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Dynamic beam shaping for thick sheet metal cutting

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Abstract

From industrial view, nothing has a higher priority than a reliable and sustainable machine. This applies not only for specialized tasks rather for a spectrum of applications. Thin sheet cutting is well controlled but limitations of the cutting mechanism are challenging in case of thick metal plates above 6 mm. The solution approach of Fraunhofer IWS pursues dynamic beam shaping (DBS), which is influencing energy distribution and thus essential heat conduction for the laser cutting process. As a consequence, DBS provides the possibility to improve the performance for laser fusion cutting of thick metal plates. The authors will give an insight into changed mechanism during laser fusion cutting process due to DBS and explain how that enables an all-in-one cutting machine of industrial demands.

Keywords: dynamic beam shaping; distribution; laser fusion cutting; oscillation; thick metal

1. Introduction

One of the latest analyses of laser trends from Hilton and Gillner [1] point out a persistently annual stronger growth of laser system market by a factor of 4 referring to machine tool market. That is a clear indication for the enhancing relevancy of lasers as tools. Analysis of the European Photonics Industry Consortium [2] predicts a high development potential for laser material processing sector over the next years. Nevertheless, about three-quarters of laser market revenues are allotted to macro processing. Especially sheet metal cutting is leading application in macro range with a share of 36% and primarily treated by solid state lasers [1-6]. Main cutting tasks in industry deal with the two materials mild steel and stainless steel. Mild steel is well controlled and can be separated up to 25 mm sheet thickness in a good quality by laser flame cutting [7-12]. In contrast, laser fusion cutting of mild steel avoids oxidised cut edges. But so far,

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separation of sheet thicknesses above 10 mm is not possible with an acceptable quality [12]. Stainless steel is separated by laser fusion cutting and changes its cutting performance with increasing sheet thickness. Above 8 mm, cut edge is dominated by striation and burr [11,13-22]. But thick plate cutting is a benchmark of laser cutting machines. Hence, necessity of research and development activities in laser material processing sector, especially metal cutting, is reflected by the laser market.

In the first part, different beam shaping methods and their properties are discussed. Theoretical considerations support the understanding of influences from DBS on laser beam cutting. Especially selected oscillation pattern highlight changed cutting mechanism. Finally, advantages of DBS are demonstrated on examples of everyday industrial life.

2. Beam shaping

In fact, every laser cutting process requires adapted properties of the optical setup. Nowadays challenge deals with designing optimized beam profiles for various demands within the frame of feasibility and optimum. Further basic condition is a lossless beam modulation system for high laser powers. Additionally, easy integration into machine beam guidance entails small dimensions and low weight.

Opportunities to influence the beam profile are intensity distribution [23-27], spot size [17,20,28], spot shape [29-33], and focal position [17,34-37]. One possibility to obtain such modifications presents static beam shaping (SBS), prevailing by spatial methods. Thus, prepared laser beam is provided before treatment starts and cannot be changed anymore. Examples are the conventional scaling of laser beams by the magnification ratio of optical setups [17,20], additional implemented zoom-optics [38], polarization state [39-41], adjusted fibre structures [42], and many more diffractive optical elements to shape, split, or homogenize the beam. A schematic overview of different laser beam modifications is illustrated in figure 1.

The second way to modify a laser beam has a dynamic character. In this case, properties of the laser beam may change during processing. On the one hand, a temporal influence is feasible by laser pulsing as common in micro laser material processing. On the other hand, spatiotemporal effects are achievable by transient beam modifications. For the sake of clarity, some spatial modulation methods could be also performed dynamically, e.g. adaptive optics.

