Trends and basic investigations in High Power Laser Material Processing

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Abstract

Continuous application development in combination with advancements in laser sources and accessories enabled several trends in laser material processing. This paper will show investigations in process understandings based on modern process diagnostics like high speed videos. We will focus on applications related to thick sheet welding, welding with wobbling techniques, hot forming materials and dissimilar materials. Additionally we link the gained process understandings to possibilities how to successfully introduce the knowledge in industrial applications.

1.0 Introduction

Ongoing improvements of 1 µm disk and fiber lasers in combination with a consequent application development lead to a high number of applications which have been transferred from lab status to industrial 24/7 applications. In this paper we will show interesting results in thick sheet welding of mild and stainless steel. We continued our investigations on metal vapor plumes and focused on welding with shielding gas in combination with removal of the plume itself. Additionally the investigation of different batches of mild steel generated interesting results. We could achieve comparable results regarding process windows of 1 µm compared to 10 µm CO2 lasers, which are still the benchmark regarding high quality and process windows in very thick sheet welding.

On the other hand, trends in electricity and batteries (e.g. for cars) increase the interest for high power thick sheet welding of copper materials. Hence we investigated the behavior of copper welding in thin and thick sheets up to 6 mm thickness. Beside the possibility of welding thick materials there is a clear trend of weight reduction and hence of light weight constructions. Therefore more and more lightweight materials like aluminum and hot formed steels are used. We will show weld preparations of hot formed steels with nanosecond short pulse lasers (removal of AlSi layers) and focus on further process steps like welding and cutting.

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2.0 Approaches to optimize application results in mild and stainless steel

2.1 Metal vapor plume behavior at mild and stainless steel

Based on the investigation shown in [14] we have demonstrated a clear influence of the metal vapor plume on penetration depth and spatter ejection. The spatter behavior can be traced back to melt pool oscillations: the out flowing metal vapor irregularly tilts along the laser axis in all directions with high dynamics. On the other hand, since there is a strong interaction between the metal vapor and the incident laser beam [8, 9, 10, 11], this leads to a spatially and temporally inhomogeneous coupling of the laser into the work piece.

When the feed rate is increased the capillary front becomes progressively more flat and the weld pool dynamics increases significantly at 6 m/min. As a result, the weld pool starts to bulge behind the capillary aperture and becomes more turbulent. This produces a slightly inhomogeneous upper bead. At this feed rate a transition zone between two different process regimes at low and high welding speeds is attained.

When the feed rate increases further to 8 m/min, larger amounts of molten spatters fly off mainly from the rear of the capillary opposite to the feed direction (see fig. 3). Apart from contamination, this causes a considerable loss of material in the seam whereby no weld reinforcement occurs and therefore the strength of the seam is reduced, especially for dynamic loading. This behavior can be explained by a stronger mean inclination angle of the keyhole, whereby the absorption of laser power occurs increasingly on the capillary front [12]. From this follows a stronger overheating of the melt and a resulting stronger vaporization rate, which is the driving force behind all dynamic effects in laser welding [4].

To reduce the influence of the metal vapor a coaxial nozzle was designed (figure 2). Compressed air is blown in the direction of the workpiece to cool down the metal vapor and blow it out of the process area. The interaction length of the laser beam and the metal vapor is reduced to a minimum. Below 8 m/min the effect is clearly visible in figure 1 and 3.

