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# Beam oscillation – periodic modification of the geometrical beam properties

C. Goppold<sup>a</sup>, T. Pinder<sup>a</sup>, P. Herwig<sup>a</sup>, A. Mahrle<sup>a</sup>, A. Wetzig<sup>a,b</sup>, E. Beyer<sup>a,b\*</sup>

<sup>a</sup>Fraunhofer IWS, Winterbergstrasse 28, Dresden 01277, Germany

<sup>b</sup>University of Technology, Institute of Surface and Manufacturing Technology, Dresden 01069, Germany

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## Abstract

Sheet metal with thicknesses above 8 mm has a distinct cutting performance. The optical configuration, composed of fiber diameter, collimation and focal length, allows for many opportunities to influence the stationary beam geometry. Previous analysis points out the limits of this method in the thick section area. The achieved cut quality of a stationary beam shape is restricted by the laser power. Most operators would like to improve the cutting results without changing their available laser sources, even for thicker materials. To overcome some limits, new approaches are desired. Within the present study an experimental investigation of fiber laser fusion cutting of thick section stainless steel was performed, by means of dynamical beam oscillation. The aim is to compare stationary and dynamical beam shaping, through evaluation of the cut quality, the kerf geometry, and the applied process parameters. The investigation emphasizes promising procedural possibilities for improvements of cutting performance in fiber laser cutting of thick stainless steel.

*Keywords: laser fusion cutting; beam shaping; oscillation; dynamic; cut kerf*

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## 1. Introduction

The stationary beam shaping means, that the beam is modified before the machining process starts. The geometrical properties could be influenced as well as the intensity distribution. An advantage of a uniform intensity distribution is the sharp edge of the focus spot, which creates a high-defined transition between treated and untreated zone. The so called “top-hat shaper” consists of refractive or diffractive optics [1,2,9].

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\* C. Goppold. Tel.: +49 351 83391-3542; fax: +49 351 83391-3300.  
E-mail address: cindy.goppold@iws.fraunhofer.de

Another possibility is the geometrical modification of the laser beam. Solutions for the cutting branch are changing the optical setup to utilize different beam dimensions [3,4], or separating the single beam into patterns [5,15]. An optical setup that creates a larger focal spot is commonly discussed to improve the cutting performance for thicker sheets [6]. This method increases the interaction zone of the laser beam and material surface, but limits the capabilities. The optical setup is the minor influencing factor of the cutting performance for 15 mm thick stainless steel plates at a steady power level [7]. One suggestion is that heat conduction is the limiting factor on the maximum cutting rates [5]. A recommendation is the utilization of beam oscillation to obtain quasi-static heat conduction, meaning: the relaxation time of the atoms is higher than the required time for one oscillation period [6]. Beam oscillation is a dynamic method of beam shaping, which implies a superimposed modification of the beam regarding the feed direction during the process. Thus, the beam oscillates around the generated cut kerf and thereby shapes the interaction zone into an arbitrary geometry. This new methodology is not to be confused with laser remote cutting, another form of scanning technology [8]. The laser remote cutting procedure deflects the beam over the workpiece along the component outline without shaping the focus spot. One of the most noted applications for beam shaping through oscillation is in laser beam welding [10-13]. Due to the available slight frequencies there are no comprehensive investigations for the cutting branch, just initial trails [14]. A major challenge is to improve the possible frequencies of a scanning system to above 20 kHz [6]. Commercially available devices currently offer up to 4 kHz in two-dimensions.

## 2. Experimental Procedure

Laser fusion cutting experiments were performed with a fiber laser at 1.07  $\mu\text{m}$  wavelength. A laser output power of 3 kW and a randomly polarized beam were utilized for all investigations, as well as a conical gas nozzle and nitrogen as assist gas. Stand-off distance between nozzle and sheet surface was kept constant. The chosen optical setup is a standard configuration for laser fusion cutting of thick metal plates and summarized in Table 1. Stainless steel sheets AISI 304 (1.4301) with the thickness 12 mm were applied as workpieces. The specifications of the scanner system are outlined in Table 2. Figure 1 illustrates the conjunction between orientation of the scanner coordinate system and the feed direction of the cutting machine.