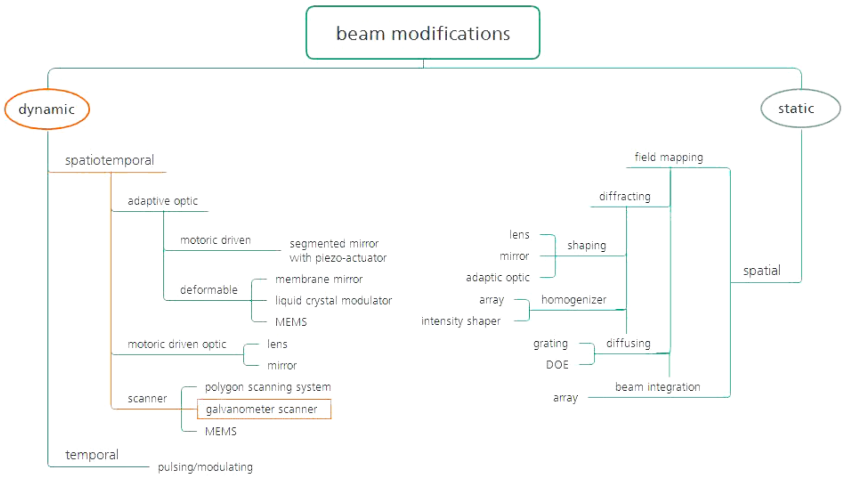

Fig. 1. Overview of laser beam modification methods (no raise of completeness); orange path marked beam modification method addressed by DBS

However, SBS entails benefits for specialized tasks, as serial production, whereas DBS is advantageous at frequently varying operations as daily business of industry. Furthermore, laser beam cutting of thick plates is a three-dimensional topic whereas a two-dimensional beam modification is desired at least. To the best of the author's knowledge, galvanometer scanner meets these requirements the most (orange path in figure 1). There are first experiences with DBS regarding laser beam cutting [43-46], which will help to understand the changed influence mechanism.

2.1. Theoretical considerations

In the following, limitations will be discussed of SBS and the resulting hint to utilize dynamic approaches. Figure 2 illustrate the arguments.

At the beginning are two (at a first glance) contrary demands of a laser beam cutting process: productivity and quality. The higher the feed rate, the higher is the productivity. Unfortunately, physical limitations restrict the increase of cutting speed and will be considered closer therefore. In fact, laser beam acts upon material with a certain energy distribution defined by spot size and laser power. Key factor for cutting is transforming absorbed laser energy into heat, to melt material. The energy coupling is determined by many factors and interacts with cut kerf conditions for instance. An increasing laser energy lead to higher feed rate and that flattens the cut front angle [36,44] on the one hand. Hence, transmission losses are reduced and more laser energy can be absorbed [36]. That implies a temperature rise in melt zone which in turn induces heat accumulations. In contrary, quality cuts require a constant temperature field [22] to stabilize the melt flow. Because heat accumulations initiate melt fluctuations whereas melt flow change to be unstable and striations arise [47]. With increasing cutting speed, flow gets stable at cut front first and with a further rise also at side walls [10]. But higher feed rate narrows the kerf width [13,47,48] on the other hand. The kerf width has an essential influence on the interaction between gas jet and melt flow which is responsible for melt ejection. Thus, interaction area as well as time of gas jet and melt is reduced by what ejection is stemmed. A high cut quality requires sufficient cut kerf dimensions to perpetuate the melt ejection. Upscaling the spot size to increase the kerf width and in turn enhance the melt ejection is restricted by less feed rate. Also the gain of laser power to cut faster has to be in line with the need for a sufficient kerf width to sustain the melt flow without overheating the material. Hence, there is a conflict between productivity and quality in case of SBS.

