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High dynamic beam shaping by piezo driven modules for efficient and high quality laser beam cutting and welding

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Abstract

Today's laser remote processing e. g. cutting and welding is often limited by comparatively low oscillation frequency of the beam focus. Traditionally, high frequency in plane oscillations of the beam is realized with galvo-scanners. New requirements in industry are demanding for not only fast in plane motion but for high-speed active vertical distribution of the beam energy within the workpiece. For laser beam cutting of thick plates, an increase of cutting edge quality is expected. In terms of laser beam welding of aluminium material, a significant process stability improvement is aimed in connection with a weld seam quality enhancement. This paper describes a novel concept of beam shaping optics using piezo actuators for fast focus modulation in z-direction with working frequencies above 2.5 kHz. The development of the actuator concept will be presented as well as the technical realization of the piezo driven modules and their integration into commercial cutting and welding optics. Optical characterization of the beam propagation and the possibilities for dynamic z-modulation will be demonstrated. First application-oriented experimental investigations are presented too, proving the functional capability and showing basic interrelations between z-modulation and process behaviour for typical cutting and welding processes.

Keywords: material processing, highly dynamic beam shaping, piezo driven moduls, laser beam cutting, laser beam welding;

1. Introduction

Smart laser machining processes become more and more interesting for many industrial applications in cutting and welding. In many instances, a flexible modification of the focus position or the beam density is required in order to react to changing process conditions. Furthermore, industrial laser processes can be

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significantly enhanced by a high-frequency oscillation of the beam in x-y plane, typically realized by galvo-scanners [1] [2]. New industrial requirements however demand active high-speed vertical shift of the beam focus and the energy distribution within the workpiece. But up to now the vertical oscillation, mainly using electromechanical or pneumatical devices is still limited by low frequency oscillation of the beam focus [3]. If higher frequency values and repeatable positioning of the beam focus is possible, a significant improvement of process stability, speed and component quality can be expected. For laser beam cutting of thick plates an improved cut edge quality can be aimed [4] [5] [6] as well as a significant enhancement of the process stability and weld seam quality in terms of laser beam welding of aluminum material.

Within the cooperation project "PISTOL[3]" between the Fraunhofer Institutes IWS and IOF, Physik Instrumente (PI) GmbH and further industrial partners, a novel concept of piezo-driven dynamic focus shifter optics was developed in order to realize:

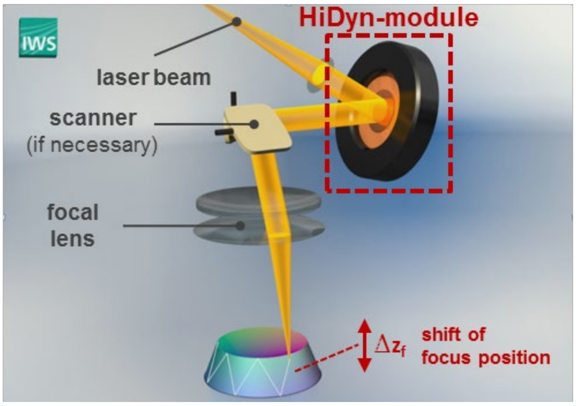
- a high dynamic beam shaping and focus shifting (fast actuator, low mass),
- a compact optics set-up to increase the dynamic behavior of machine and
- a maintenance free adaptive optical component (no moving parts).

This presentation includes the description of the technical set-up of the piezo driven so-called "HiDyn-module" as well as the optical characterization of the dynamic processing optics and first results in process technological applications for cutting and welding.

2. Technical set-up of "HiDyn-module"

The novel dynamic focus-shifter concept of the HiDyn-module is based on the use of a piezo-driven deformable mirror. This approach promises advantages especially regarding higher system dynamics in contrast to conventional solutions where lenses are shifted or pneumatically actuated deformable mirrors are used [3] [7]. In Fig. 1, the implementation of the piezo-driven HiDyn-module into a beam path of an industrial processing head is schematically illustrated. The collimated beam is reflected on a deformable mirror and then focused by the focal lens. The deformable mirror itself includes a piezo high-voltage stack actuator to deform an elliptic mirror membrane, whose shape is mandatory 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 nm to 1090 nm. The actuator excels through a large choice of designs, microsecond response times as well as through extreme reliability beyond 10^9 cycles.

The system-technical development of the HiDyn-module is described in the paper "Design, manufacturing and test of a highly dynamic piezo-driven metal mirror for laser material processing" [8] in detail.