Table 1. Laser beam parameters

Beam parameters	Data
Used output power P	3 kW
Fiber diameter d	100 $\mu\text{m}$
Collimation length $f_{\text{col}}$	100 mm
Focus length f	200 mm
Focus radius $w_0$ (86%)	97 $\mu\text{m}$
Rayleigh length $z_R$	3 mm
Beam quality factor $M^2$	9.1

Table 2. Specifications of the scanner system

Scanner parameters	Data
Maximum laser power	4 kW
Maximum amplitude (@2 kHz Sinus)	3.1 mrad
Typical speed	40 rad/s
Maximum speed	50 rad/s
Repeatability	< 22 $\mu\text{rad}$

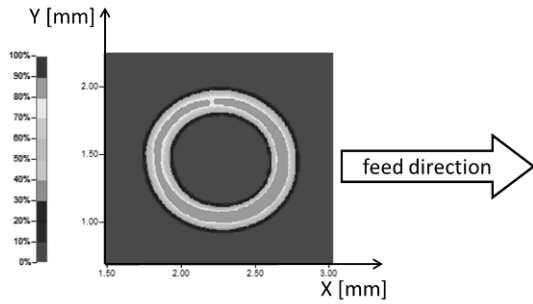


Fig. 1. Scanner coordinate system regarding feed direction by reference to a beam measurement

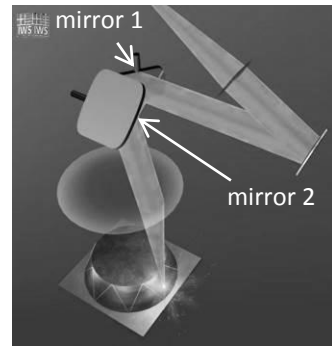


Fig. 2. Schematic view of a two-dimensional scanning system

The aim of the cutting experiments was determining the best cut edge quality at maximum reachable cutting speed for each studied oscillation parameter combination. The main criteria for cut quality were the absence of burr and a homogenous, smooth appearance of the cut edge. Evaluation of the cut was performed through roughness measurements of the cut edge at three positions – 1 mm below the upper cut edge, in the middle of the cut edge, and 1 mm above the lower cut edge. To assess the surface roughness a classification was used, as depicted in Table 3. Furthermore, an inspection of the burr was accomplished. Different burr conditions were separated into 8 levels, with level 1 as the best. Differentiation in levels was dependent upon burr size and symmetry, and can be found in Table 4.

The oscillation movement is characterized by the *Lissajous* figure. In turn, this pattern is described by the frequency and amplitude for both mirrors in X- and Y-direction, as well as the phase shift that defines the delay of the two oscillatory motions (compare to Figure 2).

Table 3. Classification of surface roughness measurement

	mean value $R_z \leq 50 \mu\text{m}$	mean value $R_z \geq 50 \mu\text{m}$
standard deviation $R_z \leq 20 \mu\text{m}$	1	3
standard deviation $R_z \geq 20 \mu\text{m}$	2	4

Table 4. Classification of burr

level	height of burr [mm]	description
1	$x < 0.5$	two-sided
2	$0.5 < x < 1.0$	single-edge
3	$0.5 < x < 1.0$	two-sided
4	$1.0 < x < 1.5$	single-edge
5	$1.0 < x < 1.5$	two-sided
6	$1.5 < x < 2.0$	two-sided
7	$x > 2.0$	single-edge
8	$x > 2.0$	two-sided

### 3. Results and Discussion

There are several advantages found in using the beam oscillation method, as opposed to stationary beam shaping. First is the ability to maintain the intensity of high brilliance laser sources. Customized oscillation parameters also influence the melting pool, thus the arising kerf can be adjusted to the required application. Finally, reduction of the cut kerf could be addressed, accompanied by a gain in cutting speed or an increase in edge quality, which reduces the post-processing of the parts.