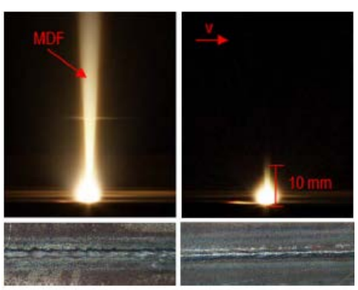

Figure 1: Lateral recordings at different times at 3 m/min feed

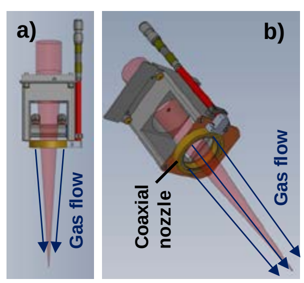

Figure 2: Coaxial nozzle connected to a cross jet

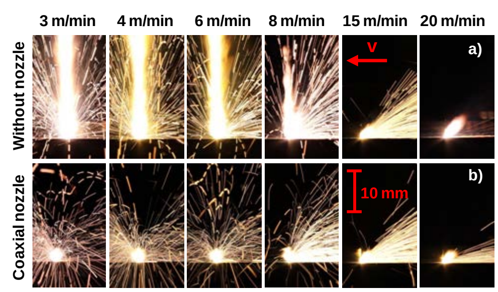

Figure 3: Lateral observation with and without using a coaxial nozzle at different feed rates

Since the laser power can be coupled into the work piece spatially and temporarily more homogeneously, the vaporization inside the capillary is more homogeneous as well. Due to this, the capillary becomes stabilized and the loss of material due to spattering is reduced for feed rates of $v < 6$ m/min compared to welds without nozzle, whereby a higher upper bead quality can be obtained (see fig. 1). Besides this, using the coaxial nozzle reduces the upper seam width and increases the penetration depth (see fig. 4), as well as the penetration depth stability.

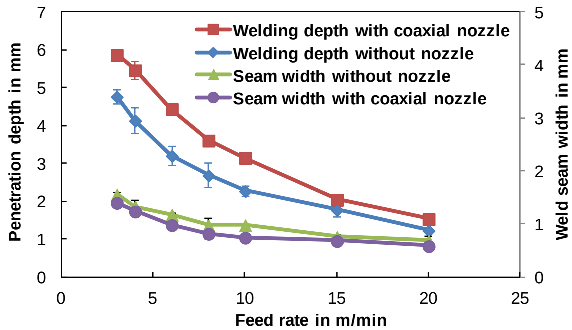

Figure 4: Penetration depth and seam width with and without the coaxial nozzle

The described effects have been investigated on mild steel when welding without any shielding gas. The next logical step is to transfer the results to stainless steel and hence to oxide-free welds where in general shielding gas is used. The experiments have been done on 3 mm stainless steel 1.4301 with a TruDisk 4001, a laser light cable diameter of 200 µm and spot sizes of 300 µm (1.5 magnification). Further parameters have been set to: feed rate 3.4 m/min, laser power 2.4 kW, defocusing of – 2 mm, flow rate of Argon of 40 l/min. Clear improvements can be seen in figure 5. The metal vapor plume was suppressed and more laser power could couple into the specimen more homogenously and hence smooth welds have been generated.

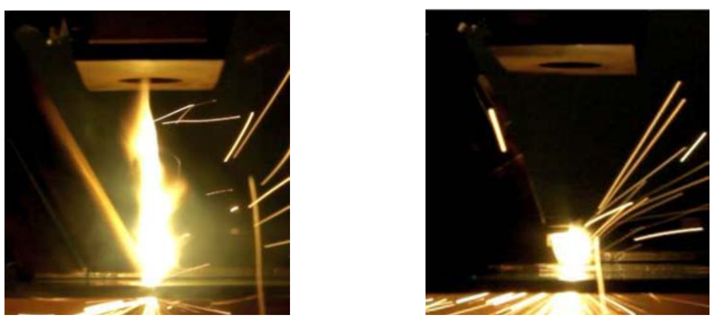

Figure 5: Welding of stainless steel 1.4301 with shielding gas lateral nozzle

2.2 Welding of different batches of mild steel

Partial and full penetration welds in mild steel S235 are carried out by a Yb:YAG solid-state disk laser (TruDisk 16002) with a wavelength of λ = 1.03 µm and a beam parameter product of 8 mm*mrad from TRUMPF Laser- und Systemtechnik GmbH. Due to a higher achievable penetration depth and a higher weld seam quality the focal position FP was set -2 up to -3 mm into the workpiece [1] and the described coaxial nozzle was used. A high speed camera on the root side in combination with an EOS 7D and another high speed camera on the top side allows a very detailed visualization of the process.

