LATEST DEVELOPMENTS OF LASER CUTTING

Paper 103

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Abstract

Laser cutting was one of the first applications of laser material processing. Today, laser cutting is the most widespread application among laser material processing besides laser marking. Meanwhile, nearly each material can be cut by means of a laser, in particular since ultra short pulse lasers are available in the power range of up to 100 W. The to be cut material can come with thicknesses from a few microns till tens of millimeters as flat stock or as free form shapes. The paper will concentrate on cutting with high power cw lasers in the near and far IR range. Latest developments in terms of thick plate fusion cutting of metals, in particular the positive impact of dynamic beam shaping, will be discussed. The state of art of laser cutting of thin sheet metal without assist gas will be described as well. In the case of non-metals, latest results of laser cutting of composites like fiber reinforced plastics by using two different wavelengths at the same time are introduced and discussed. First results of cutting by means of a novel green cw laser will be presented. Finally, an outlook of future trends of laser cutting will be given in terms of further process improvements and first steps of process control.

Introduction

Laser cutting of plastic material was one of the first applications done by CO_2 lasers in the early days of laser material processing since thicknesses of more than 1 mm could be cut with laser power of a few hundred Watts. Since many years cutting by means of high power CO_2 lasers in the typical power range up to 6 kW has been well established. A distinction is drawn between using oxygen (reactive gas cutting) and inert gas (fusion cutting) as assist gas which rejects the molten material. Material thicknesses between a tenth of mm and umpteen mm can be laser cut [1]. For many years high brightness solid state lasers like disk or fiber lasers have beam capturing the market for laser cutting applications [2]. Apart from numerous advantages which are associated with the use of disk and fiber lasers the achievable cutting quality is still behind the cutting quality by means of CO_2 lasers. High power solid state lasers with single mode beam quality allow cutting without using assist gas that is called laser remote cutting. This is a fairly new process suitable to cut thin metallic materials with high velocities. Nowadays, even direct diode lasers with a beam parameter product better than 8 mm*rad as well as green high power cw lasers have been tested for fusion cutting processes. Another field with huge potential for lasers is cutting of non-metals like plastic, composite material, fabrics, paper, cardboard and many more besides.

Conventional Laser Cutting Using Assist Gas

State of the art

Laser beam cutting is an established thermal cutting technology. The separation of work pieces is achieved by removal of the material within the kerf by means of a combined action between laser beam and cutting gas jet. The most typically used laser beam source for cutting is the CO_2 laser with a wavelength of 10.6 µm. An attractive alternative is represented by the high brightness solid state disk and fiber lasers with a wavelength of about 1 µm. Main advantages are in terms of power efficiency, beam delivery, beam quality, and low maintenance costs [3,4,5]. More recently, direct diode lasers (DDL) are being introduced as a new generation of sources suitable for sheet metal cutting [6,7,8]. Diode lasers are strong competitors for the previous described lasers since they are more efficient, more compact, wavelength versatile and have lower investment costs. Meanwhile, even the beam quality of direct diode lasers with 4 mm*mrad is in the range of multi mode fiber or disk lasers.

There are no real differences in quality and cutting velocity between 1 µm and 10 µm radiation as long as reactive gases are used even for large sheet thickness up to 20 mm [10] although higher absorption of the fiber laser beam by the workpiece is experimentally confirmed [11,12]. Recent results showed that the layer of liquid FeO that covers the cut front during laser-oxygen cutting has a high absorptivity to both CO_2 and fiber laser radiation. Since the oxidation reaction contributes a significant proportion of the energy to the process the differences between the 1 µm and 10 µm wavelength laser-material interactions are limited [13]. This is also confirmed by experimental results obtained for the oxygen cutting performed with DDL lasers where cuts with good surface quality and speed similar to cuts performed on a fiber and CO_2 laser were achieved [9].

