Lasers in Manufacturing Conference 2025

Optimizing Laser Beam Interaction for High-Power Cutting of Stainless Steel Using Dynamic Beam Shaping

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Abstract

The article demonstrates the potential of axial dynamic beam shaping in laser fusion cutting, as evidenced by cutting tests. Although lateral beam shaping is already well-established, axial dynamic beam shaping has been demonstrated to enable faster process optimization by reducing the number of degrees of freedom at laser powers up to 20 kW. The technology utilizes high-frequency beam oscillations along the beam propagation to regulate the energy distribution within the material. Tests were conducted on 10 mm-thick stainless steel using laser powers ranging from 8 kW to 20 kW. The results demonstrated that axial dynamic beam shaping increased the cutting speed by up to 82% and reduced the burr height by a factor of 11. This suggests that axial dynamic beam shaping improves energy distribution in the component, reduces the risk of burr formation and optimizes cutting quality while increasing productivity. In conclusion, an explanatory approach has been devised to elucidate the impact of axial dynamic beam shaping on the cutting process.

Keywords: axial dynamic beam shaping; laser cutting, stainless steel

1. Introduction

The optimisation of cut quality and productivity in laser fusion cutting represents a pivotal challenge in the context of industrial manufacturing. The quality of the cut is determined by a number of factors, including the width of the kerf. A sufficient kerf width is necessary to ensure uniform melt flow, sufficient expulsion of the molten metal and thus the avoidance of burr formation (Alsaadawy 2023). Concurrently, elevating the cutting speed is a pivotal factor in enhancing process efficiency. However, these two objectives frequently prove to be in opposition. Increasing the speed of the process has been shown to increase the thickness of the melt film at the cutting front. This has been demonstrated to hinder the melt flow, thus increasing the risk of burr formation and uneven cut edges. Furthermore, the selection of process parameters, including laser power, cutting speed, and focus position, has been demonstrated to exert a substantial influence on the quality of the cutting process.

At present, static beam shaping, in which the laser beam remains constant, is standard in industry. Nevertheless, it should be noted that this method is not without its limitations, in that it is only able to resolve the aforementioned conflicting objectives to a limited extent. New approaches, such as dynamic beam shaping, in which temporal and spatial changes are made to the beam while maintaining constant beam characteristics, offer the potential to overcome these conflicting objectives. Adaptive beam control has been demonstrated to optimise energy distribution and beam shape during the cutting process, this improves cutting quality and increases cutting speeds. (Goppold, 2020)

Studies have demonstrated that the implementation of this technology can enhance both cutting quality and velocity without compromising either of these characteristics (Levicheva 2022). This signifies a substantial advancement within the domain of laser cutting. Moreover, the combination of this technology with AI-based optimization is a subject of ongoing research, with the objective of enhancing the cutting process with an increasing number of cutting parameters and thus further increasing efficiency.

2. Dynamic beam shaping

The current state in dynamic beam shaping for laser cutting is characterised by a variety of technological approaches and continuous further developments. In particular, lateral (transverse) dynamic beam shaping is already well established and is used in industrial manufacturing to significantly improve cutting quality and speed. In this method, the laser beam oscillates transversely to the cutting movement, utilising various oscillation patterns, each of which offers distinct advantages and challenges. The three oscillation patterns that have gained the most renown are circular, transverse line and oscillation along the feed direction.

