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Innovation in high power fiber laser applications

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ABSTRACT

Diffraction-limited high power lasers represent a new generation of lasers for materials processing, characteristic traits of which are: smaller, cost-effective and processing "on the fly". Of utmost importance is the high beam quality of fiber lasers which enables us to reduce the size of the focusing head incl. scanning mirrors. The excellent beam quality of the fiber laser offers a lot of new applications. In the field of remote cutting and welding the beam quality is the key parameter. By reducing the size of the focusing head including the scanning mirrors we can reach scanning frequencies up to 1.5 kHz and in special configurations up to 4 kHz. By using these frequencies very thin and deep welding seams can be generated experienced so far with electron beam welding only. The excellent beam quality of the fiber laser offers a high potential for developing new applications from deep penetration welding to high speed cutting. Highly dynamic cutting systems with maximum speeds up to 300 m/min and accelerations up to 4 g reduce the cutting time for cutting complex 2D parts. However, due to the inertia of such systems the effective cutting speed is reduced in real applications. This is especially true if complex shapes or contours are cut. With the introduction of scanner-based remote cutting systems in the kilowatt range, the effective cutting speed on the contour can be dramatically increased. The presentation explains remote cutting of metal foils and sheets using high brightness single mode fiber lasers. The presentation will also show the effect of optical feedback during cutting and welding with the fiber laser, how those feedbacks could be reduced and how they have to be used to optimize the cutting or welding process

Keywords: High-power fiber laser, fiber laser applications, remote cutting, beam scanning

1. INTRODUCTION

High-power fiber laser systems represent a new generation of lasers for materials processing purposes. The high beam quality of these sources can be considered as the most distinctive feature of available single-mode fiber lasers in comparison to competitive laser sources. This fact is caused on the one hand by the short emission wavelength of λ_{Yb} = 1070 nm (as compared with the emission wavelength of λ_{CO2} = 10600 nm of CO_2 lasers) and, on the other hand, by the technical feasibility to construct systems which are capable of emitting nearly diffraction-limited beams (as compared with laser systems which emit laser radiation of a similar or even shorter wavelength). The resulting beam parameter product BPP

$$BPP = w_0 \cdot \theta = \frac{M^2 \cdot \lambda_{Yb}}{\pi} \tag{1}$$

of single-mode fiber lasers with beam propagation ratios of typically $M^2 < 1.3$ is consequently smaller than that of other laser systems in a wide power range; see Figure 1 on the left-hand side. As a result, a fiber laser beam with a given beam waist radius w_0 possesses the lowest divergence during its way of propagation, or, vice versa, for a given divergence angle θ it can be focused to a smaller focus size as compared to laser beams with a higher beam parameter product.

Another term or quantity that is often used in the context of the new solid-state laser sources, which besides the fiber laser also comprise the disk laser, is brightness [1]. The brightness of a laser source is understood as being equivalent to its radiance, which is originally a radiometric measure that describes the amount of light that passes through a particular area, and then propagates within the solid angle in a specified direction.

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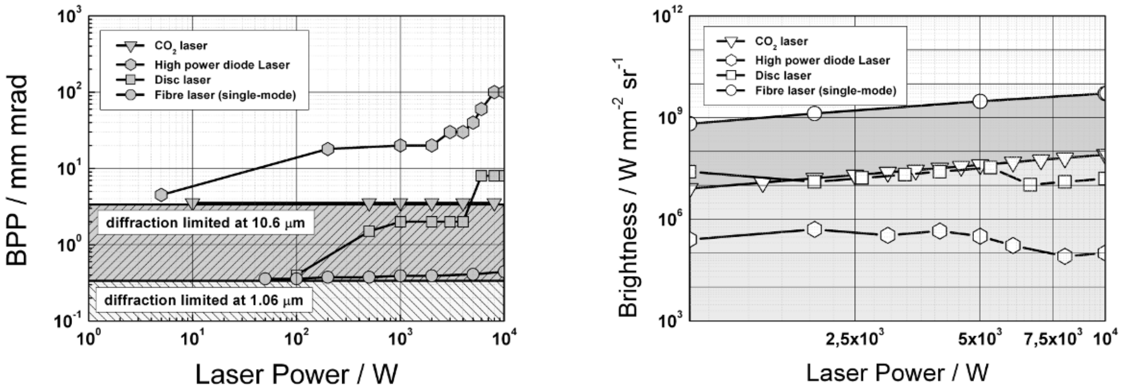


Figure 1: Beam parameter product BPP and brightness of currently available solid-state, CO_2 and diode laser systems.

