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Realization and first time operation of a high-power laser-water-jet system

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Abstract

Micromachining industry successfully uses the advantageous properties of laser-water-jets (LWJ), e.g. high depth of field, cooling and cleaning effect of water as well as high kerf parallelism. Until now short-pulsed laser sources with average powers of few 100 W are the main beam sources used in laser-water-jets applications. In machining, the comparably low average powers limit processing speeds, especially when high material thicknesses are present.

The objective of ongoing research at Fraunhofer IPT is to expand the range of possible applications for laser-water-jets to macro laser processing by using a continuous-wave fiber laser source with a maximum average power of 30 kW. Using high laser power within a macro-water-jet enables a significant increase in processing speeds while maintaining the above-mentioned beneficial properties of laser-water-jets. In a previous publication, using up to 2 kW laser power of an infrared fiber laser coupled in a laser-water-jet generated by an industrial micro machining system, the need for a dedicated high-power laser system, capable of dealing with thermo-optical and thermo-mechanical issues, was identified.

For the first time a laser head for the generation a laser-water-jet for macro machining has been designed, built and tested in a new high-power laser test rig with active laser safety at Fraunhofer IPT. In order to increase the transmittable laser power the internal water supply was up-scaled to high flow rates and specialized high power optics as well as suitable cooling strategies were developed to ensure increased thermal stability. Using a 30 kW fiber laser the new machining head is tested and its thermal stability is investigated. The effects of system stability on the water-jet properties are studied in order to identify further system improvement. Finally, possible applications for using the new technology are outlined and first processing trials are performed.

Keywords: Laser-Water-Jet, High-Power, Laser Head Development, Macro Processing

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1. Introduction

Laser-water-jets in micro machining show advantageous properties including e.g. a high depth of field (DOF) and the cooling effect of water. As shown in Brecher et al. (2016) available systems for machining are limited to average laser powers of up to 200 W. Ongoing research at Fraunhofer IPT (project LaserJetDrilling) aims at using of laser-water-jet technology for geothermal rock drilling applications. Thus, a LWJ system with average output power of up to 30 kW was developed. The absorption in optics and water-jet in the wavelength regime of current high-power laser sources is a main limitation for upscaling of laser powers. Thermal effects within beam shaping optics and within the water-jet decrease the operation capacity of a LWJ system. Brecher et al. (2016) have developed an analytical model in order to describe the temperature distribution within a laser-water-jet. The model includes the initial laser power, the water-jet diameter, water-jet speed and the propagation length of laser radiation within the water-jet. According to the thermal model, an upscaling to 30 kW requires the increase in jet diameter to the millimeter range in order to increase the thermal capacity of the water-jet. This paper covers the development of a 30 kW laser-water-jet system. Finally, the first time operation of the newly developed laser head with laser powers of up to 5 kW is discussed.

2. State of the Art of CW-Laser-Water-Jets

The principle of a laser-water-jet (Fig. 1) is described in Brecher et al. (2016) and Richerzhagen et al. (2004). A laser beam is focused into a water-jet within the coupling unit. The jet is formed by a cylindrical nozzle. Due to the light guiding properties of a stable water-jet, the jet diameter, and thus the laser spot diameter, remain constant until jet-breakup. By use of a laser-water-jet, the working range of a laser beam compared to a conventionally focused laser beam can be increased significantly.

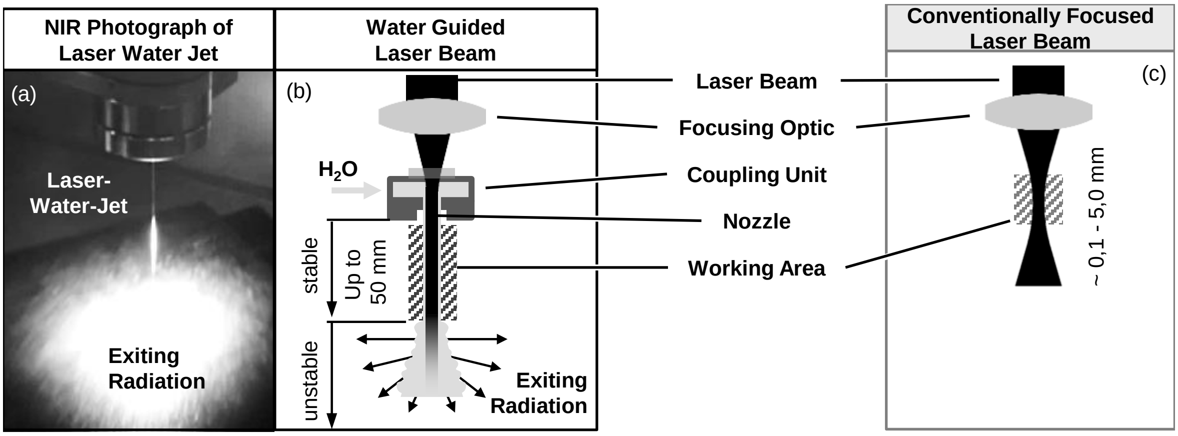

Fig. 1. NIR Photograph (a), schematic principle of a laser-water-jet (b) compared to conventional laser focusing (c)