The preferred technology for cutting high alloyed steel is the inert gas fusion cutting process but in this case the differences between CO_2 and disk/fiber lasers are significant. It was confirmed by many experimental studies in literature that, when cutting stainless steels with nitrogen as cutting gas and at the same power level, the achievable maximum cutting speeds with solid state lasers are much higher if compared to cutting with CO_2 lasers and this difference decreases with increasing sheet thickness (Figure 1). Furthermore, the surface roughness of the cutting edges significantly increases with the material thickness for cutting with solid state lasers as well as the tendency for dross formation (Figure 2). Fusion cutting of steel became the unrestricted domain of the fiber and disk lasers up to 2 mm but market acceptance is emerging for a sheet thickness up to 4 mm [10].

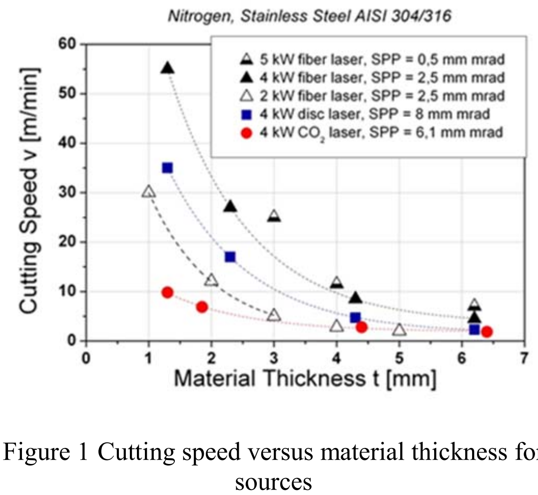

Figure 1 Cutting speed versus material thickness for sources

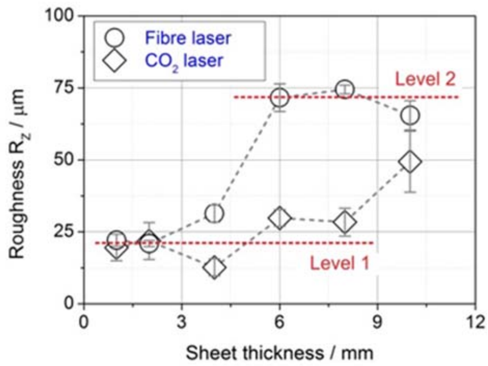

Figure 2 Roughness of cutting edge measured different laser 1 mm above bottom side

As regards the differences between CO_2 and solid-state laser cutting, various efforts have been undertaken to explain the involved phenomena as well as to overcome the limitations of the cutting edge quality. The most important explanations are related to the dynamics of material removal [4,10], the action of higher recoil pressures [14], the difference in the wavelength that affects the absorptivity behaviour at the cut front [15,16], primary losses [17], the absorbed intensity and its derivative [18], the decisive role of multiple reflections [19,20] and the temperature at the cut front [21,22,23,24]. Anyway, the different explanations are still source of controversial discussions and recent papers in literature highlighted new aspects starting from experimental, analytical and numerical modelling approaches.

Laser beam cutting with beam oscillation

One possible approach to meet current challenges in laser beam fusion cutting with high brightness solid-state laser sources is the implementation of beam oscillation techniques. This technology was originally developed for electron beam welding and found already some very interesting applications in laser beam welding. It relies on the principle that the laser beam is periodically deflected relative to the beam axis under normal processing conditions in addition to the common uniform motion along the cutting path at given speed. In comparison to conventional processes, additional variables are addressable that can be used for an increased process control, e.g. the chosen deflection method, the oscillation pattern, the frequency and the amplitudes of the pattern.

Recent experimental investigations on laser beam cutting with beam oscillations were focused on thick-section fusion cutting of stainless steel with thicknesses between 8 and 15 mm by use of high-frequency scanning devices with oscillation frequencies up to 4 kHz [25,26,27]. These investigations were performed both with a single mode and multi mode fiber laser sources. It has to be considered that the application of beam oscillation is inherently linked to a higher number of process variables that have to be set to appropriate values in order to reach optimal processing results. Specifications are required with respect to oscillation pattern, oscillation amplitudes and frequencies. Figure 3 shows the distribution of the laser power which can be achieved by means of a two-dimensional beam oscillation.