In the context of laser technology, the brightness B_L of a laser with an available output power P_L, the beam propagation ratio M^2 and the wavelength λ is given by the relation

$$B_L = \frac{P_L}{\pi \cdot w_0^2 \cdot \pi \cdot \theta^2} = \frac{P_L}{\pi^2 \cdot BPP^2} = \frac{P_L}{\left(M^2\right)^2 \cdot \lambda^2} \quad . \tag{2}$$

Calculated brightness values of single-mode fiber lasers in comparison to some other current laser systems are shown in Figure 1 on the right-hand side. A high brightness value means that the corresponding laser source is capable of providing a high intensity for a particular application. High intensities may be very beneficial in order to improve the performance of welding and cutting. However, it is also fair to say that a high brightness cannot be considered as a general guarantee that a particular process works very well with respect to efficiency and quality. Indeed, working with high brightness lasers has also revealed new problems and challenges to contend with. In this way, the market launch of high brightness laser sources has stimulated a lot of fundamental experimental and theoretical research that further improved and still improves our understanding of the process behavior during laser materials processing.

An often discussed issue within the framework of high brightness laser beam sources concerns the increased demands on the involved optical components. Thermal lensing and cooling of optics became a serious problem due to the higher power loads of high brightness laser beams resulting in drift of focus position, distortion of the beam profile and reduced beam quality. So, a focus shift in the order of the Rayleigh length was observed during operating with high power disc and fiber lasers with conventional optical components even if they are in a clean and new condition [2]. The laser induced focal shift is mainly caused by a thermal load of the involved lenses and optics giving rise to mechanical deformations and a radial gradient of the refractive index (thermal lens effect). This effect consequently depends on the power density of the laser beam. Additionally, the focal shift has also to be considered as a temporal process and affects the results of a particular process not until a certain critical processing time [3].

2. CUTTING AND WELDING WITH HIGH POWER FIBER LASERS

2.1 Cutting

The continuous development of fiber and disc lasers in the multi-kW power range has particularly stimulated increased research efforts in the area of laser cutting with the aim to evaluate the cutting abilities of the new solid state laser beam sources in comparison to the well-established CO_2 laser cutting process. Corresponding experimental investigations revealed much promising results with considerably increased cutting speeds in thin and medium section applications. On the other hand, it had to be recognized that the advantages of the improved process performance noticeable fall as section thickness increases [4-6]. Exemplary, Figure 2 on the left-hand side shows experimentally determined maximum cutting speeds by Wandera et al. [4] as a function of sheet thickness for fusion cutting of stainless steel with CO_2 and fiber lasers at 4 kW laser power.

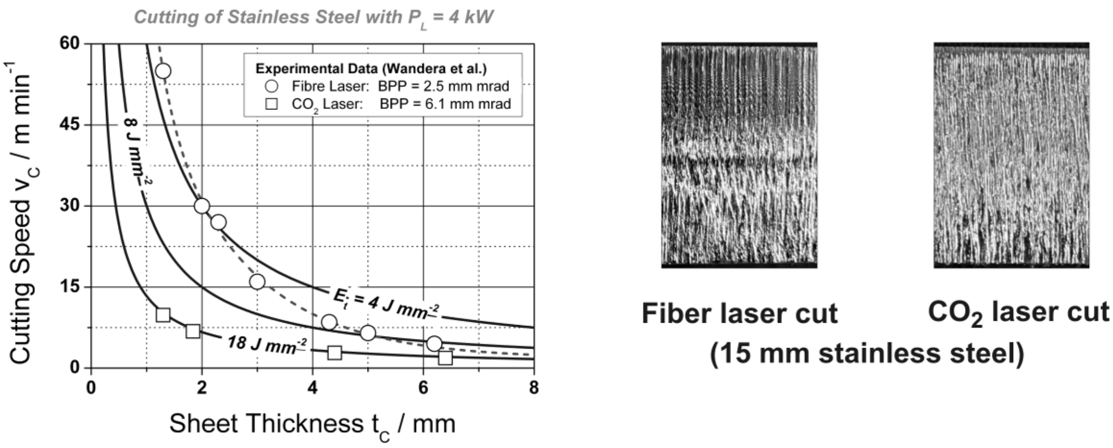


Figure 2: Maximum cutting speeds for CO_2 and fiber laser fusion cutting as a function of sheet thickness (left) and cut kerf appearance of fiber and CO_2 laser cuts for cutting 15 mm thick stainless steel.