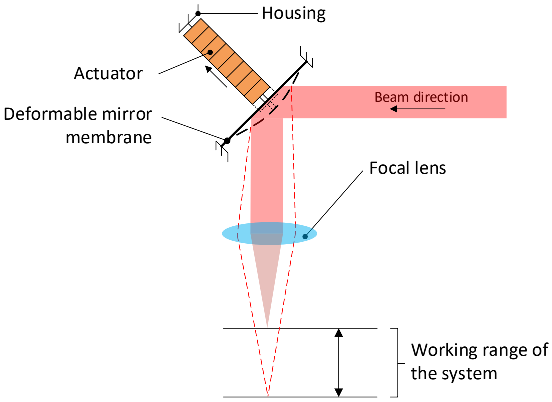


Fig. 1. Concept of dynamic vertical focus shifting by a piezo driven deformable mirror (left). Operation principle of the HiDyn-module, using a stack-actuator and a deformable mirror (right).

The HiDyn-module can be integrated in commercial laser processing optics. Fig. 2 (left) shows the elliptic membrane the deformable mirror. Further, the integration unit (Fig. 2 middle) and a welding head, completely equipped with a HiDyn-module (Fig.2 right), are demonstrated too. The module incorporates a compact 3" housing to enable an easy integration into existing laser machining heads and systems.

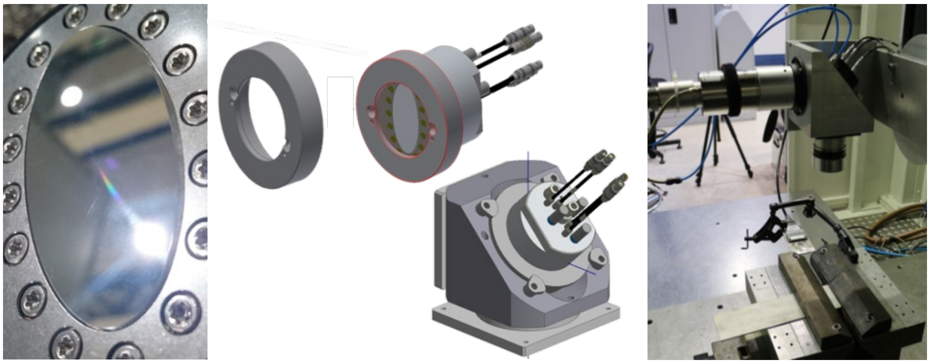


Fig. 2. Elliptic surface of the "HiDyn-module" mirror (left), components for HiDyn-module integration into a commercial laser processing head (middle) and a completed processing head for experimental welding tests (right).

The piezo-actuator is controlled by a low-voltage generator. The signal has to be amplified in order to provide the required high power voltage of the implemented stack-actuator. Table 1 contains technical data of the piezo-actuator.

Table 1. technical parameter of piezo-driven HiDyn module

Parameter	Value
Oscillation mode	Focus position (z-position)
Frequency	0 – 2.5 kHz
Math. function	Sine
Control voltage	0 – 10 V
Drive voltage (stack actuator)	0 – 1000 V

3. Optical characterization of dynamic focus shifting optics

Within the project, the HiDyn-module has been technically implemented in commercial processing heads for cutting and welding. Table 2 shows for example the used optical parameters and the data of the laser source.

Table 2. parameter of laser source and optical components of typical cutting set-up

Parameter	Value
Laser source	multi-mode fiber laser
Beam parameter product	3.2 mm*mrad
Laser power	3 kW
Fiber diameter	100 µm
Collimation length	100 mm
Focal length	200 mm

The z-shifting properties of the highly dynamic HiDyn-module result from the deformation of the mirror-membrane as well as from the beam parameters and the optics configuration. The deformable mirror is capable to deform the mirror surface between flat and convex. In plane state, the focal point of the mirror-lens-system is at the nominal focal distance of the focal lens. Providing a high-voltage, the stack-actuator expands and this leads to a convex deformation of the mirror which shifts the focus of the mirror-lens system away from the nominal focal distance. Thus the focus is shifted into the workpiece (see Fig. 1 and 3 right). The actual position of the focus point directly depends on the control voltage (0 – 10 V) applied at the amplifier of the system. Fig. 3 gives the measurement of one HiDyn-module, where the focal shift increases with the control voltage.

Within the validation process, a maximum shift of the focal plane up to 17 mm has been reproducibly achieved for the used optical configuration. The full-stroke of the piezo actuator is generated by 1 kV of drive voltage which realizes an actuator expansion of 28 µm. This full-stroke operation was further on proven for a drive frequency of up to 2.5 kHz. Although it is operated in open-loop mode the deformable mirror 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 to monitor the actuator and the membrane during operation.