The simplest two-dimensional *Lissajous* figure is a circle. For a circle, the frequency ratio and the amplitude ratio are 1. The phase shift determines the direction of rotation and must be  $90^\circ$  or  $270^\circ$ . In the current investigation, the value was set to  $90^\circ$ , which reduces the degree of freedom to two scanning parameters (frequency and amplitude) in addition to two conventional cutting parameters (focal plane and cutting speed) to influence the result. The amplitude is stated as multiples of the focus radius  $\omega_0$ , while the focus position is a constraint and not considered in the following. There is no significant effect of the scanning parameters on the cutting speed, as illustrated in Figure 3. Achieved feed values are in the range 0.5 m/min and 0.6 m/min for the 12 mm stainless steel sheets. Therefore, criteria for the cut quality, namely surface roughness and burr will be the most important evaluation. An average burr level of 4 to 5 was found for all investigations with the *Lissajous* figure circle. A reduction of the burr is possible with a frequency of 2.8 kHz and an amplitude of  $2.2\omega_0$ . These parameters achieves burr at level 3, only small, scattered attachments of molten material. The surface roughness on average was level 3 to 4. Best results for surface roughness (level 1) can be reached for a frequency of 1.7 kHz and an amplitude of  $2.2\omega_0$ . At this level the cut edge is smooth and homogenous. There is no operating point that combines low surface roughness and slight burr. Both criteria are contrary. Hence, an adjustment of the scanner parameters to the requirements of specific applications is necessary.

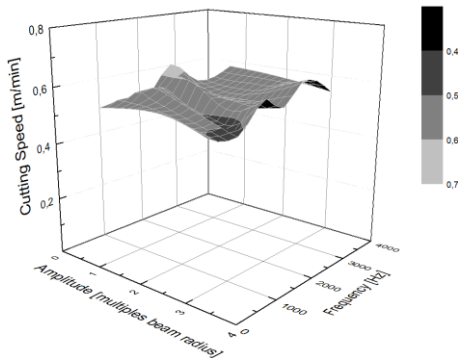


Fig. 3. Resulting cutting speed in dependency of the frequency and amplitude for the *Lissajous* figure circle

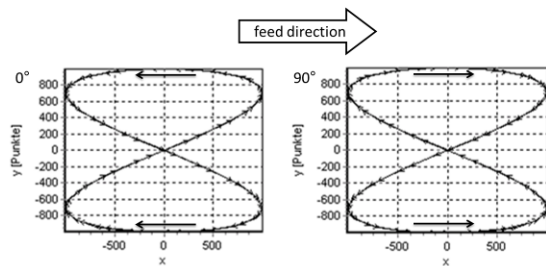


Fig. 4. Rotational direction for *Lissajous* figure eight with  $0^\circ$  (left) and  $90^\circ$  (right) phase shift; direction of movement differs on flank

Another possibility for a *Lissajous* figure is an eight. In contrast to the circle it is an axisymmetric *Lissajous* figure. As a consequence, the directional movement of the beam on either cut edge is the same, as depicted in Figure 4. This offers the advantage of a probably steadier melt flow without turbulences. Oscillation movement in this case is determined by a frequency ratio X:Y of 2:1 ("8" across the cut kerf) and a phase shift of  $0^\circ$  or  $90^\circ$ , dependent on the rotational direction. The amplitude ratio is arbitrary. In total, four scanning parameters (frequency in X-direction, amplitude in X and Y-direction, and phase shift) are available to improve the cutting quality. One more degree of freedom is added with the cutting speed. In the trials, cutting speeds ranged from 0.4 m/min to 0.7 m/min. Results of a statistical analysis method are represented

in Figure 5. There are slight differences between the two phase shifts. The rotation clockwise at the cut front ( $0^\circ$ ) has a slower maximum cut speed than the  $90^\circ$ . Highest cutting speeds are achieved at medium frequencies, with a high amplitude ratio and low amplitude values. Dominant influencing factor is the frequency. Standard cut quality is reached at 0.4 m/min feed rate. In comparison, beam oscillation technology does not forfeit cutting speed. As a matter of fact, the productivity of a cutting system with implemented scanner technology is retained or even improved.