The falling process performance of fiber laser fusion cutting with sheet thickness clearly corresponds with increased needs of the severance energy E_t [7]. The severance energy is a derived quantity of the global power balance of the cutting process with the physical meaning of a linear energy per unit thickness according to

$$E_t \equiv \frac{P_L}{v_C \cdot t_C} = \frac{w_K \cdot \Delta h_{V,FC}}{\eta_{FC}}. \tag{3}$$

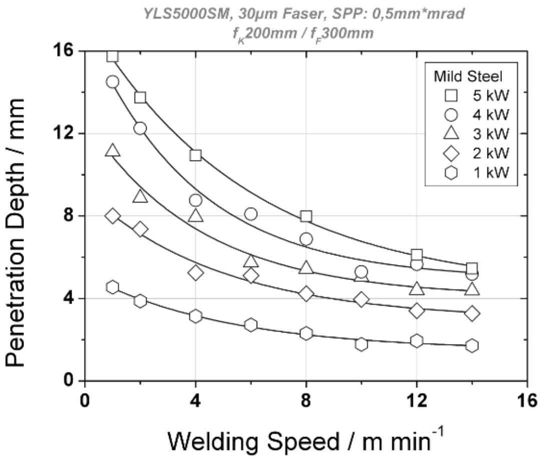
In this relationship, P_L denotes the delivered laser power, v_C is the achievable cutting speed, t_C the sheet thickness, w_K the width of the cut kerf, $\Delta h_{V,FC}$ the necessary increase in enthalpy per unit volume of the material to cause melting, and η_{FC} the overall efficiency of the process [8].

Another aspect of high practical relevance concerns the achievable edge quality of solid-state laser cuts in comparison to the almost smooth and low roughness cut edge surfaces known from CO_2 laser inert-gas fusion cutting, see Figure 2 on the right-hand side. Comparative experimental investigations by Hilton [9] with disc and CO_2 lasers at equivalent power levels revealed that the cut edge quality of solid-state laser cuts can be similar or even better in terms of nominal surface roughness in case of cutting thin stainless steel sheets with 0.6 and 1.2 mm thickness. However, and maybe corresponding to the observations with respect to the process performance, the cut edge quality noticeably degrades with sheet thickness particularly in terms of surface roughness. Possible reasons for this phenomenon are still a subject of controversial scientific discussions [10-14] and it remains a pivotal question if there are technological means by proper parameter settings to overcome this limitation or if the degraded cut quality is unavoidably caused by an implicated physical limitation of the shorter emission wavelength of solid-state lasers. Regarding this aspect it is worthwhile to note that the use of a solid-state fiber laser allowed for the first time the generation of striation-free cuts in case of oxygen-assisted laser cutting of 1 and 2 mm thick mild steel sheet with proper parameter settings of oxygen pressure, stand-off distance, focal plane position, laser power and cutting speeds [15-17]. Subsequent theoretical considerations by Powell et al. [18] revealed that this phenomenon must be a specific feature of thin section cutting with 1 micron wavelength laser beam sources. The effect is caused by a favorable interplay of cut front inclination and Brewster angle at the particular wavelength of solid-state lasers giving rise to optimal conditions for beam absorption at the inclined cut front. Due to purely geometric reasons such an optimal constellation cannot be achieved if CO_2 lasers are applied.

2.2 Welding

Fields of welding applications that may preferably benefit from high brightness laser beam sources comprise remote welding processes with large working distances, welding thick structures at very high laser power levels as well as welding of very fine structures [19]. The last one is a typical need in micro fabrication where low power single mode fiber lasers have already gained major market shares in competition to conventionally applied pulsed Nd:YAG lasers [20]. The excellent mode quality and high focusability of low power single-mode fiber lasers are the most important features for achieving small spot sizes in the range of some microns, thus allowing high intensities and keyhole welding at noticeably very low power levels. As a result, welding of micro parts with very high processing speeds, lowest energy input, reduced heat-affected zones and minimized distortion can be achieved [21,22]. Furthermore, the emergence of fiber and disc lasers has allowed new processing regimes of laser micro welding to be explored [23].

In case of macro welding, a high brightness of the applied laser beam source offers the potential to improve standard processes in terms of processing speed. Exemplary, Figure 3 on the left-hand side shows penetration depths as a function of welding speed achieved with a single-mode fiber laser system in bead-on-plate welding mild steel S235 at different power levels in the range between 1 and 5 kW. The resultant weld seam geometries, as additionally shown in Figure 3 on the right-hand side, possesses noticeably high aspect ratios of penetration depth to seam width that were known a few years ago from electron beam welding only.