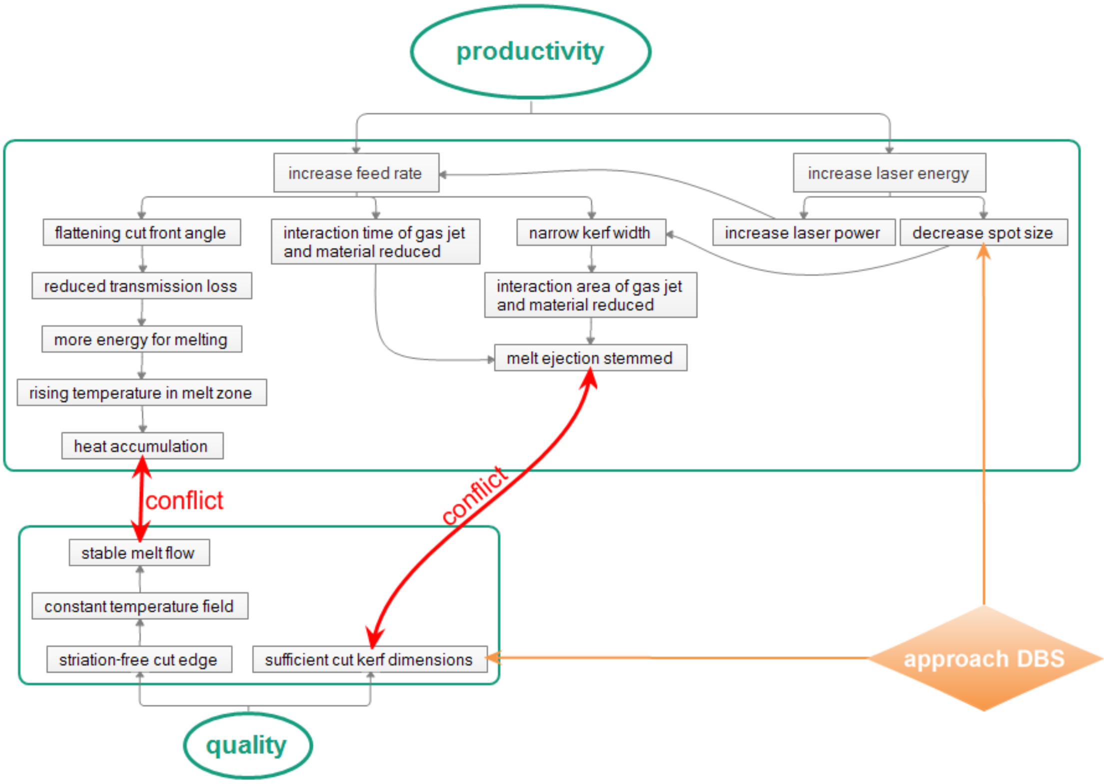

Fig. 2. Schematic illustration of limitations at laser beam cutting with SBS and approach of DBS

However, DBS allows an additional temporal influence to the described spatial one. Through spatiotemporal distribution of laser energy over the material surface, a crucial challenge will be addressed: sufficient kerf dimensions at a decreasing spot size to gain the obtainable laser energy. For this purpose, high laser energy of a small spot size oscillates periodically and is superimposed with the feed. Thus, energy is distributed around the generated cut kerf and thereby acting as an artificial bigger spot. At that, kerf width is enlarged, which procure an unimpeded melt ejection. Moreover, the distribution prevents heat accumulations, because interaction time of laser beam to material is decreased. In conclusion, limitations of SBS can be shifted with utilization of DBS.

2.2. Influence of oscillation pattern on cutting performance

Usually, heat accumulations occur at the cut front due to melt ejection and heat conduction mechanism. Already, *Mahrle* and *Beyer, 2007* [43] introduced influences of some oscillation patterns on the energy deposition in generalised manner. Quickly summarized, longitudinal harmonic oscillations transfer deposited energy successively in several steps not instantaneously. The changed behaviour is visualized in figure 3. At first, material is heating up (left and middle) and melting including ejection (right) occur delayed. Thus, temperature peak is shifted to melt centre whereby temperature gradient is reduced at the cut front. This is referable by experimentally demonstrated impact of longitudinal harmonic oscillation on the cut front inclination [44].

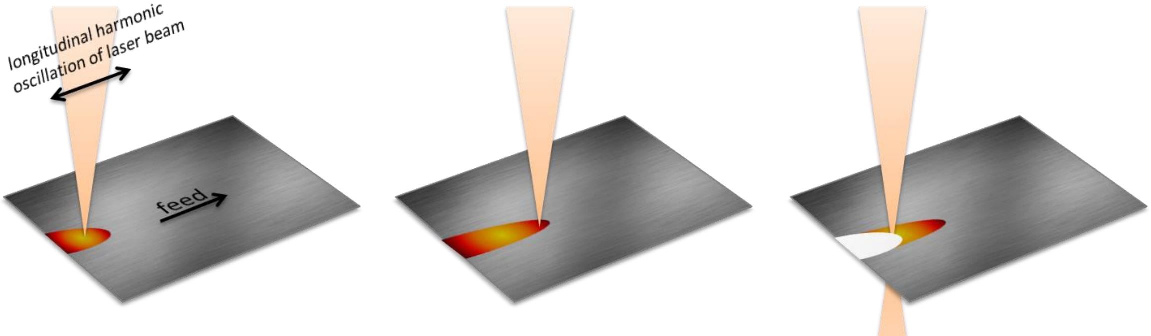

Fig. 3. Heat transfer mechanism of longitudinal harmonic oscillation during laser beam cutting, starting with heating up the material (left and middle) until the time-displaced melting and subsequent melt ejection (right) occur