First lab experiments with a conventional laser-water-jet system for micro-machining have been performed in Brecher et al. (2016) using a multi-mode fiber laser and laser powers of up to 2 kW. Though a cw-laser-water-jet was created successfully, the laser power was limited by the thermal capacity of the laser head. On the one hand the absorption in the optical system led to critical focal shifts, on the other hand thermal instabilities within the water-jet occurred. Due to the high absorption coefficient of water for laser radiation of 1070 nm, jet-heating to temperatures close to 100 °C lead to jet breakup and nozzle damage.

3. Design of a LWJ System

Based on the findings of Brecher et al. (2016) and further research on high-power optics at Fraunhofer IPT laser head development targets the reduction of thermal influences on optics and the laser head structure by development of a specialized optical system. Furthermore, the design of a coupling unit suitable to create a high-power LWJ with adapted fluid parameters was carried out.

The LWJ system design covers the design of the *optical system* to realize the coupling of a multimode laser beam into the water-jet as well as the mechanical design of the *laser head*. To perform experiments with the new LWJ system safely a specialized *high-power test rig* with active laser safety for 30 kW is designed to facilitate laser head movements during processing trials.

3.1. Optical System

Due to the unconventional requirements of building a laser head for the integration into a rock drilling system a specialized optical system was developed. The optical system has to provide the functionality to focus and deflect a diverging laser beam from a multimode fiber into the nozzle of the coupling unit. To increase the efficiency of the LaserJetDrilling process, a tilt of the LWJ to the optical axis by 5° has to be realized. A standard optical design involves, as illustrated in Fig. 2a, three optical elements (two spherical lenses and a wedge prism) to subsequently collimate, focus and finally to deflect the laser beam from the fiber optic.

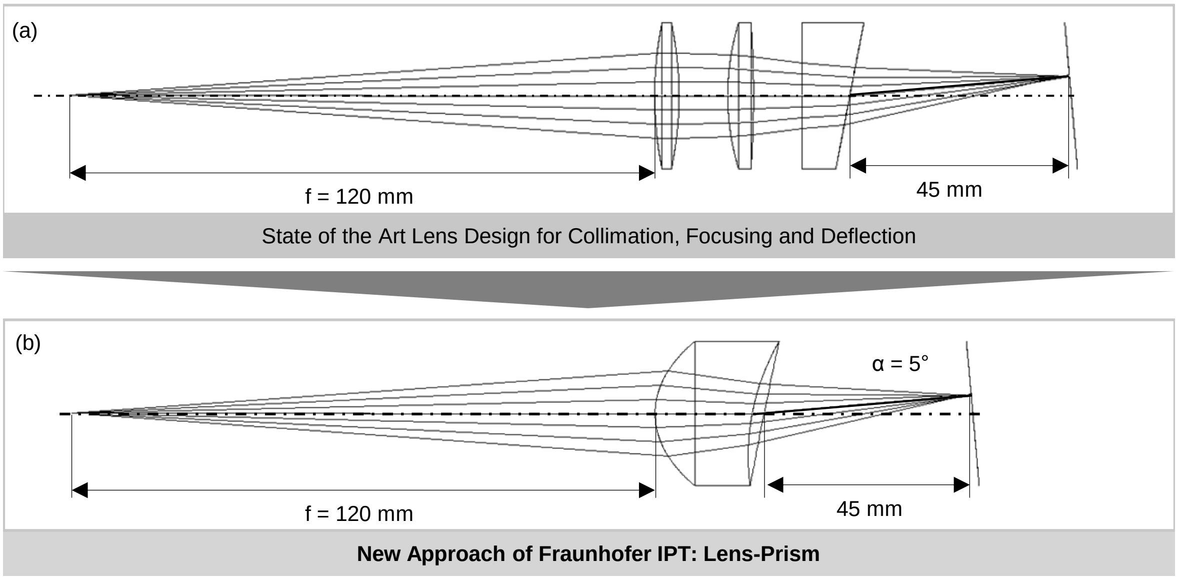

Fig. 2. State of the Art lens design (a), integrated collimation, focusing and beam deflection by Fraunhofer IPT Lens-Prism (b)

Though a three optical element design enables the use of standard optical elements, it incorporates several drawbacks for the high-power LaserJetDrilling application. These are thermal lensing due to absorption of laser radiation within multiple elements, thermal load on the laser head by scattered radiation from six optical surfaces and the necessity for long and complex optical system with the requirement for precise alignment.