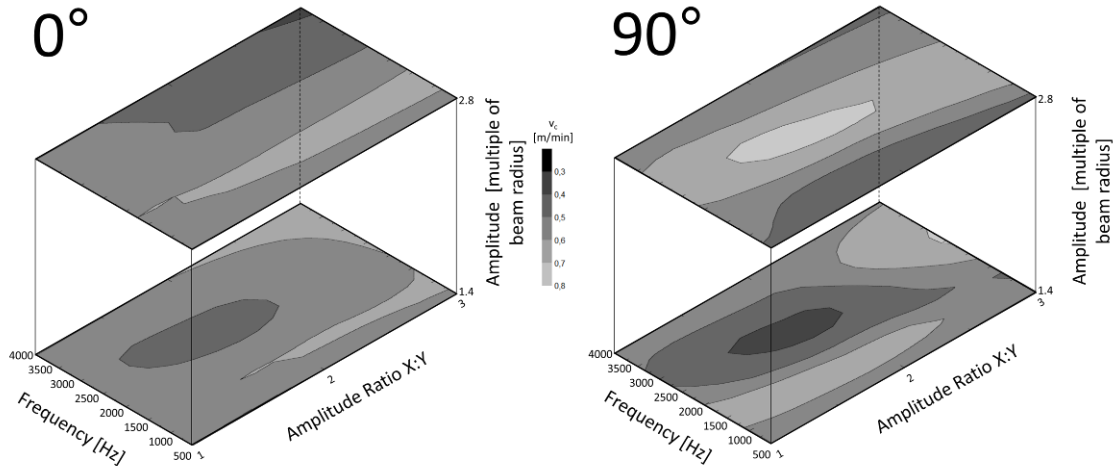


Fig. 5. Resulting cutting speed dependent on frequency, amplitude and amplitude ratio for the *Lissajous* figure “8” with a phase shift of  $0^\circ$  (left) and  $90^\circ$  (right)

The correlations between the scanning parameters and the cut quality criteria for the *Lissajous* figure “8” are depicted in Figure 6 and 7. An obvious point is the similar compliance of burr and surface roughness within a parameter combination (e.g.  $0^\circ$  and  $1.4\omega_0$ ), meaning that the maxima are coincident. One exception is the  $90^\circ$  phase shift, with amplitude of  $1.4\omega_0$ . In this case, both quality criteria are reversed, as with the *Lissajous* figure circle. The cutting speed acts contrary to the quality for all four combinations. If the scanner parameters are adjusted to improve the cut edge, the cutting speed will be decreased.

The phase shift has no significant influence on the resulting cut edge in respect to the quality. The main influencing factor on cut quality is the frequency. The given optical setup enables two different operating points. For a small amplitude the best operating point is found at 2.5 kHz with an amplitude ratio X:Y of 2:1. With higher amplitude the operating point shifts to a higher frequency and amplitude ratio. The precise position of the maximum at  $2.8\omega_0$  cannot be identified, because the available scanning technology does not reach sufficient frequencies accompanied with high amplitudes. Capability for good cutting results is assumed above 4 kHz for higher amplitudes, as indicated in Figure 6 and 7.

The main improvement considering the cut quality during the present investigation was achieved by a parameter set with a frequency of 2 kHz, frequency ratio X:Y of 2:1, amplitude of  $1.4\omega_0$ , amplitude ratio X:Y of 2:1, and phase shift of  $0^\circ$ . Burr, as well as surface roughness, scored level 1. This favorable operating point is compared with cutting results of a standard cut quality in Figure 8 and 9. Standard cut quality with 3 kW output power produces rougher and more inhomogeneous cut edges (level 4) with significant burr (level 8). By increasing the power up to 6 kW, cut quality is almost comparable to the beam oscillation technology. The surface roughness is still slightly higher than that of the beam oscillation and the cut edge of the standard sample at 6 kW is evaluated at level 8. Taking the cut kerf geometry into consideration, an extension is apparent for the utilization of the beam oscillation method. Images of the cut kerfs of stationary

beam shaping, compared to the scanning technology are depicted in Figure 10. Due to the dynamic modification of the interaction zone of laser and material surface, the melt volume is enlarged, as expected.