Another one-dimensional spatiotemporal beam modification is transversal harmonic oscillation. In order to achieve a consistent energy distribution, overlapping of single oscillation periods is necessary (figure 4). That is realized by an appropriate proportion of feed rate and oscillation frequency.

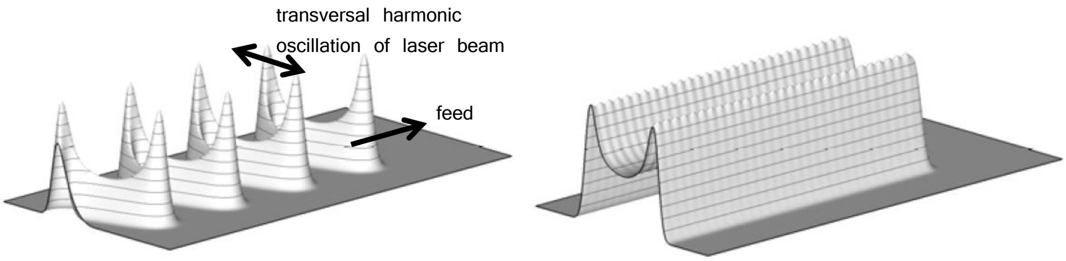

Fig. 4. Simulated energy distribution for transversal harmonic oscillation without (left) and with (right) overlapping of oscillation periods [43]

As obvious from figure 4, energy deposition takes place at the side walls of cut kerf due to reduced oscillation speeds at the reversal points. Based on this, kerf width could be broadened. But this effect is limiting the feed rate. Simultaneously, a broad kerf is advantageous for melt ejection. Thus, cut quality could be enhanced by minimizing dross attachment.

Two-dimensional oscillations are for instance circle or eight. The energy deposition looks the same as for transversal harmonic oscillation in figure 4 right. Nevertheless, energy distribution mechanisms vary as described by *Mahrle* and *Beyer, 2007* [43]. In case of a circle, direction of laser beam movement alters at the side walls as depicted in figure 5. Hence, instabilities can occur. In contrast, an eight-shaped oscillation has equally motion directions on both cut edges.

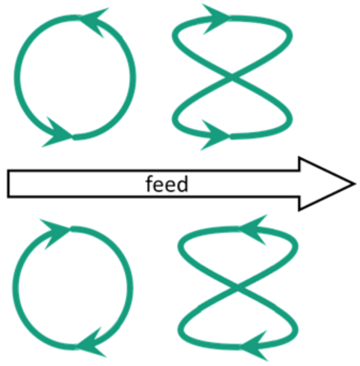

Fig. 5. Rotational direction of oscillation movement on the two cut edges with a circle and eight

Through energy deposition with symmetric beam motion on the side walls, a good cutting performance is achievable. The transversal orientation respectively to feed, enlarges the kerf width to attain a stable melt ejection. The longitudinal orientation prevents the rise of heat accumulations. According to whether quality or productivity has priority, oscillation parameters have to be adapted to peripheral conditions as material, sheet thickness, optical setup, laser source, etc.

3. All-in-one cutting machine

After giving an insight into changed mechanism during laser fusion cutting due to DBS, it will be explained how that enables an all-in-one cutting machine of industrial demands.

3.1. Improvement of the machine by DBS

The spatiotemporal beam oscillation is realized by a commercial high-dynamic 2D-scanner unit which is ready for integration into the collimated beam path of cutting machines. Thus, optical properties get not affected. The scanner consists out of two oscillating mirrors where each mirror has a time-dependent position, defined by a certain frequency and amplitude. The phase shift between both mirrors is the fifth parameter to specify the energy distribution. Controlling of DBS is executed by an IWS proprietary software tool.