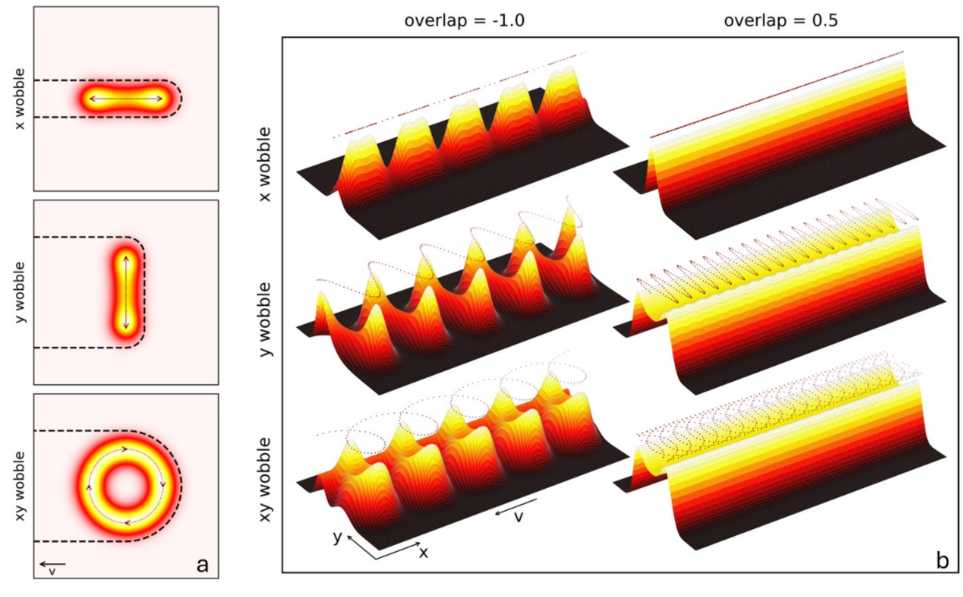

Figure 1:
a) Intensity distribution for different oscillation types, b) Energy distribution with negative and positive overlap

Transverse line oscillation (along the Y-axis in Figure 1), in which the beam oscillates transversely to the cutting direction, primarily influences the kerf width and allows for a slight increase in cutting speed. By overlapping the oscillation ranges, a homogeneous energy density can be achieved in the cutting area, which in turn improves the cutting quality. See Goppold 2020, for a definition of the overlap that is equally used in lateral and axial dynamic beam shaping. The oscillation of the cutting tool (laser spot) along the feed direction (along the X-axis in Figure 1) offers the possibility of specifically controlling the energy distribution along the cut, which leads to a significant increase in cutting speed without compromising quality. In this instance, the amplitude is employed to regulate the energy density within the material, whilst the frequency exerts an influence on the energy distribution along the cut. (Bach 2024, Kardan 2022, Pinder 2020)

In circular oscillation (in the XY plane in Figure 1), the beam oscillates in a circular path, resulting in uniform energy distribution on the material. This method has been shown to be particularly effective in reducing roughness at the cut edges, thereby facilitating post-processing and significantly improving surface quality. However, the chiral nature of the rotation introduces an asymmetry between the cutting edges, which can lead to uneven adhesion and thus impair the cut quality. (Goppold 2015)

General drawbacks of lateral beam shaping, the optical systems currently used in industry are limited to a maximum power of 15 kW, as higher laser power can restrict or even destroy the systems. The large number of degrees of freedom further increases the complexity of process optimisation.

Axial dynamic beam shaping involves the oscillation of the beam along the beam propagation direction through the workpiece, see Figure 2-a. In contradiction to lateral oscillation, the number of degrees of freedom is reduced. The parameters of axial dynamic beam shaping include focus position, oscillation amplitude and frequency, and feed rate. It is possible to set all parameters independently of each other to achieve optimal results. (Morimoto 2015) This facilitates more efficient process optimisation in comparison with lateral dynamic beam shaping. Moreover, contemporary advancements indicate that laser powers of up to 20 kW can be employed, aligning with the prevailing trend towards increasing laser powers.

The oscillation amplitude is a key factor in determining the focus diameter, Rayleigh length and intensity distribution in the axial direction (see Figure 2b). It has been demonstrated that the Rayleigh length can be stretched up to a factor of 2.5. The spot diameter can be increased by up to 250%. The oscillation frequency, in conjunction with the feed rate, governs the overlap, thereby modulating the energy density variations along the feed direction. It can be assumed that a homogeneous energy density band is present, given an overlap of 50%.