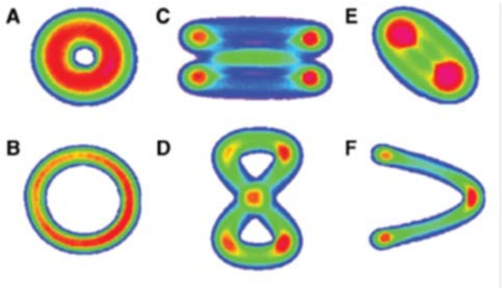

Figure 3 Beam measurement of different Lissajous figures representing the power distributions through beam oscillation

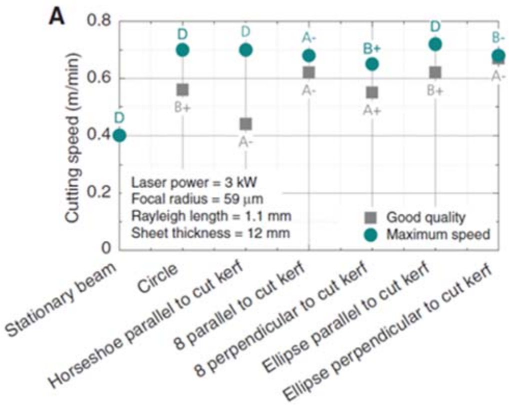

Figure 4 Cutting speed for different Lissajous figures in the case for best cutting quality and maximum achievable feed rate for 12 mm stainless steel

Figure 4 shows an increase of the cutting speed for different laser power distributions compared to laser fusion cutting with stationary beam configuration. Character A, B, C, and D are representing the cutting performance which includes surface roughness, burr formation, and cutting speed with a certain weighting. It can be clearly seen that an "8" (shape D in Figure 3) provides the best improvements in terms of maximum cutting speed as well as cutting quality. The improvement of the surface roughness (R_z) by means of beam oscillation in particular for the lower part of the cutting edge is to be seen in Figure 5.

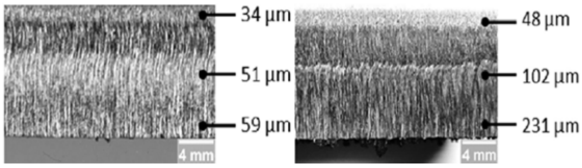

Figure 5 Appearance of the cutting edge cut with beam oscillation (left) and without (right)

In summary of the experimental experience achieved so far it can be stated that the application of beam oscillation techniques enables a control of the process characteristics of laser beam cutting and related advancements of the cutting performance in separating thick-section stainless steel. The exploitation of this technology, however, requires additional work to reveal the supposed close relationships between oscillation parameters on the one hand and particular quantities to be optimized on the other. It is expected that the further development will strongly benefit from advancements in system technology promising significantly increased oscillation frequencies by new technologies such as MEMS based scanning mirrors in the future [28].

Effect of Polarization

In order to avoid cutting results which are depending on the cutting direction stastic or circular polarized laser radiation is used both for CO_2 lasers and solid state lasers. There are many publications describing the effect of polarization in case of CO_2 lasers whereas the effect for solid state lasers is more pronounced [29]. Theoretical calculations that are based on the Fresnel equations [30] are showing distinguished absorptivity behavior at an incidence angle of 86° and 87° (Figure 6).

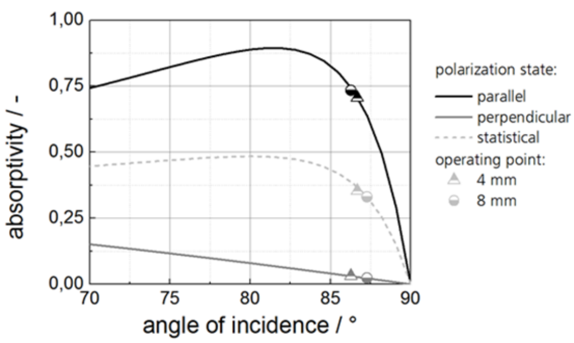

Figure 6 Absorptivity vs. angle of incidence for various-polarization states of laser radiation with 1.07 µm wavelength for molten iron