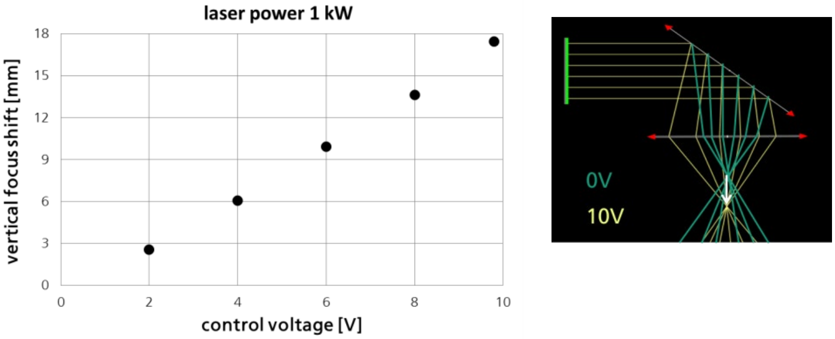


Fig. 3. Piezo-driven focus shift over control voltage, measured in static mode (left). Focal length increases due to rise of control voltage from 0 V to 10 V (right).

Optical transformation of the beam profile is influenced by the deflection angle and the optical quality of the set-up and the mirror surface. Additional failures occur due to the variable deformation of the mirror, which is partly mitigated through a special shape of the mirror-membrane. However, a remaining astigmatism especially in lager distance of the focal plane was detected (Fig. 4).

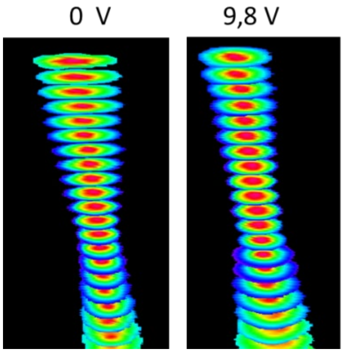


Fig. 4. Results of beam measurement at stationary focus-shift (9,8 V) in relation to the reference state (0 V). The plots show slight astigmatism effects resulting from the deformation state of the mirror.

Typically, the HiDyn-module operates in the high-frequent oscillation mode. Therefore the stack-actuator is driven by a sine function provided by a frequency generator via the mentioned amplifier. The control-voltage signal is used for monitoring the mirror movement. A strain gauge signal from the deformed system is also available for monitoring issues, for instance when operating in stationary mode. However, for high frequency oscillation mainly the system operates in the open-loop mode.

4. Process technical testing

4.1 Laser beam cutting

Laser beam cutting has the largest market share in the field of macro laser processing. The cutting parameters correspond to the work piece properties, especially material and thickness. In general the Rayleigh length has to be enlarged, if thick material has to be cut. Static beam shaping is able to increase

Rayleigh length, but also influences spot diameter and beam intensity negatively.

The use of the HiDyn-module allows a highly dynamic beam shaping. This will keep the spot size and intensity constant and achieves an artificial larger Rayleigh length. This approach should overcome the limitation of static beam shaping.

The performed investigations use a combination of laser power and material thickness next to the border of process window. Therefore a fiber laser (λ=1070 nm; BPP 3.2 mm mrad; P =3 kW) was used in combination to a laser cutting head (f_{coll}= 100 mm; f_{foc}= 200 mm). The HiDyn-module was integrated in between the parallel beam path. The chosen investigation material was defined to 10 mm thick stainless steel (1.4301). State of the art cutting machines achieve a cutting speed of v_s= 0.4 m/min at the laser power level of 3 kW.

In the first step a reference cut was produced without using the HiDyn-module. Focal position and cutting speed were variated to achieve good cutting quality and maximum cutting speed. The investigation delivered a reference cut at v_s= 0.5 m/min. The optimal focus position was detected in the center of the material at z_F = -5 mm.

In the next step the HiDyn-module was used. The system allows shifting the focal point through the complete material thickness. Fig. 5 shows an peak to peak value of 3 mm (relates to 2 V input voltage) and 9 mm (relates to 7 V input voltage) around the chosen focal position of z_F = -5 mm.