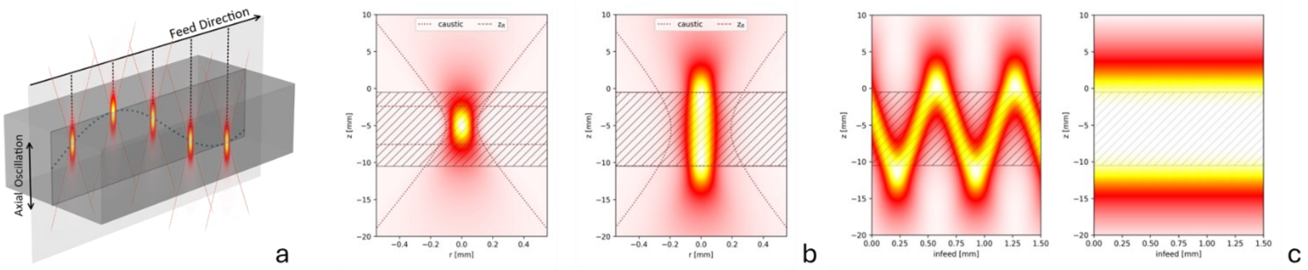

Figure 2: a) concept, b) Intensity distribution for different oscillation amplitude, c) Energy distribution with negative and positive overlap

3. Cutting results of the axial dynamic beam shaping

The experimental tests were conducted on a 2D cutting system utilizing a 20 kW fiber laser. The fiber diameter was measured to be 100 µm, and the magnification was set at 1:2, with a focusing focal length of 200 mm. For the experiments with static focus, the parameter set optimised in advance was used as the starting point for the test series with axial dynamic beam shaping. The oscillation frequency, oscillation amplitude, cutting speed and focal position were subjected to variation. Finally, the gas pressure was varied to achieve the highest possible cutting quality.

For evaluating the burr, the cut sample's edge was meticulously divided into ten sections. In each section, the maximum burr is measured, mean and standard deviation are calculated from that. To detect asymmetrical effects, samples were analysed on both long sample sides of the rectangle. Moreover, the cutting edge was measured to determine the surface roughness R_a at three different heights using the profile method. In addition to the burr and roughness, cutting speed and the demoulding of the components from the rest grid are used as the basis for the following evaluation.

The analysis starts with a detailed review of the test series performed using laser power P=8 kW and P=20 kW. Subsequently, a comprehensive analysis of all four power levels 8 kW, 12 kW, 15 kW and 20 kW is provided.

For P=8 kW, a thorough analysis of the cut edges reveals a substantial enhancement in the quality of the cuts, as compared to the best reference cut with a static focus, see Figure 3-a. In particular, the burr height exhibited a decrease by a factor of 4.5 to 55 µm ± 31 µm. The surface roughness exhibited an average decrease of 1.5 from from Ra_{stat}=12 µm to Ra_{DBS}=8 µm. In contrast to the static cut, the surface roughness does not increase in the lower half of the sample. Furthermore, the axial dynamic beam shaping resulted in an increase in cutting speed of approximately 82% from 1.92 m/min to 3.5 m/min, without any concomitant loss of cutting quality. The distribution of energy along the cutting front created by an extended focus (along the beam propagation direction) enabled a more homogeneous energy distribution across the material thickness, which minimized burr formation.