Fraunhofer IPT has developed an alternate, single-element approach (Fig. 2b) to realize an optical system tailored for the use in a compact high-power LWJ system. By integrating the three optical functions into a single optical element, all drawbacks are addressed without a decline in image quality. The developed "lens-prism" (Fig. 4b) consists of an aspherical front surface and a tilted, spherical back surface. Thermal lensing and scattered radiation are minimized by the sole reduction of optical elements and thus optical surfaces from six to two. The reduction of optical elements facilitates the realization of a compact optical system for a compact laser head. In addition, the alignment between fiber output and lens-prism is realized by machining tolerances and does not require further alignment. The optical performance of the lens-prism is demonstrated in Fig. 3 using a fiber laser (fiber diameter 200 µm).

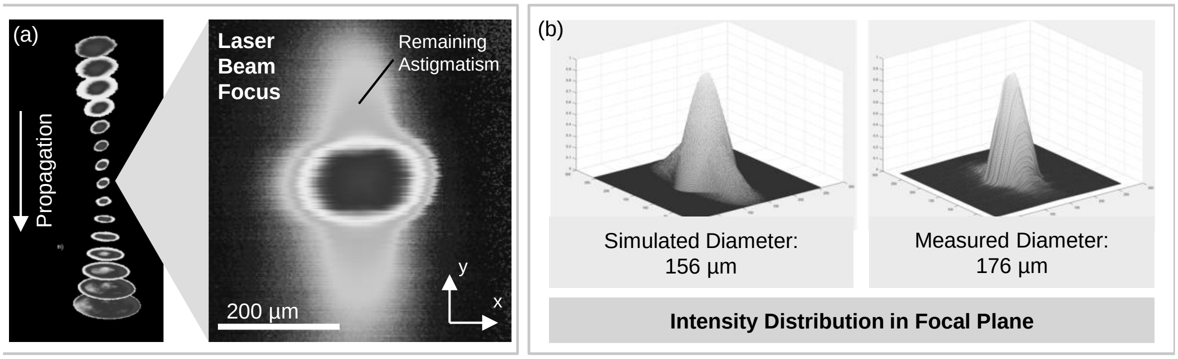

Fig. 3. Lens-prism caustic measurement result (a), simulated and measured 3D intensity distribution in focal plane (b)

Optical aberrations, which occur due to the beam deflection by a prism, are critical for the performance of the optical system. Especially astigmatism leads to asymmetric beam diameters along the caustic. In order to focus the laser beam properly into the cylindrical nozzle, front and back surface of the lens-prism are optimized to reduce aberrations, and to minimize the focal diameter. The intensity distribution in the focal plane (Fig. 3a) is characterized by a small, low intensity aberration along the y-axis. However, a good spot symmetry (0.96) is achieved. The measured intensity distribution matches the simulated distribution quite precisely. The lens-prism enables the use of small nozzle diameters compared to the focal diameter.

3.2. Laser Head

The laser head (Fig. 4a) contains the optical system and protects it against the rough environment within the mechanical drill bit. Due to the confined space for the drilling application, the laser head measures 80 mm in diameter and 280 mm in length. A specialized fiber connector developed by IPG Photonics is plugged directly into the laser head in order to minimize possible geometrical deviations between fiber connector and lens-prism. The lens-prism is mounted in an exchangeable optics module for easy maintenance.

The distribution of fluids (water, air) from the drill string into the coupling unit inside the laser head is realized by a pluggable interface. Subsequently the fluids are guided by integrated channels into the coupling unit to form the LWJ. The water for the jet is also used to thermally stabilize the laser head and minimize thermal expansion of the mechanical components.

Due to the limited possibility to feedback cooling water for the fiber optic plug from the laser head to the chiller (via the drill string), cooling is realized via a bypass of the purge water for the drilling process.