One routine related to SBS is adapting the optical setup at varying cutting tasks by physical replacement of the optics. DBS makes laser beam cutting possible for a wide sheet thickness range without any operator interaction. The properly beam characteristics for a certain task becomes a smart parameter stored in a database and controlled by industrial improved PLC components. Just one universal optical setup is required for a cutting machine. Hence, keeping multiple optics in stock is obsolete for setup changes. This again avoids the occurrence of a fault during the adaption process like contaminations of the optics. Moreover, trimming one production step saves work time. Altogether, DBS accomplishes the precondition of an operator-free process.

3.2. Enhancement of the cutting performance by DBS

Besides system technology, DBS also offers benefits regarding the cutting result. There are two main criteria, which characterize the process: feed rate and cut edge quality. The impact of DBS will be demonstrated by taking the example of two main materials in metal processing: stainless and mild steel.

In case of laser beam fusion cutting of stainless and mild steel above 8 mm sheet thickness, an increase of productivity by up to 100 % is possible. Besides, cut quality is comparable to state of the art when utilizing the same laser power level. The process stability is similar to established conditions in industry today in the event of fluctuations.

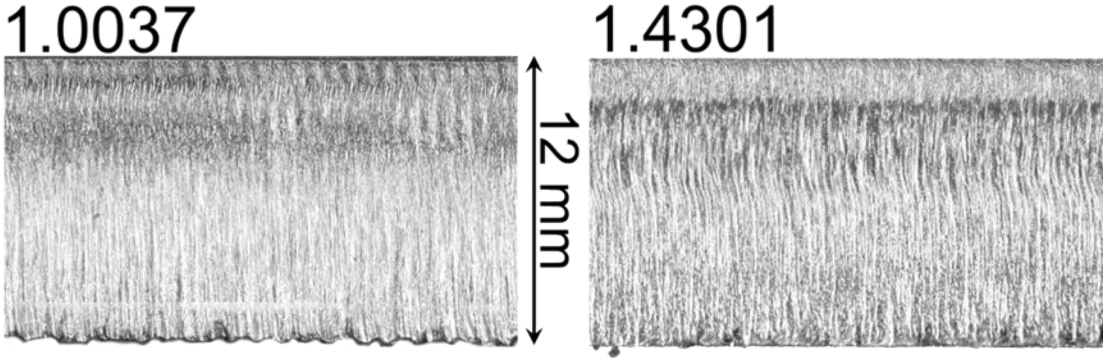

Fig. 6. Cut edges at 3 kW laser power

Quality enhancements are visualized in figure 6. In case of laser beam fusion cutting of stainless steel, the dross attachment is significantly reduced. Additionally, the generated kerf is almost parallel. Both are favorable for downscaling post-treatments to a minimum. Moreover, broaden the kerf simplifies unloading of parts from sheet skeleton for thick plates. Mild steel is commonly separated by laser flame cutting, but the generated oxygen layer on the edge has to be removed for follow-up production steps. Nitrogen can be used as assist gas to solve this issue. But so far laser fusion cutting was not able to separate mild steel plates above 8 mm sheet thickness with an acceptable quality. DBS affords this the first time and yield dross-free, non-oxidised edges. After all, results of DBS depicted in figure 4 are achieved with 3 kW and are competitive to higher laser power combined with static beam shaping. An enhancement of cut edge quality by DBS and following reduction of subsequent post-processes means a drop of work time and machinery as well as an improvement of the productivity.

4. Summary

Eventually, DBS offers economic potential like cost reduction and increased efficiency for thin and thick material cutting with the use of only one optical setup, outstanding feed rate, and remarkable quality. The functionality and technological benefits have been proofed sufficiently.

References

[1] Hilton, P., Gillner, A., 2016. "Portfolio and Trend Analysis for LASER BASED MANUFACTURING EU-Funded Projects and Markets", Photonics21 work group 2 workshop. Brussels, Belgium.

[2] EPIC: Laser Market Report 2015, 2016.

[3] Optech Consulting: Global Market for Industrial Laser Systems Grows by 10% in 2015, Press Release, 17.03.2016.

[4] Optech Consulting: Global Demand for Industrial Lasers Reaches $3.2 Billion, Press Release, 31.03.2016.