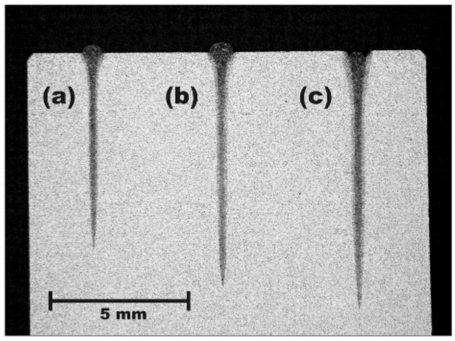


Figure 3: Penetration depth versus welding speed for single-mode fiber laser welding of mild steel as a function of laser power (left) and weld seam geometries of single-mode fiber laser welds at 5 kW laser power in mild steel S235 as a function of welding speed, (a) 8 m min^{-1}, (b) 6 m min^{-1}, (c) 4 m min^{-1}.

In general, solid-state laser welding is considered of being much less sensitive to plasma effects than CO_2 laser welding. Spectroscopic measurements and analysis of the weld plume by Katayama et al. [24] during welding 304 stainless steel with a 10 kW fiber laser beam at the ultra-high power density of about 1 MW mm^{-2} in argon shielding gas have demonstrated that almost all emissions origin from neutral atoms. Emissions from the argon gas were not detected and the effect of inverse Bremstrahlung seems to be negligible small in welding with solid-state laser beams. Consequently, deeply penetrated welds can be generated at high power levels even in argon gas shielding atmosphere.

However, it was observed by Michalowski et al. [25] that the fiber laser welding process can be accompanied by particle generation, which is capable of forming a dense weld plume above the surface of the material to be welded. The particles being present in that plume attenuate the incident laser radiation by scattering, refraction and absorption effects. Without removal of such a weld plume the welding process might become unstable and the penetration depth can be significantly reduced. This fact is especially important for remote welding applications.

The strong focusability of high brightness laser beam sources is often accompanied by a considerable gain in weld penetration. There is however a limit of adaptable focus dimensions, where the penetration depth indeed increases with smaller focus radii. As recently found out by Weberpals et al. [26,27], the divergence angle of the focused laser beam can have a decisive impact on the welding depth. Below a limit value of the focus diameter the penetration decreases with smaller focus dimensions. The limit value is a clear function of the beam parameter product BBP of the applied laser system. Laser beams with a low BPP consequently allows higher welding depths.

3. APPLICATION EXAMPLES

The continuous advancement of high brightness laser beam sources and their growing availability in research and industrial facilities has stimulated many investigations with the aim to assess their capabilities and limits in the field of laser materials processing. For many applications, the use of high brightness laser beam sources has led to significant enhancements of the process performance but besides such a pure quantitative improvement also totally new and innovative processes were developed. Some of these new technologies and approaches are presented in the following.

3.1 Remote cutting

Inert-gas or high-pressure fusion cutting is considered as the most common laser-assisted material processing technology for separating stainless steel and diverse non-ferrous metal alloys in a wide thickness range. This process is based upon the combined use of a high-intensity laser beam and a high-pressure inert-gas jet (nitrogen or argon at pressures up to 2 MPa), which both simultaneously act in a coaxial arrangement. During cutting, an inclined cutting front throughout the whole depth of the sheet is formed. The material on the surface of this cutting front is continuously melted by the incident laser radiation and then blown out of the resultant cut kerf by the gas jet. The distance between nozzle exit and surface of the material being cut has to keep small in order to guarantee an efficient blow out of the melt. In order to complete a particular cutting job, the cutting gas nozzle and/or the workpiece has to be moved relative to each other along the desired cut contour by the handling system of the corresponding cutting machine with commonly mechanical linear drives. The maximum average cutting speed for complex 2D-parts will be limited in the range of between 20 to 30 m min^{-1} due to the inertia of the handling system during the necessary decelerations and accelerations before and after changes of the cutting direction. For thin-section cutting the achievable processing speeds with high brightness solid-state laser beams are however much higher. Such a noticeable gap between physically possible and technologically realizable cutting speeds gave rise to the development of the remote cutting process as efficient technology for separating thin sheets and foils. Figure 4 shows the principal experimental set-up of a remote cutting station that allows maximum processing speeds in the range of up to 15 m s^{-1} on the surface of the material being treated [28].