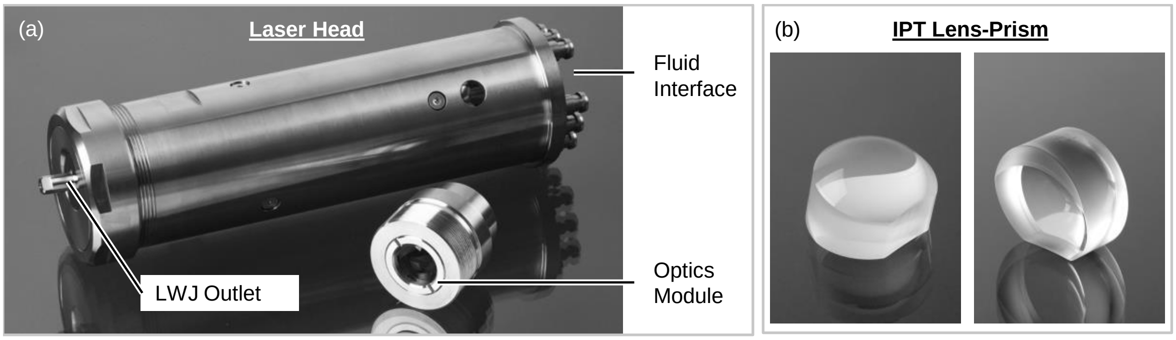

Fig. 4. IPT Laser Head (a), Lens prism designed by IPT and manufactured by Sill Optics (b)

The LWJ is created in an up-scaled coupling unit for high flow rates and nozzle diameters between 1 - 2 mm. The coupling unit is designed as another exchangeable module at the bottom of the laser head for in field nozzle maintenance. By adding shielding air after the nozzle the laser-water-jet is stabilized and protected against environmental influences. The air shielded LWJ exits the laser head via a cylindrical outlet.

3.3. High-Power Laser System

A key component of the laser system (Fig. 5 a) for the LaserJetDrilling process is a 30 kW fiber laser developed by IPG Photonics. The laser source can be used in continuous emission mode and modulated up to 8 kHz at full output power, in order to provide increased flexibility for process research. Through a two-way beam switch, different optical fibers can be used. In addition, the investigation of back scattered radiation via an out-coupling at the beam switch enables a possibility for process monitoring or control. By using a chiller system with high temperature stability and cooling capacity of up to 100 kW the high-accuracy power measurements at full output power is facilitated.

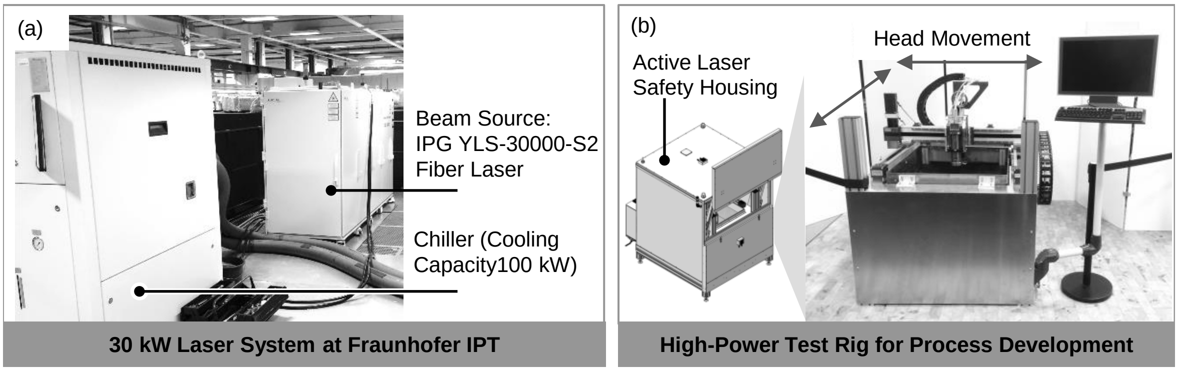

Fig. 5. High-power laser system at Fraunhofer IPT (a), high-power laser test rig (b)

An important aspect of designing a test rig for high-power experiments is laser safety. Due to the very high laser powers even in monitored laser processes, passive laser safety by e.g. using a casing with suited material type and thickness is a security risk. Fig. 5b shows the main components of the high-power laser test rig. The laser-save housing is currently being built. In order to enable different novel high-power applications a test ring with a complete active safety housing will be available at Fraunhofer IPT.

The LaserJetDrilling project follows a two-stage approach for investigating and developing a laser assisted drilling process. Initially lab experiments are conducted to investigate the basic interaction of a LWJ and hard rocks, subsequently a field test is carried out on a demonstrator drill string. In order to simulate the relative movement between LWJ and rock while drilling, a defined relative movement between laser head and rock sample is performed with a 2D-axis system. Thus, linear or circular movements can be realized with relative speeds of up to 1 m/s.