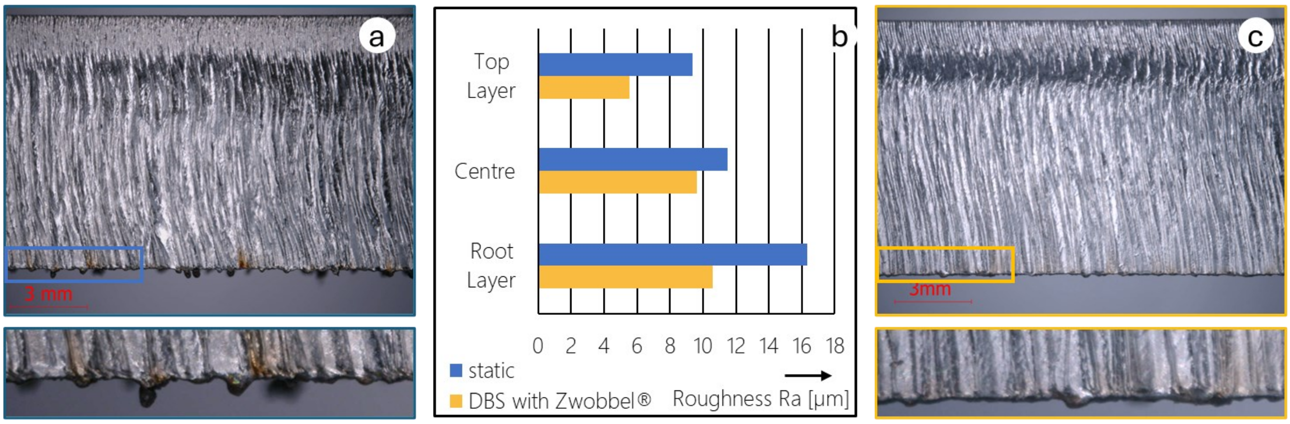

Figure 3: Comparison of cutting quality between static focus (a: P=8 kW, v=1.9 m/min, FP=-7.2 mm, p=12 bar) and axial dynamic beam shaping with the Zwobbel® (c: P=8 kW, v=3.5 m/min, FP=-5.6 mm, p=11 bar), b: Comparison of the roughness of the cut edge

When the laser power was increased to P=20 kW, axial dynamic beam shaping led to an improvement in cutting speed of 37%, from 7.6 m/min to 10.4 m/min, compared to the test series using a static focus. The cut quality achieved by axial dynamic beam shaping is enhanced with increasing laser power. In detail, the burr height exhibited a decrease to 40 µm ± 20 µm. Figure 4-b shows the measured surface roughness for static spot and dynamic beam shaping. For both, the roughness increases towards the root layer. But for axial dynamic beam shaping it remains relatively consistent in the upper and middle regions of the sheet. In general, the roughness exhibited an average decrease of approximately 2.6 from Ra_{stat}=13 µm to Ra_{DBS}=5 µm. The same figure shows also the bottom of the cut edge.

The optimization of the axial dynamic beam shaping parameters revealed the best results with an overlap of 13%. This contrasts with initial educated guesses where overlaps of 50% and more had been expected. The low overlap resulted in the formation of a more inhomogeneous energy density profile along the feed direction. Indeed, this reduction in overlap was found to be optimal for achieving the best outcome. The minor increase in gas consumption, amounting to 9%, could be compensated by the elimination of post-processing.