[5] Overton, G., Nogee, A., Belforte, D.A., Holton, C., 2016. Annual Laser Market Review & Forecast: Can laser markets trump a global slowdown?, Laser Focus World 52 (1).

[6] Belforte, D.A., 2016. Industrial Laser Sales – Grow in a Slowing Global Economy, Lasers Today, December.

[7] Sobih, M., Crouse, P.L., Li, L., 2007. Elimination of striation in laser cutting of mild steel, Journal of Physics D: Applied Physics 40 (22), p. 6908.

[8] Powell, J., Al-Mashikhi, S.O., Kaplan, A.F.H., Voisey, K.T., 2011. Fibre laser cutting of thin section mild steel: An explanation of the 'striation free' effect, Optics and Lasers in Engineering 49 (8), p. 1069.

[9] Wandera, C., Kujanpää, V., Salminen, A., 2011. Laser power requirement for cutting thick-section steel and effects of processing parameters on mild steel cut quality, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 225, p. 651.

[10] Hirano, K., Fabbro, R., 2011. Experimental observation of hydrodynamics of melt layer and striation generation during laser cutting of steel, Physics Procedia 12, p. 555.

[11] Rodrigues, G.C., Duflou, J.R., 2016. Into polarization control in laser cutting with direct diode lasers, Journal of Laser Applications 28 (2), 8p.

[12] Harrer, T., Hesse, T., 2015. "Power of Choice", 7th Workshop Laser Alta Brillanza. Milan, Italy.

[13] Wandera, C., Salmien, A., Olsen, F.O., Kujanpää, V., 2006. Cutting of stainless steel with fiber and disk laser, LIA 599 (99), p. 211.

[14] Sparkes, M., Gross, M., Celotto, S., Zhang, T., O'Neill, W., 2008. Practical and theoretical investigation into inert gas cutting of 403 stainless steel using a high brightness fiber laser, Journal of Laser Applications 20 (1), p. 59.

[15] Hilton, P.A., 2009. "Cutting stainless steel with disc and CO_2-lasers", 5th International Congress on Laser Advanced Materials Processing, 6p.

[16] Poprawe, R., Schulz, W., Schmitt, R., 2010. Hydrodynamics of material removal by melt expulsion: Perspectives of laser cutting and drilling, Physics Procedia 5, p. 1.

[17] Wandera, C., Kujanpää, V., 2011. Optimization of parameters for fibre laser cutting of a 10 mm stainless steel plate, Proceedings of the Institution of Mechanical Engineers, Part B (Journal of Engineering Manufacture) 225 (5), p.641.

[18] Olsen, F.O., 2011. "Laser cutting from CO2 laser to disc of fiber lasers – possibilities and challenges", Proceedings of the 30th ICALEO, p. 6.

[19] Hirano, K., Fabbro, R., 2012. Possible explanations for different surface quality in laser cutting with 1 and 10 µm beams, Journal of Laser Applications 24 (1), p. 012006-1.

[20] Goppold, C., Zenger, K., Herwig, P., Wetzig, A., Mahrle, A., Beyer, E., 2014. Experimental analysis for improvements of process efficiency and cut edge quality of fusion cutting with 1 µm laser radiation, Physics Procedia 56, p. 892.

[21] Zhou, Y., 2014. A review on fiber laser striation-free cutting for thick section stainless steel, Proceedings of SPIE – The International Society for Optical Engineering 9294, p. 92940H-1.

[22] Pocorni, J., Petring, D., Powell, J., Deichsel, E., Kaplan, A.F.H., 2015. The effect of laser type and power on the efficiency of industrial cutting of mild and stainless steels, Journal of Manufacturing Science and Engineering 138 (3), p. 031012-1.

[23] Laskin, A., 2006. Beam shaping? Easy!, Industrial Laser Solutions 21, p. 17.

[24] Gómez, C.G., 2012. Laser beam shaping, Master Thesis, Brno University of Technology.

[25] Doan, H.D., Noaki, I., Kazuyoshi, F., 2013. Laser processing by using fluidic laser beam shaper. International Journal of Heat and Mass Transfer 64, p. 263.