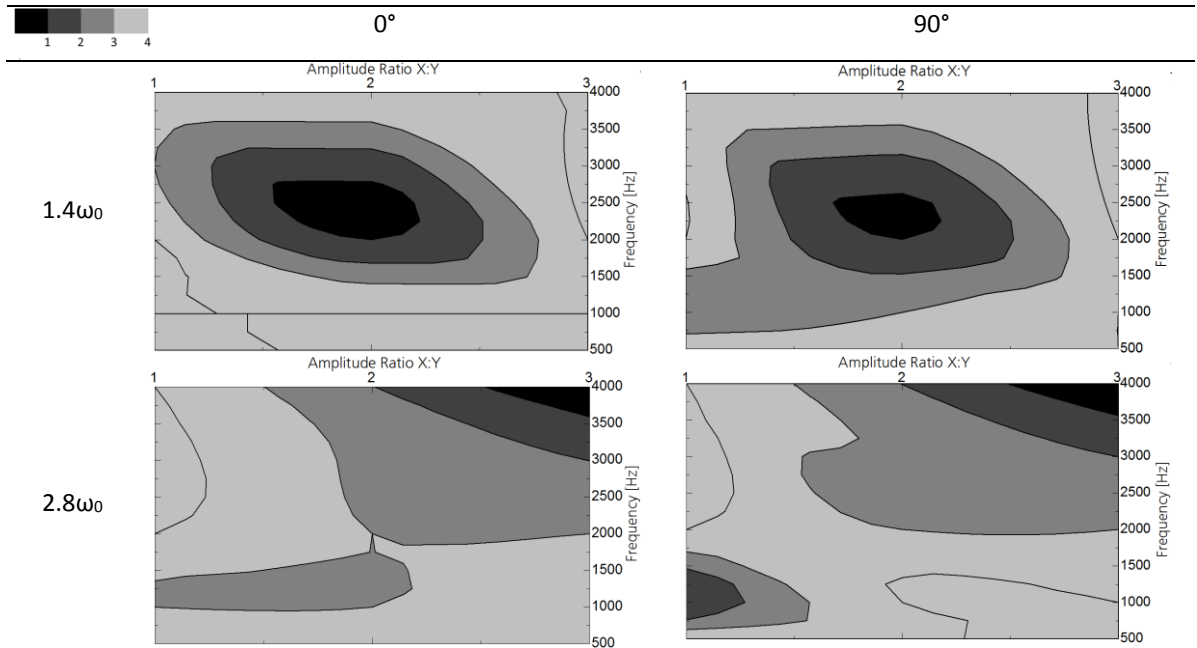


Fig. 6. Analysis of the surface roughness for the Lissajous-figure "8"

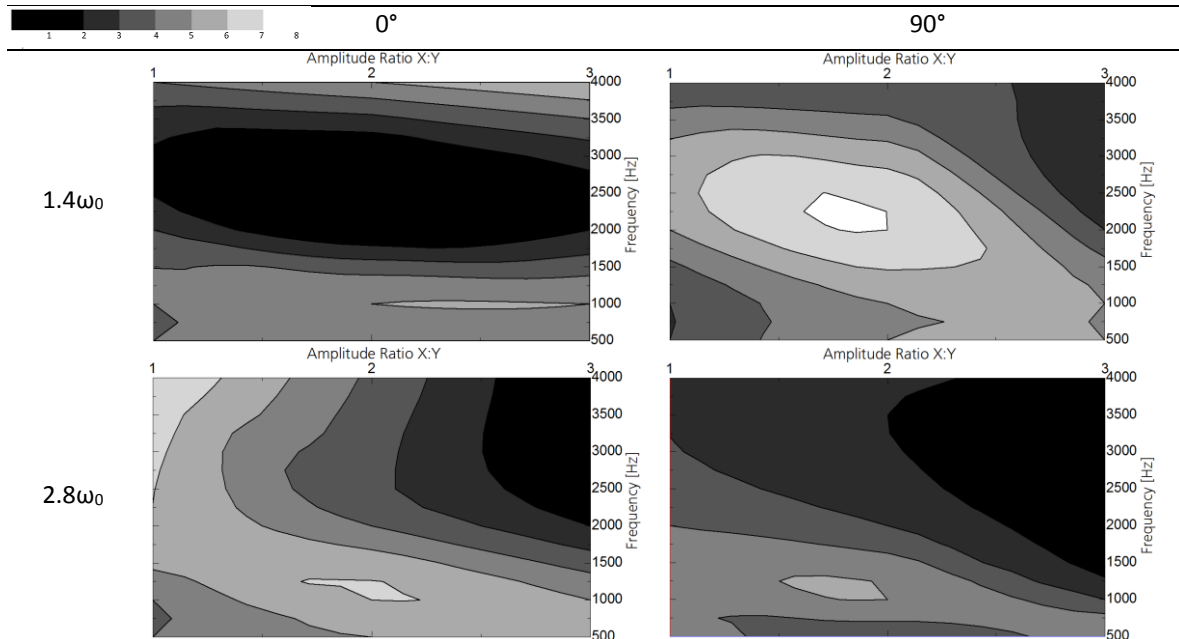


Fig. 7. Analysis of the burr for the Lissajous-figure "8"