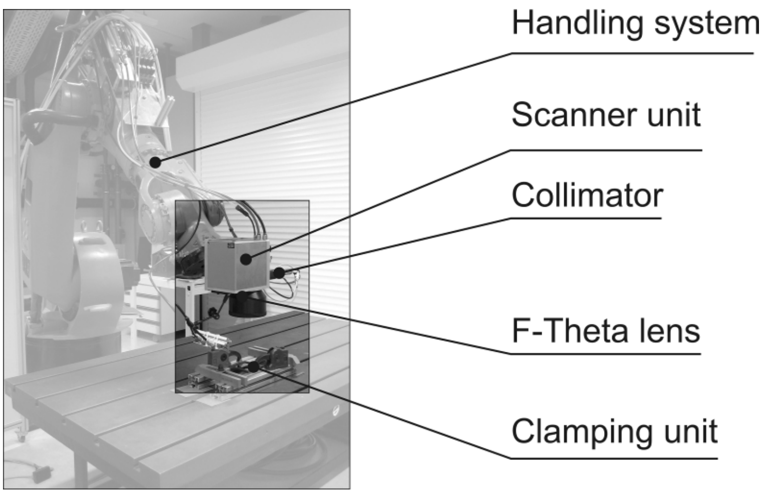


Figure 4: Experimental set-up of a remote cutting station consisting of the handling system, the collimator and scanning unit, the F-Theta lens and the clamping device for the workpiece.

The particular feature of remote cutting is the realization of the relative motion between workpiece and cutting tool not by the movement of a weighty processing head (beam optics plus gas delivery and nozzle) by mechanical drives but by deflections of the massless laser beam only by means of highly dynamic scanner mirrors. Such a methodology requires large working distances and thus high brightness laser beams providing small spot dimensions at simultaneously long focusing lengths. Another essential precondition of remote cutting concerns the necessary abandonment of the cutting gas nozzle and thus the blow-out of the melt away from the cut kerf without any external gas support. Own experimental investigations on remote laser beam cutting revealed a strong correlation between the realized cut rate and the effectiveness of the melt removal from the cut kerf. The penetration is indeed high below a critical value of the processing speed but the kerf is characterized by an obvious lack of melt removal, while there is an effective melt removal for cutting speeds above the critical value. This characteristic behavior separates the remote process into two different regimes without and with melt removal (regime I and II), see Figure 5, on the left-hand side [29].

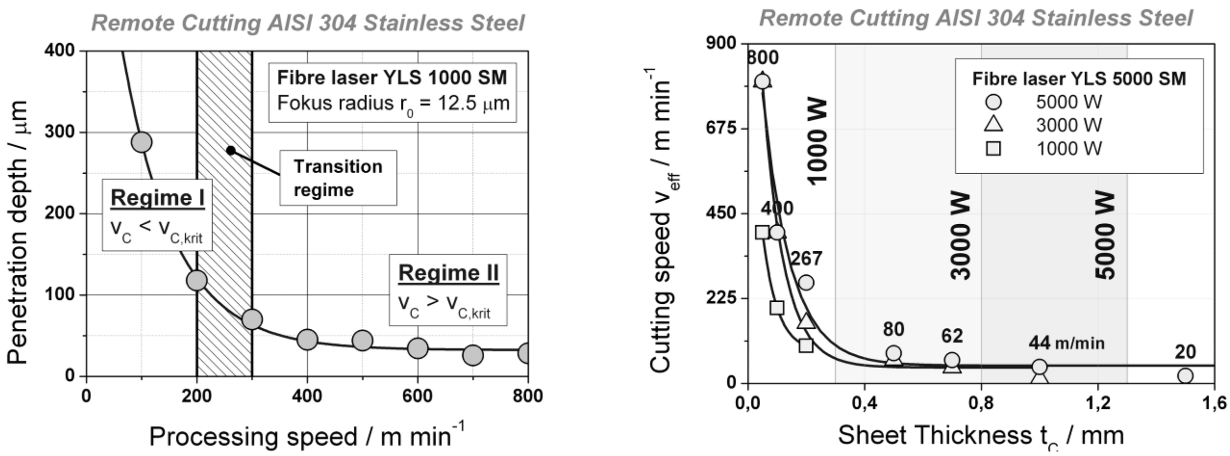


Figure 5: Penetration depth as a function of processing speed for fiber laser remote cutting and resulting process regimes (left) and effective cutting speeds vs. material thickness for remote cutting of circles (radius = 5 mm) with different laser power levels. Parameter: processing speed = 800 m min^{-1} and focus diameter = 25 μm (right).