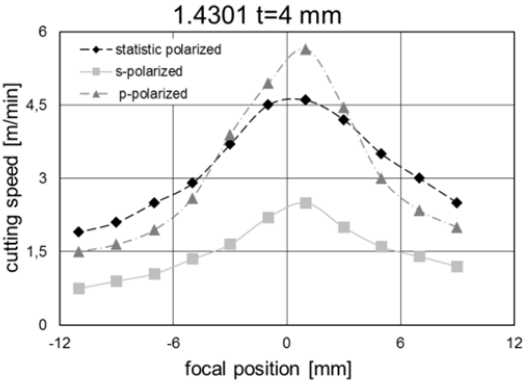

Figure 7 Maximum reachable cutting speed for a decent cut quality as function of the focal position and the polarization

A beam splitting module consisting of a Brewster windows divides the laser beam into two orthogonal linear polarized beams. The investigations were carried out by well-known experimental conditions on 4 mm and 8 mm thick stainless steel (1.4301) by means of a fiber laser with an output power of 4 kW. Compared to statistic polarized radiation cutting of 4 mm thick material with p-polarization reaches slightly higher feed rates (Figure 7). On the other hand, cutting with s-polarization results into a wider cut kerf associated with a significantly lower feed rate which is the case for both 4 mm and 8 mm thickness. In order to benefit from the positive effect the p-polarization needs to be retraced depending on the cutting direction for a 2D or 3D cutting process. Secondly, a solid state laser needs to be used that generates linear polarized radiation in the first place like single mode fiber lasers are doing. These results of cutting trials with a high power linear polarized fiber laser beam at stainless steel plates (4 mm and 8 mm) are published for the first time in [31].

Cutting with different wave lengths

The wavelength effect between CO_2 (10.6 µm) and solid state lasers in the range of 1 µm has been discussed before. As already mentioned, direct diode lasers with beam parameter product of 4 mm*mrad are entering the market. Results of fusion cutting of stainless steel with DDL demonstrated that industrial relevant cutting speeds with acceptable cutting quality were achieved. It was reported that 2 kW diode laser (BPP of 4 mm*mrad) has a similar performance as the 2 kW version of fiber or disk laser for thin sheets [7,8]. This concerns the achievable cutting speed as well as the cutting quality in terms of dross and surface roughness for a variety of metals.

Most recently, a green laser with a wavelength of 515 nm, 1 kW output power (900 W at the workpiece), and a beam parameter product of 2.5 mm*mrad was utilized for fusion cutting of copper, brass, and stainless steel. The cutting results for stainless steel and brass are comparable to cutting with laser radiation in the near IR. The feed rate for stainless steel was 1 m/min and for brass 2.5 m/min. Cutting of copper with a maximum feed rate of 2 m/min by means of an inert gas with 1 kW laser power is unique. High pressure oxygen is normally needed if fiber or disc lasers in the near IR are used to cut copper. However, a significant improvement is expected for hard to cut metals by means of green cw lasers with a power level of 2 or 3 kW (Figure 8).

Figure 8 Cut samples with cw green laser with 515 nm

Laser Remote Cutting

As shown in Figure 1 cutting velocities in the range of up to 100 m/min can be achieved for thinner sheet metal by means of high brightness solid state lasers. In reality, a medium cutting speed of less than 20 m/min can be reached for a typical laser cutting contour [32]. This results from permanent acceleration and deceleration phases of the linear axes of the flatbed cutting machine. If a laser cutting process like remote cutting is established which does not need cutting gas anymore the relative motion between laser and work piece can be done by beam manipulation by means of galvanometer scanners. The principle of the laser remote cutting process has been published several times [34], resulting cutting speeds for thin metal sheets made of stainless steel are shown in Figure 10. It is crucial to have lasers with more 500 W focused to a diameter of less than 100 µm. Laser remote cutting is a fast and cost-effective alternative to fusion cutting for cutting of thin metal of less than 1 mm thickness [33].