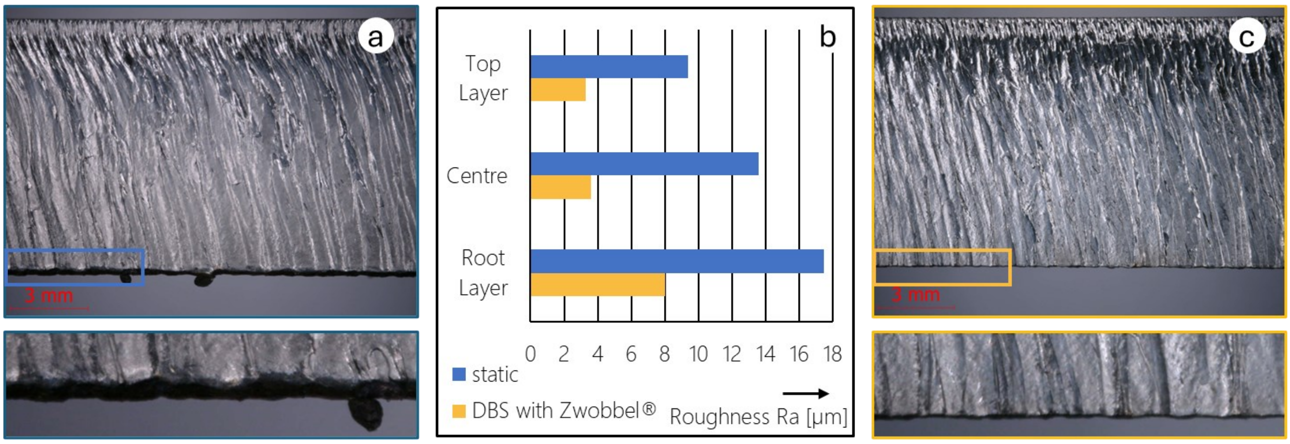

Figure 4: Comparison of cutting quality between static focus (a: P=20 kW, v=7.6 m/min, FP=-4.0 mm, p=6.5 bar) and axial dynamic beam shaping with the Zwobbel® (c: P=20 kW, v=10.4 m/min, FP=-5.5 mm, p=9.0 bar), b: Comparison of the roughness of the cut edge

Figure 5-a shows the cutting speed achieved for laser powers of P=8 kW, 12 kW, 15 kW and 20 kW for static (blue circles) and dynamic beam shaping (yellow triangle). The cutting tests with axial dynamic beam shaping method demonstrated an enhancement in velocity from 82% at 8 kW to 37% at 20 kW. It has been demonstrated that the cutting speed of the 20 kW cut with static focus can be achieved with around 6 kW less laser power.

Axial dynamic beam shaping has been demonstrated to be particularly efficacious in the context of burr adhesion. It has been demonstrated that when cutting with a static focus at P=8-20 kW, the average burr height is 200 µm. Conversely, when

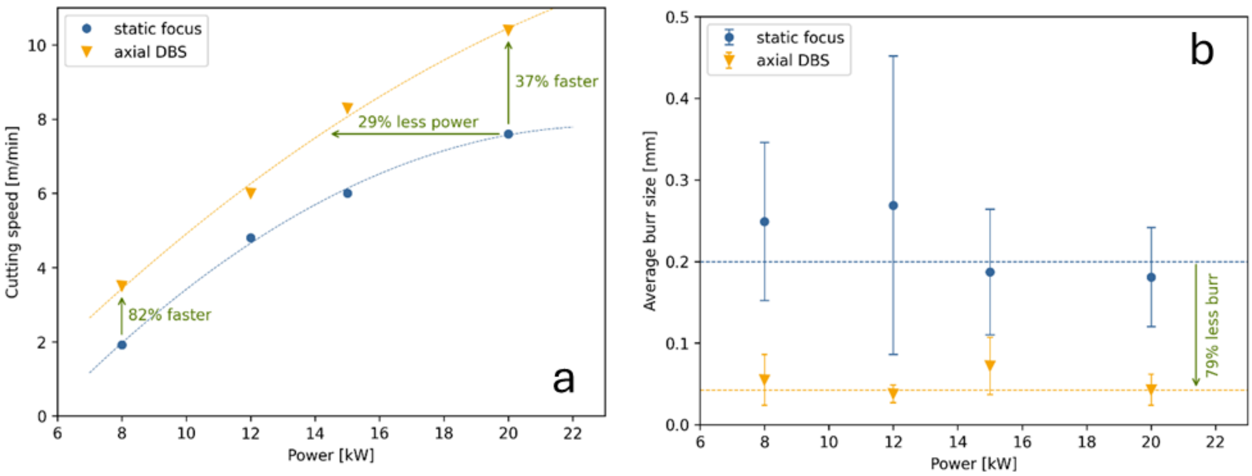

Figure 5:
Increase in cutting speed (a) and reduction in burr formation (b) depending on the laser power with and without axial dynamic beam shaping