The need of a particular processing speed limits in turn the thickness that can be cut with a single pass. For higher thicknesses, a cut groove with partial penetration of typically between 30 and 50 μm is initially formed. Thicker materials have to be separated by a multi-pass technique, i.e. a rescanning of the cut contour. The cut kerf is then formed step by step or layer by layer until the material is completely severed and the effective cutting speed v_{eff} is equal to the processing speed divided by the number of scans. Such a methodology however works in a certain range of material thicknesses only. Remaining molten and resolidified material within the groove causes a reclosing of the generated cut kerf. Experimental investigations with a single-mode fiber laser have demonstrated that the separable thickness increases with increased laser power or brightness, respectively. Increasing the laser power from 1000 W to 3000 W enlarges the separable sheet thickness from 0.3 mm up to 0.8 mm. A further power enhancement to 5000 W allows separating sheets of up to 1.3 mm thickness. The corresponding parameter windows of a high-brightness single-mode fiber laser as well as the achievable effective cutting speeds v_{eff} at different power levels are shown in Figure 5, on the right-hand side [30].

The laser remote technique can easily cope with various materials and complex contours. One issue of practical importance is still the limited working area being proportional to the used focal length and working distance, respectively, of the scanner unit. The working distance cannot be chosen to large in order to reach the necessary threshold intensities for effective laser remote cutting. Only parts with a size of less than the particular working area of the scanner unit can be processed in one manufacturing step. Developed solutions to overcome such a limit comprise patching and on the fly techniques [30, 31].

Patching is characterized by successive treatments of partial sections of a complete workpiece. After completion one section, the scanner unit and/or the workpiece are moved relative to each other to reach the particular working position of the following section. As an example, this technique is illustrated by means of manufacturing a working model of a cylinder head gasket as shown in Figure 6. Between the two successive sections a certain overlap region is commonly considered in order to achieve good cutting results. In contradiction to patching, the workpiece or the scanner unit continuously moves relative to each other by applying on-the-fly techniques. In that particular case, the scanner thus works in a moved working field [31].

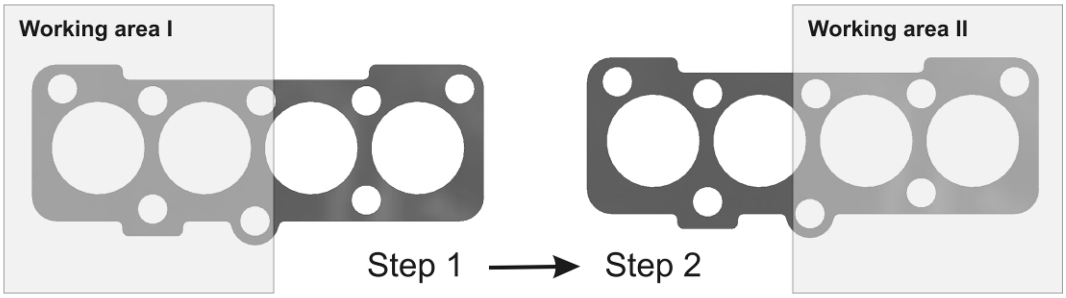


Figure 6: Enlargement of the practical working area or the treatable workpiece size, respectively, by patching the system-inherent working area.

Currently, the potential of remote cutting for an optimization of the manufacturing of electrode materials for lithium-ion batteries is under investigation. Cutting speeds in the range of more than 600 m min^{-1} could be realized by use of a highly focused 5 kW single-mode fiber laser at simultaneous good quality of the cut edges. In comparison to conventional mechanical punching, the contact-free laser process offers a high degree of flexibility and low handling times without any tool wear [32].

3.2 Welding with oscillating beams

It has been demonstrated that laser welding with high brightness laser beam sources is capable of directly competing with electron beam welding in terms of weld seam narrowness, aspect ratio and parallelism of the seam edges. Furthermore, the achievable travel rates, the corresponding amounts of linear energy and the life time of the generated melt pools are of comparable order. Due to the reduced dimensions of high brightness laser beams also advances in spatial and temporal manipulations of the process behavior by improvements of the scanning technology could be achieved. A currently designed laser beam tool allows 2D spatial beam oscillations above 2 kHz with and without power modulations. Oscillating working regimes can be applied to influence the properties of the welded joints. Figure 7 shows the applied scanning system (left) and as an example weld seam geometries in stainless steel in case of transversal beam oscillations with 0.5 mm amplitude and 1500 Hz frequency with and without additional power modulation (right).