Remote cutting of metals

A lot of developments were taken since the first presentation of laser remote cutting with continuous-wave high-brightness lasers and a wavelength of one micron. The economical cut-able sheet thickness was increased from 100 microns to 500 microns. The problem of geometric accuracy was solved by adapted control software. A burr prevention process strategy could reduce or remove the burr which can be seen in Figure 10. The limited working field can be enlarged by on-the-fly cutting or high dynamic working field batching [34]. Finally, the material variation spreads from stainless steel to all kinds of steel, aluminum, copper, braze or even exotic ones like tungsten or lead [35]. But the process properties are as different as the material properties itself. The process is characterized by a cyclic ablation of cut kerf material as shown in Figure 9.

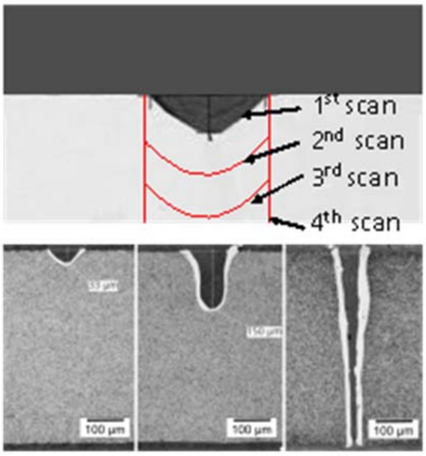

Figure 9 A cyclic ablation of a remote cutting process

The process uses a mix of molten and vaporized material in the process area. The vaporization is needed to eject the molten material out of the cut kerf. The single ablation depth depends on material, laser power, laser intensity, feed rate, and existing groove. Figure 10 shows the resulting cutting speed for different laser power and identical intensities for a single path speed of 1000 m/min as a function of the material thickness for remote cutting of stainless steel (1.4301). Absorption, heat conduction, melting and vaporization temperature of each different metal influence the optimal cutting parameters enormously. For a lot of materials the behaviour or rather the strategy to find them out is well known.

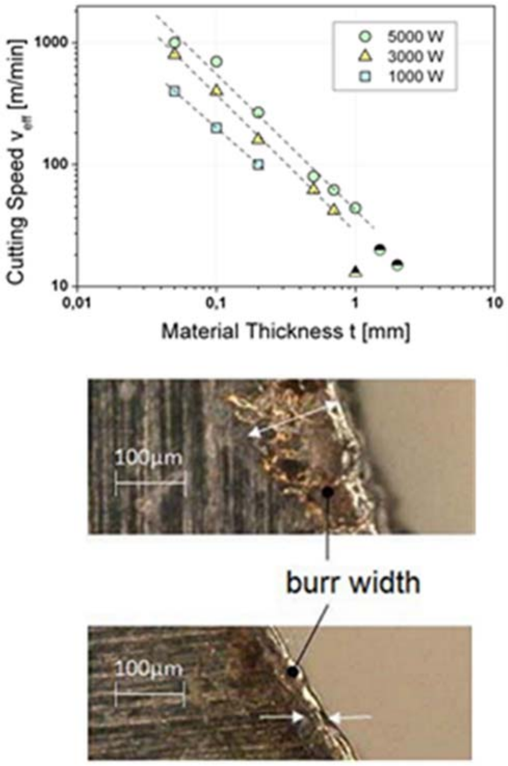

Figure 10
a: achievable cutting speed as a function of laser power and material thickness,
b: different shapes of burr

Battery foils and metal foam

Another field of laser remote cutting is to cut battery foils and metal foam. For sizing into a definite geometrical outline, state of the art manufacturing processes like punching have disadvantages. Here to name the lack of flexibility, the tool wear, the tool costs, and the possible burr that could influence the power density [36]. Concerning open cell metal foams, which were used as new current collectors, punching lead to a squeezing of the edges, decreasing the power density, respectively.

The laser remote cutting technology offers a smart solution in order to overcome those challenges. Due to the high dynamic beam deflection, cutting speeds of more than 600 m/min are reachable. Most important is the cut quality of the edge. Compared to the state of the art, the laser remote cutting achieves perpendicular edge geometry as shown in Figure 11.