utilizing axial DBS, this figure is reduced to 43 µm, which corresponds to a factor of 4.7. The greatest reduction in burr height was observed at P=12 kW. Here, the burr height is measured to 296 µm ± 183 µm (static spot), while it drops to 38 µm ± 11 µm with axial dynamic beam shaping, which corresponds to a factor of 7.7. Furthermore, a black seam edge was observable on the bottom of the sheet during the process with static focus across all power levels (see Figure 5-b). This is also known as nano burr. However, with optimized oscillation parameters, this black seam can be effectively addressed and eliminated. Across all power levels, the focus position with axial dynamic beam shaping around half the sheet thickness was identified as the most effective configuration for achieving optimal results in terms of minimum burr height and surface roughness of the cut edge.

In addition to the enhancement in cut quality, experimental findings utilizing DBS technology have demonstrated that process stability, with respect to variations in the focus position and nozzle distance, could be substantially elevated without compromising cut quality.

4. Explanatory approach for the mode of action

The maximum cutting speed can be estimated by analysing the power balance, Formula 1 (Hügel 2009).

$$P \cdot \eta_A = P_L + P_P \tag{1}$$

Where η_A corresponds to degree of coupling of absorbed laser power, P_L is the power loss due to heat conduction and P_P the process power. The process power is calculated according to

$$P_P = F \cdot \rho \cdot v \cdot \left(c_p \cdot \Delta T_P + h_s\right) \tag{2}$$

In this context, the letter F is the beam cross-sectional area in the cutting kerf, v the cutting speed, ΔT_P the difference between the temperature of the ejected melt and the ambient temperature, ρ the material density, c_p the specific heat capacity and h_s the latent heat of fusion. It is evident that, in consideration of the power loss to heat conduction the maximum attainable cutting speed v_{max} from formula 1 and 2 is ascertained. As a preliminary estimate, the segment not designated in blue in formula 3 can be considered constant. (Hügel 2009)

$$v_{max} = \frac{\eta_A \cdot P - P_L}{F \cdot \rho \cdot \left(c_p \cdot \Delta T_P + h_s\right)} \tag{3}$$

It shows, that v_{max} is determined (among others) by beam cross-sectional area in the cutting kerf F, as well as the degree of coupling η_A. The beam cross-sectional area in the cutting kerf is given by the sheet thickness s, focus radius ω_o, the focus position z and the Rayleigh length z_R by

$$F = 2\omega_o \cdot \int_0^s \sqrt{1 + \frac{(z-z_0)^2}{z_R^2}}\, dz. \tag{4}$$

It can thus be concluded that the beam cross-sectional area in the cutting kerf (in the denominator) is directly proportional to a reduction in cutting speed, while the speed increases linearly with the degree of coupling (numerator).

Figure 6-a compares the beam cross-sectional area in the cutting kerf of the intersection of the oscillating beam with the static beam. The static beam is represented by the blue curve, while the oscillating beam's resulting beam cross-section profile is shown in yellow. The dynamic beam shaping process has been shown to result in an augmentation of the beam cross-sectional area in the cutting kerf. Conversely, this would result in a reduction in cutting speed as the cross-sectional area increases. However, the results of this study demonstrate that it is possible to increase the cutting speed. The approach, which is abstracted from Formula 4 and neglects the multiple reflections in the kerf, suggests that the angle of the cut front is significantly influenced by the dynamic beam shaping. As demonstrated in Figure 6-b, the absorption is shown as a function of the cut front angle. It is evident that the efficiency of the energy coupling is enhanced as the angle of the cut front is near the Brewster angle. Consequently, this results in an enhancement of the maximum cutting speed. Furthermore, it can be hypothesised that the modification of the other process variables will result in a superior outcome in comparison to the static process.