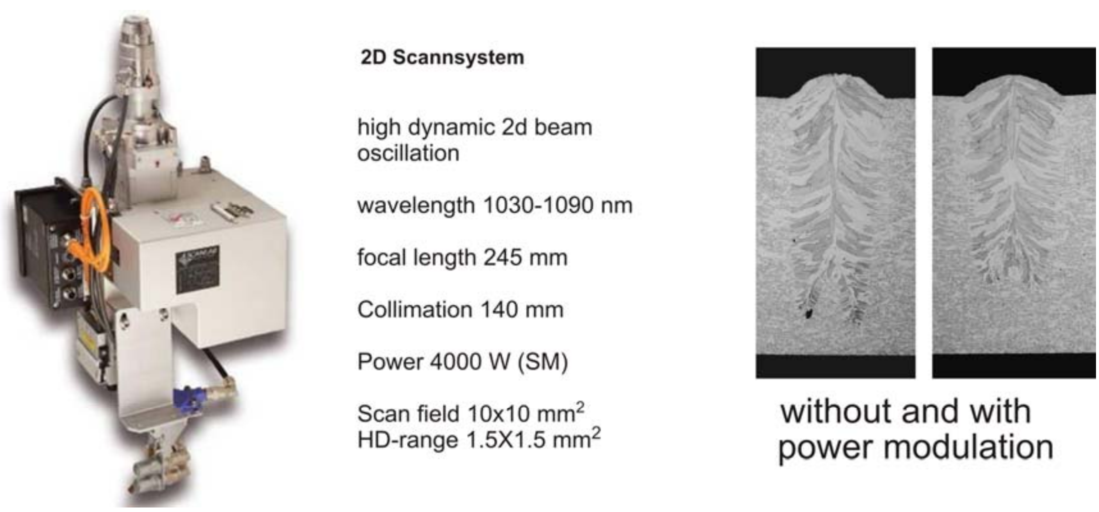


Figure 7: 2D-Scannsystem (left) and weld seam geometries of bead-on-plate welds in stainless steel made by single-mode fiber laser welding with transversal beam oscillations.

Scanning the beam may be a very useful tool in suppressing the spiking phenomenon that preferably occurs during partial penetration welding with high power single mode fiber lasers at low welding speeds and corresponding high penetration depths or aspect ratios, respectively. Figure 8 shows the weld seam shapes for welding trials in stainless steel with a single-mode fiber laser with a laser power of 4 kW. The spiking phenomenon is clearly obvious for a welding speed of 2 mm but it can efficiently suppressed by applying a transversal beam oscillation with 100 μm scan width and 2500 Hz frequency. It is worth mentioning that the penetration depth itself is hardly affected by the periodic deflection of the beam. Thus, the linear energy of the welding process that is necessary for achieving the desired penetration can be kept constant in comparison to the welding process without beam oscillation.

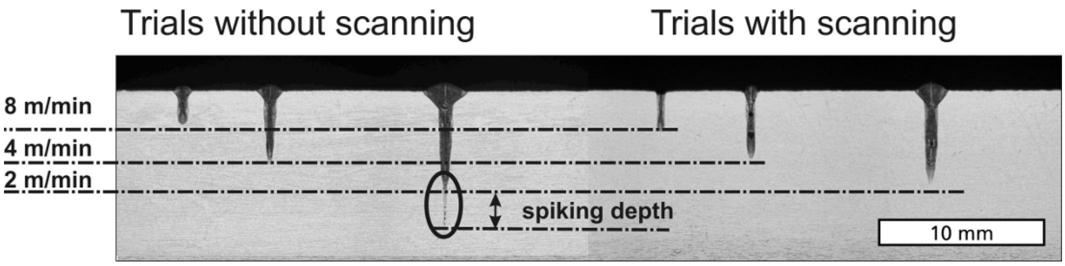


Figure 8: High-power single-mode fiber laser welding stainless steel without and with additional transversal beam oscillation. Oscillation frequency = 2500 Hz, scan width = 100 μm.