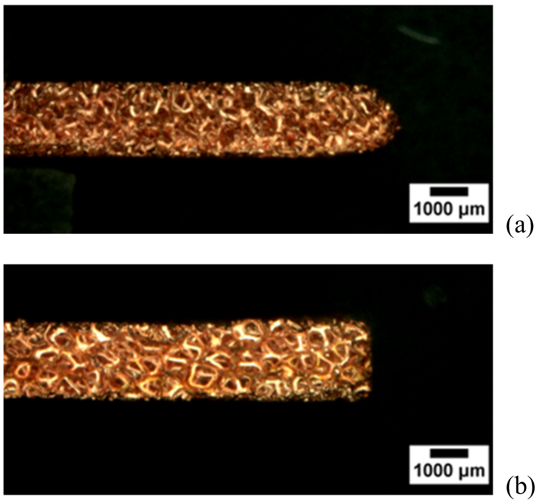

Figure 11 Edge geometry of punched (a) and remote laser cut (b) metal foam

Laser Cutting of Non-Metals

Laser cutting of non-metals was one of the first laser applications at all. Since many years, a broad variety of different materials like polymers, fiber reinforced polymers (FRP), fabrics, paper or cardboard has been cut by means of lasers within high volume production. Comparable to metal cutting, the CO_2 laser is state of the art [37]. Numerous advantages became obvious when laser cutting systems are compared to tool based cutting systems, most of which derive from the tool-free nature of the laser cutters. There are no costs for tools or any production delays for tool manufacturing. Also, tool-based mechanical cutting systems are characterized by intrinsic limitations, which result from the physical contact between the cutting edge and the material. The ability of tool-free laser cutting systems to reliably handle thin substrates is another benefit. Several fields of applications for laser cutting are possible, wherefore tailored laser cutting processes are required.

Processing of paper and cardboard

The use of laser technology opens up opportunities to substitute the mechanical cutting and punching. Because there is no melting of the paper material remote laser cutting is a suitable method to cut paper and cardboard because evaporated material can easily escape to the top of the material [38]. An image of the remote laser cutting process can be seen in Figure 12. The results of the fundamental studies show that the cutting process can be displayed reliably and reproducibly.

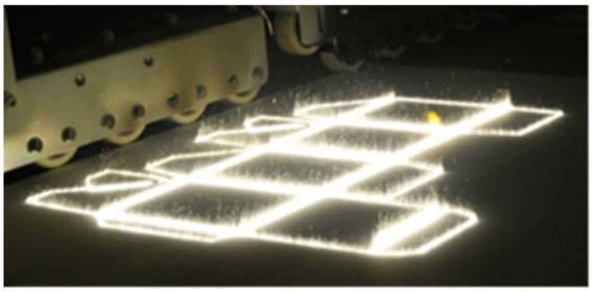

Figure 12 Process image of laser remote cutting of cardboard

Processing of thermoplastic polymers and polymer fabrics

In general, polymer materials show no laser beam absorption between the visible and near IR range. Only CO_2 lasers or UV lasers are sources to provide suitable wavelength which enables volume absorption and consequentially heating of the material through molecule or electron excitation [39]. For this and for reasons of economy the application of gas assisted laser cutting with CO_2 beam sources is and will be state of the art. Since the melting temperatures of polymers are significantly lower than of metals cutting velocities of more than 10 m/s can be achieved by laser beam sources with output power of some 100 W [37]. A typical field of application is cutting of airbag parts with gas assisted laser cutting. The basis to solve the problem of limited machine dynamics in the case of gas assisted laser cutting is the use of remote-laser technology. A concept of a single layer cutting process has been developed (Figure 13), which moves the fabric continuously underneath the scanning optics. Furthermore, the scanning optics is oscillating perpendicular to the feed direction of the fabric. Material widths of up to 3 m are possible to cut [40]. For remote processing continuously operated (cw) brilliant beam sources with 2 kW or more power are required. Figure 14 shows remote laser cut airbag parts and the appearance of the cutting edge.

