increase in processing (feed) speed and (ii) an improvement in the machining quality. Both can be realized through a faster dynamic behavior of a piezo-driven deformable mirror compared to conventional solutions where lenses are shifted or pneumatically actuated deformable mirrors are used [3-8].

The highly dynamic focus shifting module was developed to significantly enhance both laser cutting and welding processes. Figure 1 (b) schematically illustrates how the module is integrated in the beam path: A collimated beam is reflected on a deformable mirror and then focused by the focal lens. The device itself, shown in Figure 1(a) incorporates a piezo actuator to deform an elliptic mirror membrane, whose shape was chosen due to the 90° deflection of the laser beam. The membrane's dielectric coating leads to a high reflectivity of 99.2% at a wavelength of 1030 to 1090 nm.

To act as an actuator a high voltage stack actuator was implemented, as can be seen from Figure 2(a), which excels through a large choice of designs, microsecond response times as well as through extreme reliability beyond 10^9 cycles.

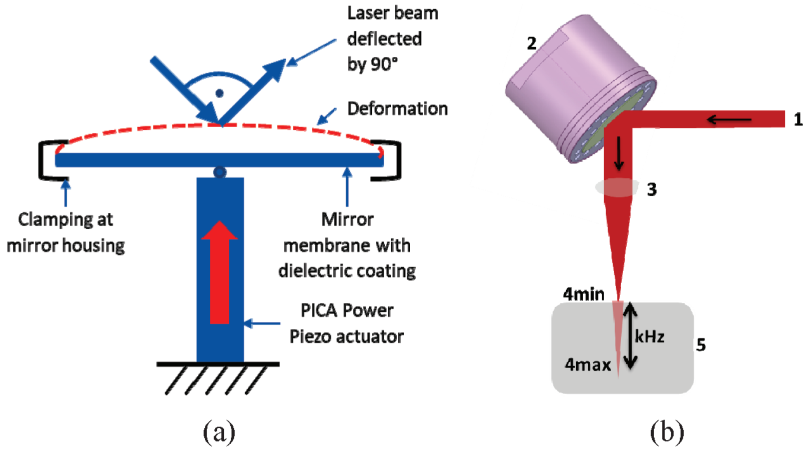


FIGURE 1
Schematic diagrams of the module's functional principle: (a) integration of Module (2) in the optical path; and (b) (1) laser beam, (3) focus lens, (4) beam focus, (5) workpiece.

The z-shifting properties of the highly dynamic focus shifting module result from deforming the membrane and the focal length of the used laser machining head, as shown in Figure 2(b). In plane state of the deformable mirror the focal point of the mirror-lens-system is at the nominal focal distance of the focal lens. A convex deformation of the mirror, however, induces a divergence in the beam which shifts the focus of the mirror-lens system away from the nominal focal distance. Thus the focus is shifted throughout the workpiece.

Within the validation a mean shift of the focal plane by 15 mm was achieved reproducibly by the investigated laser machining head. In this par-

(a) (b)

FIGURE 2
Images showing (a) examples for high voltage stack actuators [9] and (b) focus shifter device with elliptical mirror membrane.

ticular case this stroke is related to an optical setup with a collimation length of 100 mm and a focal length of 200 mm, as well as to a full-stroke of the Piezo actuator by 28 µm or 1 kV of drive voltage, respectively. This full-stroke operation was further on proven up to a drive frequency of 2 kHz.

The focus shifter module incorporates a 3” housing to enable an easy integration into existing laser machining heads and systems, respectively. Although it is operated in open-loop mode it is equipped with a strain gauge for monitoring reasons. Since the reliability of the piezo drive especially relates to the occurring temperatures, temperature sensors are applied at the actuator and membrane to establish an actively controlled temperature management.

3 HIGH DYNAMIC OPERATION THROUGH ACTIVE TEMPERATURE MANAGEMENT

The permissible temperature for the module is limited by (i) the Curie temperature of the stack actuator’s material as well as by (ii) the temperature to be considered in order to prevent de-soldering. In total this leads to a temperature limit of 150°C [7].

Two heat sources contribute to a heating of the module, which are the self-heating of the Piezo ceramic due to dielectric losses as well as the partially absorbed laser power. Considering a laser power up to 4 kW investigations showed that the module’s durability is mainly influenced by the self-heating of the actuator. The absorbed laser power, however, is mainly of concern regarding a pre-deformation of the integrated aluminium mirror membrane. Here comprising investigations are currently running to mitigate this influence and reduce the initial deformation of the mirror to a minimum, respectively.

The related dielectric losses are proportional to voltage, drive frequency as well as to the dielectric loss factor of the ceramic material (see Figure 3). As a consequence, the absence of a proper temperature management would lead to a limitation of the drive frequency at full-stroke operation to 350 Hz. This value was obtained through a measurement at a drive frequency of 700 Hz and a drive voltage of 700 V (*cf.* Figure 4). The values were chosen since testing at 1 kV without cooling would have been related to a risk of overheating the mechanics. Using the equation to calculate the dissipated power (*cf.* Figure 3) the obtained values were used to calculate the respective drive frequency at 1 kV, which is 350 Hz.