[26] Fuse, K., 2015. Beam shaping for advanced laser materials processing, Laser Technik Journal 12 (2), p.19.

[27] Laskin, A., Williams, G., Demidovich, A., 2010. Applying refractive beam shapers in creating spots of uniform intensity and various shapes, Proceedings of SPIE 7579, p. 75790N-1.

[28] Hilton, P.A., Lloyd, D., Tyrer, J.R., 2016. Use of a diffractive optic for high power laser cutting, Journal of Laser Applications 28 (1), p. 012014-1.

[29] Olsen, F.O., 2011. Laser metal cutting with tailored beam patterns, Industrial Laser Solutions 26 (5).

[30] Laskin, A., Laskin, V., 2013. Beam shaping to generate uniform laser light sheet and linear laser spots, Proceedings of SPIE 8843, 12 p.

[31] Kaakkunen, J.J.J., Laakso, P., Kujanpää, V., 2014. Adaptive multibeam laser cutting of thin steel sheets with fiber laser using spatial light modulator, Journal of Laser Applications 26 (3), p. 032008-1.

[32] Stoyanov, S., Niessen, M., 2014. Laser cutting with elliptical beam shaping, Annual Report Fraunhofer ILT, p. 116.

[33] Lin, H., Wang, H., Zhu, X., Zhu, G., Qi, L., 2016. Design of homogeneous laser-line-beam generators, Optical Engineering 55 (9), p. 095106-1.

[34] Powell, J., Tan, W.K., Maclennan, P., Rudd, D., Wykes, C., Engstrom, H., 2000. Laser cutting stainless steel with dual focus lenses, Journal of Laser Aplications 12 (6), p. 224.

[35] Gilbert J. Haas, 2002. Adaptive optics, Industrial Laser Solutions 17 (3).

[36] Scintilla, L.D., Tricarico, L., Mahrle, A., Wetzig, A., Himmer, T., Beyer, E., 2011. Fusion cutting of steel with disk and CO_2 lasers, The Laser User 62, p. 24.

[37] Laskin, A., Volp, J., Laskin, V., Ostrun, A., 2016. "Refractive multi-focus optics for material processing". Proceedings of 35th ICALEO.

[38] Precitec: ProCutter: the variable laser cutting head, Press Release, 07.11.2014.

[39] Goppold, C., Pinder, T., Herwig, P., 2016. Experimental investigation of the linear polarization state of high power fusion cutting with 1 µm laser radiation, Journal of Laser Aplications: E-Only.

[40] MacKay, P.E., Häcker, T., Hesse, T., 2014. Segmented waveplate polarisation control for laser cutting, Classical Optics, paper OTh4B.2.

[41] Golyshev, A.A., Orishich, A.M., Shulyatyev, V.B., 2015. "Effect of laser beam polarization on the laser surface quality", Lasers in Manufacturing Conference LiM.

[42] Blomqvist, M., Campbell, S., Latokartano, J., Tuominen, J., 2012. Multi-kW laser cladding using cylindrical collimators and square-formed fibers, Proceedings of SPIE 8239.

[43] Mahrle, A., Beyer, E., 2007. "Modeling and simulation of the energy deposition in laser beam welding with oscillatory beam deflection", Proceedings of 26th ICALEO.

[44] Mahrle, A., Bartels, F., Beyer, E., 2008. 2Theoretical aspects of the process efficiency in laser beam cutting with fibre lasers", Proceedings of 27th ICALEO.

[45] Goppold, C., Pinder, T., Herwig, P., Mahrle, A., Wetzig, A., Beyer, E., 2015. "Beam oscillation – Periodic modification of the geometrical beam properties". Lasers in Manufacturing Conference LiM.

[46] Goppold, C., Pinder, T., Herwig, P., 2016. Transient beam oscillation with a highly dynamic scanner for laser beam fusion cutting, Advanced Optical Technologies 5 (1), p.61.

[47] Yilbas, B.S., 2001. Effect of process parameters on the kerf width during the laser cutting process, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 215 (10), p.1357.

[48] Kheloufi, K., Amara, E.H., Benzaoui, A., 2015. Numerical simulation of transient three-dimensional temperature and kerf formation in laser fusion cutting, Journal of Heat Transfer 137 (1), p. 112101-1.