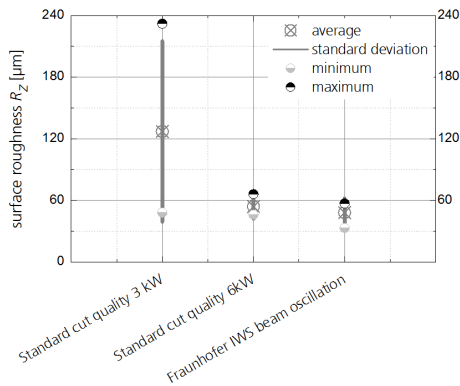


Fig. 8. Comparison of state-of-the-art cut quality with the results of the beam oscillation regarding the surface roughness

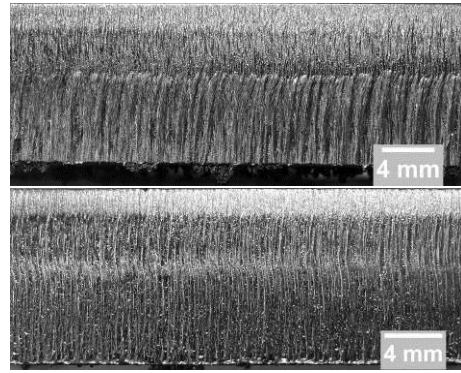


Fig. 9. Cut edge of 12 mm stainless steel sheets with 3kW laser output power cut with a standard cut quality with 0.4 m/min (top) and the beam oscillation technology with 0.5 m/min (bottom)

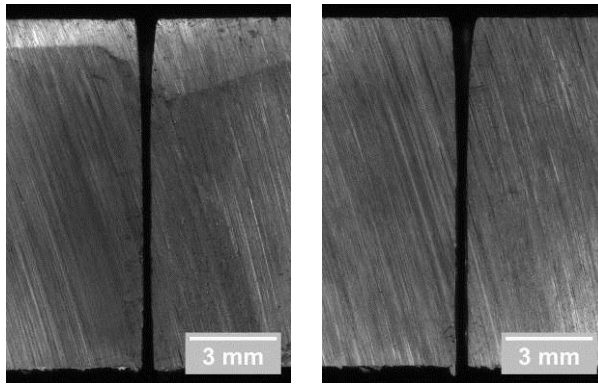


Fig. 10. Cut kerf geometry of 12 mm stainless steel sheets cut with stationary beam shaping (left) and the beam oscillation technology (right)

#### 4. Conclusion

The present investigation deals with the improvement of the performance in fiber laser cutting of thick stainless steel. The results regarding surface roughness and burr with the *Lissajous* figure “8” highlights the capability of the beam oscillation technology. In summary, the beam oscillation is a very promising method to improve the cutting performance for the thick material range. Utilization of this method is complex and there is still a need for adaptations in the remaining process conditions: optical setup, material, sheet thickness, laser parameter, et cetera.

The applied optical setup is well known for cutting applications of thick section. Using the beam oscillation, cut quality is increased in comparison to the conventional stationary beam shaping. The cut edge is smoother and more homogeneous without burr for 3 kW laser output power. Cutting speed has not been significantly influenced despite wider kerf widths. Productivity is kept constant or even improved as a result of the beam oscillation. There are two recommended operating points for the scanning parameters. The first point, detected as a local optimum, requires a medium frequency range, low amplitude range, and medium

amplitude ratio. Experimental results as well as theoretical estimation predict another optimum with even better cutting performance. Further challenge will be the clear identification of the second operating point, which currently cannot be found because of technological limits of the scanner system. The higher the adjusted frequency, the lower is the possible amplitude. As far as practicable, the second operating point is in a high frequency range, with high amplitude range, and high amplitude ratio.

More distinct advantages of the beam oscillation technology are expected for optical setups with smaller focus spots. In that case, a former investigation demonstrated a higher impact of the scanner system on the cutting performance, utilizing a single mode fiber laser.

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