Accordingly, a cooling system was implemented to control the stack temperature using scavenged air. A second, separated cooling system was implemented to being able to control the membrane in case higher laser power will be applied in the future.

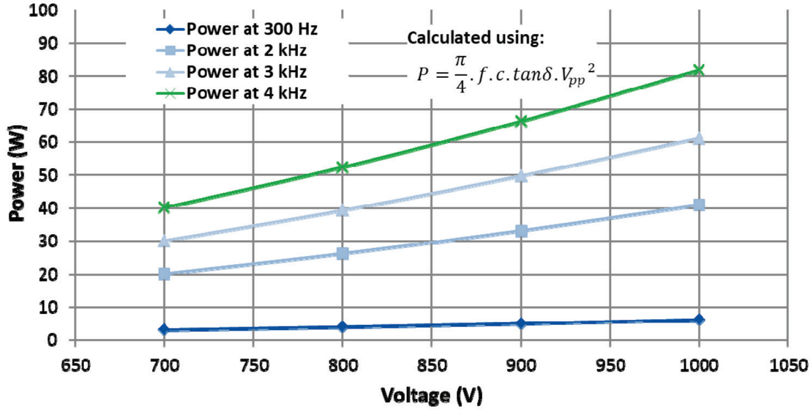


FIGURE 3
Graph showing the thermal power at the actuator as a function of voltage and frequency.

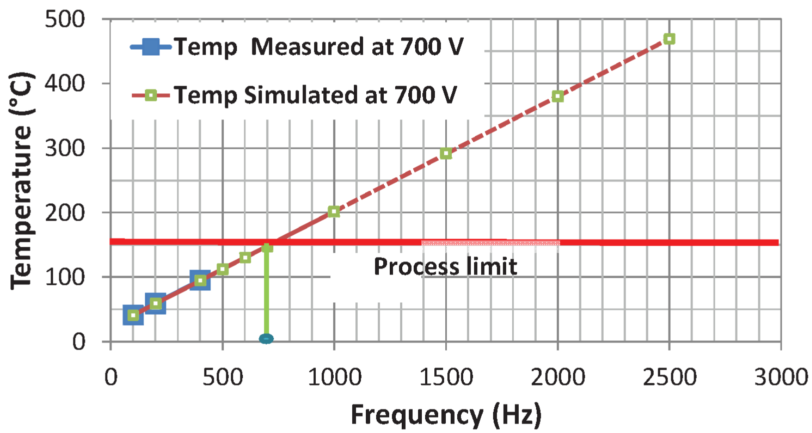


FIGURE 4
Graph showing the thermal behavior of the stack actuator without cooling with a drive voltage of 700 V and varying drive frequency.

Up to a drive frequency of approximately 2.7 kHz, safe operation of the stack using the integrated cooling system was proven both by simulation as well as by experiments, as is evident from Figure 5. The graph in Figure 5 further comprises a linear extrapolation of the obtained curves showing that the use of this cooling system further allows a safe operation up to 3.5 kHz (3 bar air pressure) or 4.6 kHz (6 bar air pressure), respectively.

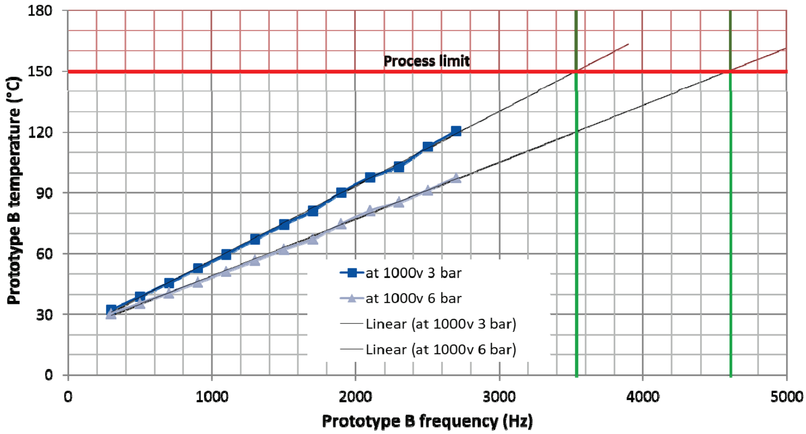
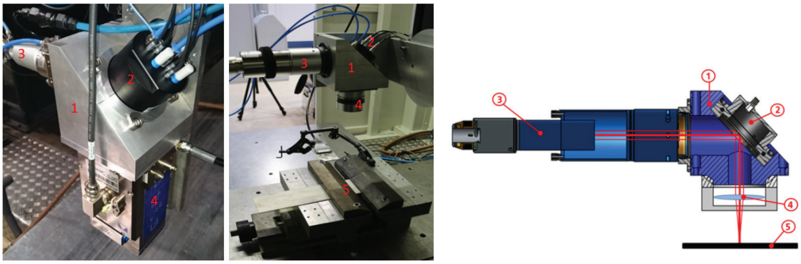


FIGURE 5
Frequencies at full-stroke operation (1 kV) using pressured air for cooling the Piezo-drive.