4. First Time Test of CW-Laser-Water-Jet System

The first tests of the new laser head have been carried out in an alternate test. Thus, the laser power that can be safely used was limited to 5 kW. The test setup is shown in Fig. 6a. The laser head with the fiber optic cable is plugged into a mount that simulates the interface of the drill string and supplied with the required fluids. For a preliminary investigation of coupling the quality, avoiding clipping at the nozzle, the built in laser pointer of the laser source was used. Subsequently, laser power was increased gradually form 200 W to 5 kW, while the LWJ was monitored via a IR-sensitive camera (Fig. 6b). The laser energy was absorbed within a water tank, which was placed below the laser head.

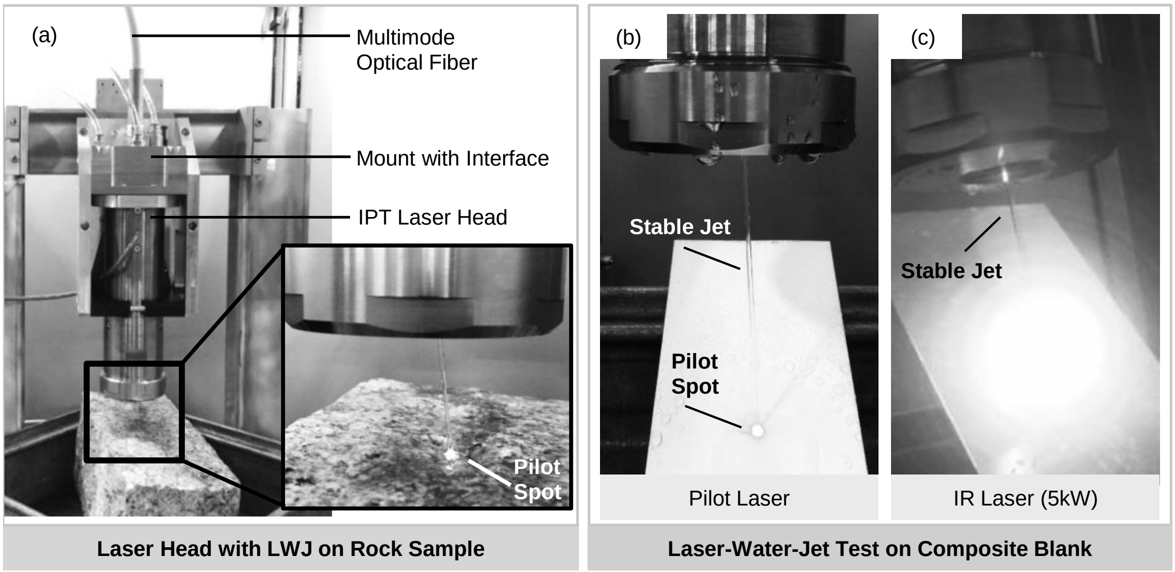

Fig. 6. Test setup in a preliminary test rig (a), processing trial on a composite blank with pilot laser (b) and IR laser-water-jet (c)

Different materials were then positioned below the laser head at different water-jet positions in order to visualize the functionality of the LWJ. The IR-image shows ideal function of a LWJ with a stable water-jet length, where no laser radiation exits the jet. The stable jet lengths that could be achieved with the newly designed coupling unit and nozzle diameters in the range of 2 mm reached up to approx. 300 mm. Also various materials e.g. a 4 mm thick steel plate could be penetrated by the LWJ.

Despite the lack of laser powers above 5 kW it was possible to already demonstrate the 2,5 times increase in laser power in comparison to previous research with a conventional LWJ. Further testing will be conducted in near future.

5. Summary and Outlook

Based on previous research on thermal jet stability a laser head including a novel optical system has been designed. By realization of a prism-lens the number of optical elements within the high power laser head was reduced to a single element, offering promising reduction in thermal loads. The laser head, designed and manufactured by Fraunhofer IPT, was used to successfully generate a laser-water-jet with up to 5 kW laser power for the first time. Compared to previously transmitted cw-laser power within a water-jet (Brecher et al. (2016)) a 2,5-fold increase in transmittable power was demonstrated.

Further system research has to proof the feasibility, and the thermal stability of the laser head and the high-power LWJ during continuous emission of up to 30 kW laser power. Subsequently the interaction between hard rock and the LWJ will be researched in order to derive suitable drilling strategies. Additionally the use of the developed technology for alternate applications e.g. drilling or cutting of thick materials will be researched in order to broaden the field of research for the cw-laser-water-jet technology.

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