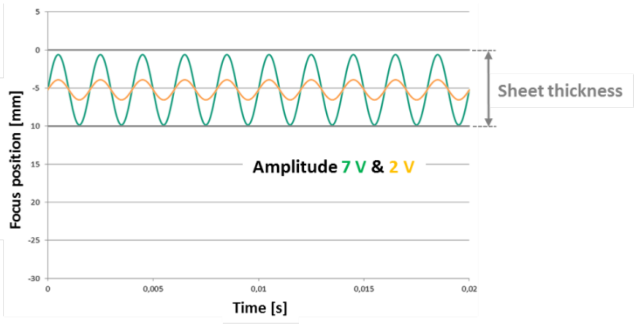
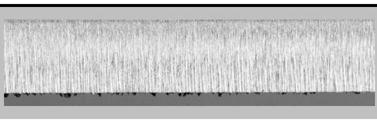
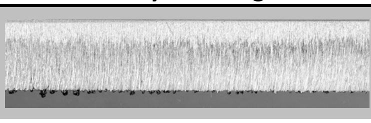


Fig. 5. Schematic focus position oscillation in relation to the sheet thickness (10 mm).

The investigation schedule analyzed a variation of frequency between 100 Hz and 1000 Hz and a peak to peak value between 1 mm and 12 mm. Investigation target was to achieve a comparable cut quality and to identify the maximum cutting speed.

The final result is shown in Table 3. Highly dynamic beam shaping increases the cutting speed v_s by 60 % (from 0.5 m/min to 0.8 m/min), while cutting quality was constant.

Table 3. results of cutting tests (10 mm stainless steel)

	Reference	**HiDyn-Cutting**
Cross section		
Process mode	no oscillation	z-oscillation
Cutting speed	0.5 m/min	0.8 m/min
Frequency	-	100 Hz
Peak to peak	-	12 mm (10 V)

4.2 Laser beam welding

Active beam modulation becomes more and more interesting also for welding applications. This is useful for focus adaptation regarding changing boundary conditions like spot offset, misalignment and gaps. Increasingly, dynamic beam shaping approaches will also be implemented in industrial production in order to enhance process stability and weld seam quality. Especially for welding of aluminum die-cast material planar high-frequency beam oscillation (x-y-plane) provides a large potential for porosity reduction. Hence, both targets will be investigated within the project work.

For the experimental work, the HiDyn-module was implemented into a commercial welding head (see Fig. 2 right). Adjustment and functional capability was proven by beam measurement. The technical equipment was used with the same parameters as in the cutting tests (fiber laser: λ=1070 nm; BPP 3.2 mm mrad; P_{max} = 3 kW).

First orienting welding tests have been performed on mild steel sheets (2.0 mm thickness). For constant welding parameters: laser power (1 kW), welding speed (2 m/min) and initial focus position (0 mm; on surface), a variation of oscillation frequency with constant amplitude (8 mm) was investigated. Fig. 6 demonstrates the possibility for seam width variation and the influence of the frequency on the weld seam surface in dependence of the oscillation frequency. In further parameter trails an enhancement of process stability was found in extreme regions of the parameter window.

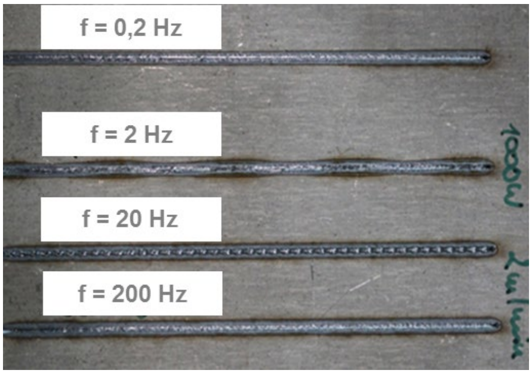


Fig. 6. Welding results for 2 mm mild steel with 1000 kW and 2 m/min.

5. Summery and outlook

Dynamic beam shaping using piezo-driven deformable mirrors has a high potential for laser processing. A novel stack-actuator concept in combination with a special shaped deformable mirror was proven for high power laser processes up to 4 kW. The developed HiDyn-module can be implemented into commercial laser processing heads.

Experimental investigations in laser cutting of 10 mm stainless steel show exemplarily a high potential for cutting speed increase. This first investigation gives an impression about the potential of using highly-dynamic beam shaping for laser cutting. Further investigations will analyze frequencies up to 2.5 kHz, several laser power levels and a variation of material and thickness to evaluate the operational area.

First welding trails display options for process stability increase and control of weld seam shape. Continuing investigations will be concentrated on difficult to weld materials like aluminum die-cast and coated sheet metals. Further, possibilities for fast focus tracking (z-position) for 3D-parts will be observed too.

The proof of industrial capability by implementation and testing of the HiDyn-module in industrial environment will finalize the project.

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