Regarding practical applications of beam oscillation welding, a corresponding integrated laser welding system was already successfully applied in combination with a 2 kW single-mode fiber laser (Rofin Sinar FL020 S) for generating dissimilar metal joints such as aluminum – copper (electrically conductive joints, joints for heat sinks in electronics), stainless steel – copper (heat exchanger, vacuum engineering) and aluminum – magnesium (body-in-white and aerospace applications). It was demonstrated that the combination of a high brightness laser beam source and a high-speed scanning system with additional power modulation offers the potential for crack-free welding of those dissimilar metal joints [33]. Weld joints between copper and aluminum are interesting for a variety of applications in the field of electrical engineering and electronics, hereby providing improved electrical conductivity and heat transfer capability in comparison to mechanically joined connections. However, the material combination of aluminium/copper is hardly weldable due to the formation of very brittle intermetallic phases which possess a poor ductility only. The formation of such phases depends on the corresponding mixing ratio of the weld. It could be shown by experimental investigations that the mixing ratio can be favorably influenced by transversal high-frequency beam oscillations. Figure 9 illustrates the distribution of the involved elements copper and aluminium within the weld seam area as a result of a SEM analysis.

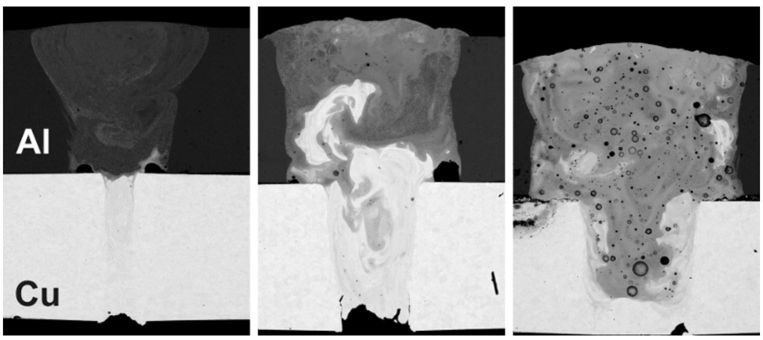


Figure 9: Mixing ratio of Al/Cu overlap welds as a function of scan width. Left: Without beam oscillation. Middle: Scan width = 0.7 mm. Right: Scan width = 0.9 mm. Welding parameter: Laser power = 2000 W, welding speed = 4 m min^{-1}, Scan frequency = 1500 Hz.

It is obvious that an adequate mixture of the weld zone is not achieved in case of conventional welding without beam oscillation. A noticeable increase of the mixing ratio is reached for welding with beam oscillation, whereby the mixing ratio can be considered as a strong function of the scan width. This effect is however accompanied by an increased porosity of the weld seam [34].

3.3 High-precision laser cladding

Conventional laser cladding with efficient diode laser sources is a well established technology, e.g. for automotive, aviation, energy, tool and medical applications. Weld beads possessing widths above one millimeter were predominantly used for the generation of contours, surfaces, bar structures or complex volume built-ups within such applications. However, by use of diode lasers it is not possible to perform efficient processing in the sub-millimeter range as required for new market needs in the field of turbine industry and medical engineering. Since the commercial availability of high-brightness single-mode laser sources, the precision of laser cladding strongly improved and structure dimensions below 100 μm became possible. Exemplary, Figure 10 on the left-hand side shows the cross-section of a structure with sub-millimeter dimensions generated by high-precision laser cladding. One potential application of the filigree structures is the improved stability of thermal barrier coatings (TBC) used in stationary gas turbines and aircraft engines. TBC which are used to protect hot engine sections are strongly affected by high working temperatures required for a high efficiency of such systems. The huge thermal load can lead to intolerable failures and delamination of the TBC. Compared to plain surfaces the structuring of turbine parts can improve the clamping conditions between part and TBC and, hence, improve the durability of the coating system as schematically shown in Figure 10 on the right-hand side [35].

Figure 10: Cross-section of a structure generated by high-precision laser cladding (left) and schematic of a surface structure generated by means of micro cladding for improved stability of sprayed thermal barrier coatings (right).

Another application is the generation of micro implants, e.g. for hearing aids. Laser cladding with single-mode fiber lasers offers a high-accuracy to build up small details which are individually fitted to human patients combined with beneficial material properties. Other applications of high-precision laser cladding can be found in the field of micro tooling, rapid prototyping of micro components, metallic coding or embossed marking as Braille printing.

4. SUMMARY AND CONCLUSIONS

The availability of high-power fiber lasers with outstanding beam quality has had and still has a remarkable impact on research and development activities at many academic and industrial institutions. Corresponding experimental and theoretical investigations revealed new insights into the characteristics of different kinds of laser materials processing such as cutting and welding. Advantages and benefits as well as new challenges to contend with were recognized. Besides quantitative enhancements of the performance of several applications, the high brightness of single-mode fiber laser beams gave particularly rise to the development of completely new and innovative processes. It is expected that the continuation of the investigations on the potential of high-brightness laser beam sources is stimulating further inventions in the field of laser material processing.

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