(a) (b) (c)

FIGURE 6
(a) Validation of the module within cutting and (b) welding, and (c) the configuration (1) beam deflection, (2) highly dynamic focus shifter module, (3) collimation, (4) focusing lens, (5) workpiece.

4 VALIDATION

The highly dynamic focus shifting module has been tested comprehensively within real-life cutting applications. Tests regarding the welding applications have been started recently. An example clearly illustrates the benefit of the highly dynamic focus shifter module: For cutting plates out of stainless steel with a thickness of 10 mm a laser power of 3 kW was applied. The module was operated with full-stroke at a drive frequency of only 100 Hz. With this setup an increase of the cutting speed by 60% was

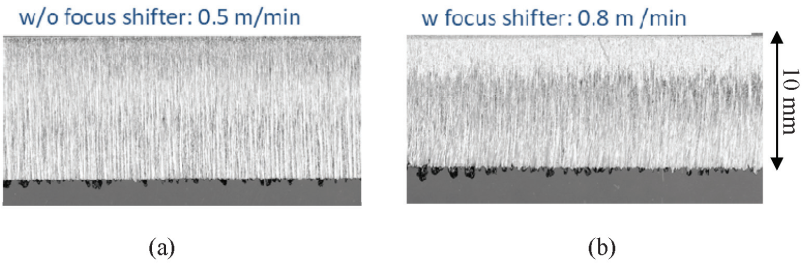


FIGURE 7
Optical images showing the cut edges and cutting speed of 10 mm stainless steel with (a) conventional laser beam cutting and (b) with additional highly dynamic focus shifting using 3 kW laser power.

achieved compared to conventional processes at unchanged cut edge quality, as shown in Figure 7. This exemplarily, but at the same time impressively shows that this significant process enhancement does not necessarily require an operation of the module with maximum drive frequency. So choosing the proper operating conditions for a certain application leads to an optimized operation of the module and thus to an efficient overall process. This will further be validated by upcoming cutting experiments at various operating conditions.

5 SUMMARY AND OUTLOOK

The great importance of laser machining processes and the need of further improvement of these applications has been considered through development of the presented highly dynamic focus shifting module. This device enables a significant enhancement of the cutting speed. It excels through compact design, ease of implementation, high reliability and thus through high cost-effectiveness. An operating range at full-stroke operation has already been validated beyond a drive frequency of 2 kHz. The next goal is to implement an operating frequency up to 4 kHz considering the same full-stroke and shift of the focal plane, respectively.

ACKNOWLEDGEMENT

All activities described in this present report are greatly funded by the German Federal Ministry of Education and Research (BMBF) within the incentive program “zwanzig20”.

REFERENCES

[1] Goppold C., Pinder T. and Herwig P. Transient beam oscillation with a highly dynamic scanner for laser beam fusion cutting. *Advanced Optical Technologies* **5**(1) (2016), 2015-0059.

[2] Dittrich D., Jahn A., Standfuss J. and Beyer E.R. Laser beam welding of atmosphere aluminium die cast material using high frequency beam oscillation and brilliant beam sources. *The 35th International Congress on Applications of Lasers and Electro-Optics (ICALEO 2016)*. 16-20 October 2016, San Diego, CA., USA.

[3] SCANLAB GmbH (2019). *varioSCAN*. Retrieved 16th May 2019, from https://www.scanlab.de/de/produkte/z-achsen-3d-erweiterungen/varioscan

[4] Geiger M., Schuberth S. and Hutfless J. CO_2 laser beam sawing of thick sheet metal with adaptive optics. *Welding in the World* **37**(1) (1996), 5-11.

[5] Okada T., Ebata K., Shiozaki M., Kyotani T., Tsuboi A., Sawada M. and Fukushima H. Development of adaptive mirror for CO_2 laser. *Proceedings of SPIE – High-Power Lasers in Manufacturing* **3888** (2000), 509-520.

[6] Morimoto Y., He D., Hijikata W., Shinshi T., Nakai T. and Nakamura N. Effect of high-frequency orbital and vertical oscillations of the laser focus position on the quality of the cut surface in a thick plate by laser beam machining. *Precision Engineering* **40** (2015), 112-123.

[7] PI Ceramic GmbH. *Piezoelektrische Aktoren.* Bauelemente, Technologie, Ansteuerung. 2012. pp. 45-64.

[8] Kugler GmbH (2019). *Adaptiver Spiegel.* Retrieved 16th May 2019, from https://www.kugler-precision.com/index.php?Adaptiver-Spiegel-

[9] Physik Instrumente (PI) GmbH & Co. KG (2019). *Adaptiver Spiegel.* Retrieved 16th May 2019, from https://www.physikinstrumente.de/de/produkte/piezoelektrische-wandler-transducer-piezoaktoren/p-010xxh-p-025xxh-pica-thru-ringaktoren-102800/