The calculation of the cross-sectional areas from the test data (Figure 6-c) indicates that, when using optimal parameters, it is mostly independent of the laser power used. However, in the static tests (illustrated in blue) the area is consistently lower than in the tests with axial dynamic beam shaping (illustrated yellow). In combination with the increase in cutting speed that could be achieved (see Figure 5-a), this serves to substantiate the hypothesis that the augmentation in cross-section does not constitute a substantial impediment to the enhancement of cutting velocity in axial dynamic beam shaping.

The resulting wider kerf can therefore be utilized to achieve a more uniform melt flow and sufficient expulsion of the molten metal, which reduces burr formation.

It can further be hypothesised that the combination of oscillating beam and reduced angle of the cutting front exerts a positive effect on the melt flow and degree of coupling, a hypothesis that is supported by the results obtained. Furthermore, the energy distribution along the cutting front is gradual and no longer continuous due to the oscillation. It is to be expected that the alteration of high temperature peaks and abrupt sequential cooling prevents the melt film from growing, which makes it possible to increase the cutting speed.

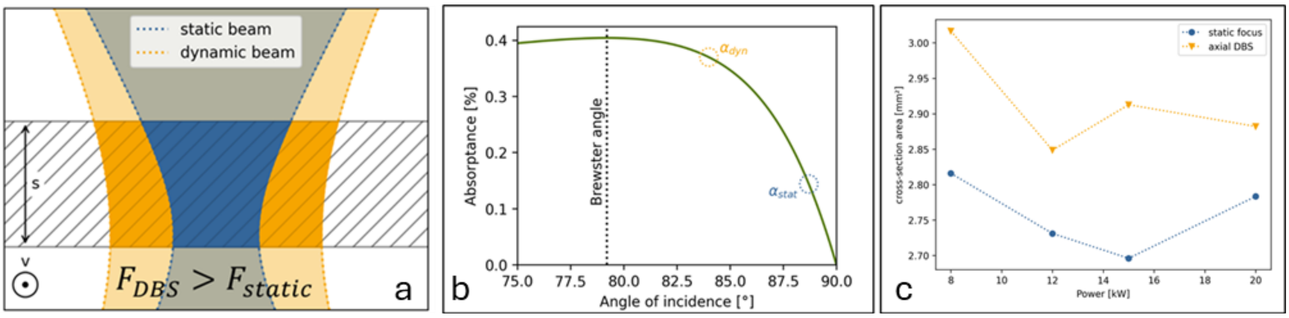

Figure 6: a) the beam cross-sectional area in the cutting kerf, b) Absorption coefficient as a function of the angle of incidence, c) Comparison of the calculation of the cross-sectional areas from the test data between static focus and axial dynamic beam shaping

5. Conclusion: axial dynamic beam shaping

The findings of our research demonstrate the efficacy of axial dynamic beam shaping in laser fusion cutting with high laser powers of CrNi steel, thus providing an worthwhile alternative to static cutting processes. A direct comparison with conventional methods demonstrates that axial dynamic beam shaping enables a reduction in burr and significantly reduced the cut edge roughness. The simultaneous increase in cutting speed was achieved without any loss of cutting quality. The highest attainable cutting quality without nano burr is achieved at 12 kW and 20 kW with an increase in cutting speed. The experimental test series of the four power levels demonstrated that the increase in speed corresponded, on average, to an equivalent of approximately 5 kW of additional laser power.

It has been demonstrated that oscillating the beam in the beam propagation direction has the effect of minimizing the conflict between the beam cross-sectional area in the cutting kerf and the angle of the cutting front. The use of axial dynamic beam shaping exerts an influence not only on the cutting speed, but also on the flow dynamics and the mechanism expulsion of the molten metal. This aspect, which was merely brushed upon in the discourse, necessitates further investigation.

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