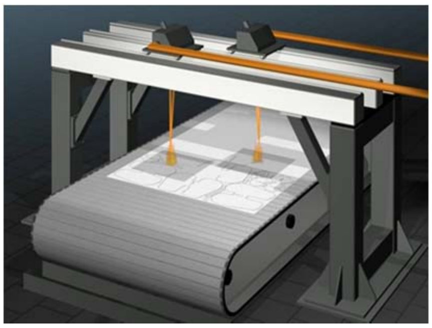

Figure 13 Principle of ContiLas Technology

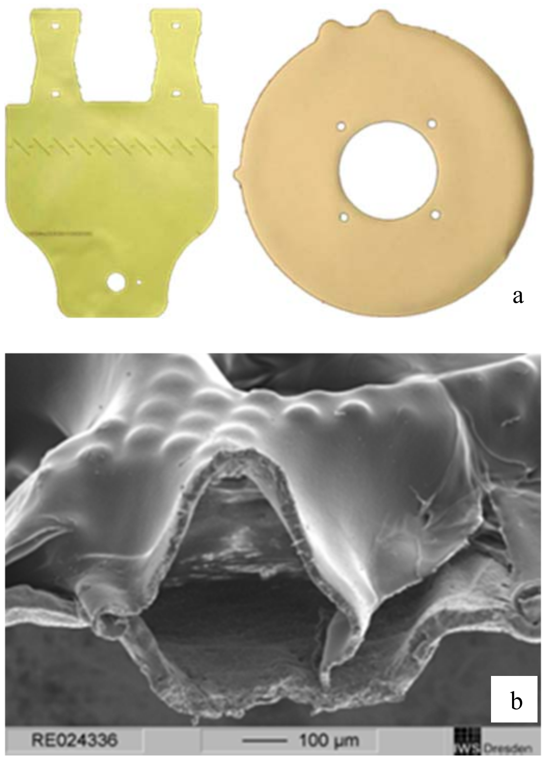

Figure 14 Laser cut airbag parts (a) and SEM image of cutting edge (b)

Cutting of FRP

The main challenge in the field of composite materials is the improvement and optimization of existing production processes and procedures [41]. Conventional methods such as water jet cutting and milling are subject to wear. In opposite to that, laser cutting as a wear and force free process can be a tool of the future. Similarly to processing of thermoplastic polymers gas assisted laser cutting with CO_2 beam sources is already state of the art. Cutting FRP with lasers is an ablation process including melting, sublimation and decomposition of matrix and reinforcement material. If the thermal and optical properties of the individual materials are close together, like aramid reinforced polymers or glass fiber reinforced polymers, good cutting qualities accompanied with high feed rates of up to 13 m/min are possible. When processing on carbon fiber reinforced polymers (CFRP) a longer interaction time has to be accepted. Due to the missing molten phase the material has to be heated up to sublimation temperatures of about 3700°C. Due to sublimation of the material over the total thickness an evaporating pressure occurs that counteracts with the processing gas. Both, the evaporating pressure and the long interaction time between laser beam and material leads to a huge heat affected zone (HAZ) with cutting edges geometrically disordered (Figure 15a).

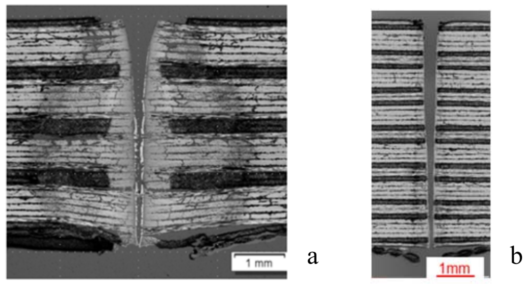

Figure 15 a: Cross section of gas assisted laser cutting (4 mm CFRP, Multimode Fiber Laser, P_L = 3 kW, v = 0.05 m/min), b: Optical micrographs showing the cyclic remote laser cut (PL=3.0kW, v=1m/s, 3 parallel lines n = 10)

Due to the challenging material behavior caused by the inhomogeneity of heat conductivity and sublimation temperatures for the matrix and fiber material, high feed rates and brilliant beam sources are needed to process the material with acceptable heat affected zones (HAZ). Several investigations have shown the advantages of remote laser cutting with brilliant beam sources with a wavelength in the range of 1.06 – 1.09 µm compared with gas assisted cutting (Figure 15b). Increasing cutting quality is achieved by the minimization of the interaction time between laser and material. Here the use of high brillant cw and pulsed laser systems in combination with a scanning technology is the key to process on fiber reinforced polymers. In general, a complete trough cut is performed by a cyclic material removal until the cutting kerf is formed (Figure 16). Nevertheless the ablation rate of pulsed systems is lower and not suitable for industrialized cutting processes [42]. By means of this technology it is possible to cut pliable reinforcement textiles, semi-finished as well as near-net-shape parts.

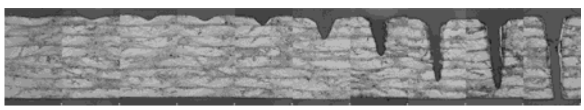

Figure 16. Cyclic removal of CFRP, from left to right increasing number of repetitions (2 mm CFRP, Single Mode Fiber Laser P_L = 1 kW, v = 1 m/s, n = 10)

Latest developments

Wavelength adapted remote laser cutting: The absorption behavior of matrix and fiber material differs drastically. Therefore, a processing system, which enables high speed beam deflection with different wavelengths, has been developed. The optimum absorption behavior of the polymeric matrix is utilized when irradiated with radiation of λ=10.6 µm in order to vaporize the polymer matrix. At the same time a sufficiently high intensity can be achieved by the good focusability of the solid-state laser beam (λ=1.07 µm) to sublimate the reinforcement fiber content. Figure 17 shows the laboratory setup for wavelength combination of a CO_2 laser (3 kW cw) and a solid state laser (1 kW cw). The solid state laser beam path (red) and the CO_2 laser path (yellow) have to be combined and imaged at the same focusing point.

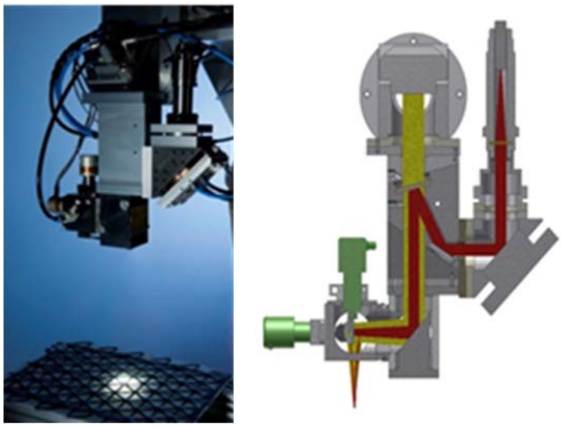

Figure 17 Multiwavelength laboratory equipment (left), schematic of cross section (right)

Fundamental strategies like simultaneous treatment have been carried out to evaluate the process efficiency. First results have shown that a laser beam power combination of 25% CO_2 and 75% solid state laser is suitable to increase the cutting efficiency compared to single solid state laser cutting by 50%. Prior investigations have shown a significant raise of absorbed proportion of the irradiated laser beam at a wavelength of λ=1,07 µm at high fiber volume content. [43]. It is assumed, that the evaporation of the matrix material lead to a locally increasing fiber volume content. Further investigations are needed to tap the full potential of the wave length combination.

Outlook

Laser cutting in general will gain a higher market share which results from smaller production batch sizes, from expensive punching tools due higher material strength, and from dropping investment costs for laser cutting machines. Solid state lasers like disk and fiber lasers will take over the market for laser cutting of metals whereas CO_2 lasers will still dominate the market for cutting of non-metals. Direct diode lasers as well as high power green lasers with a beam parameter product which is suitable for laser cutting will emerge. Whether these lasers will penetrate the market for laser cutting depends mainly on the performance of these lasers and on the total cost of ownership.Another trend is to further increase the automation level of the laser cutting machines e.g. to implement in-situ process and quality control. Closed loop processing will enable the automatic operation of laser cutting machines which will help to further reduce the costs per cut piece.

Acknowledgement

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