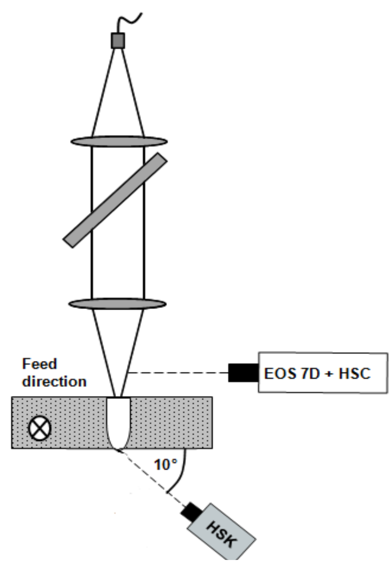

Figure 6: Experimental setup

For full penetration welds the weld seam quality can be strongly influenced by weld parameters. The laser power has been varied from 7.75 kW to 13 kW. The trials have been performed on 12 mm thick mild steel S235 and welding speed was kept constant at 1 m/min. Typical behaviors of former analysis [14] are shown in figure 7. Three main regimes can be seen: too low power leads to either just a partial penetration or a dropping effect on the root side. When Increasing the laser power to 8.5 up to 10.2 kW a very good weld seam can be achieved on the bottom side as well as on the root side. Laser powers greater than 10.2 kW lead to melt ejections and hence to a loss of material.

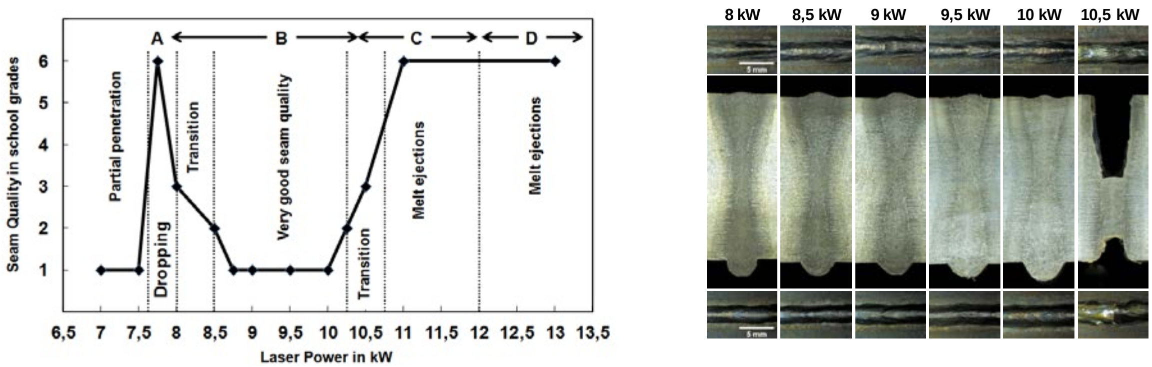

Figure 7: The influence of laser power on full penetration welds on 12 mm mild steel sheets at v = 1 m/min.
Left side: The quality is rated in school grades, where 1 equals very good quality
Right side: Weld seam quality on top side, cross-sections, and weld seam quality on root side

Based on the shown experiments and results we looked into different batches and different suppliers of mild steel S235. On the left hand side of figure 8 welding results of batch 2 and supplier 1 is shown. We see the typical regimes of poor quality (partial penetration, dropping) below 7.7 kW laser power. Increased laser power of 8 to 9 kW lead to good weld seam qualities. Hence a process window of 1 to 1.5 kW was determined. Batch 3 was performed under the same boundary conditions but the results look quite different (figure 8, right hand side). Even at low power levels of 7 kW a full penetration and good weld seams can be obtained which means that less power is needed for a full penetration weld. With power levels up to 9 kW still good weld qualities are visible and hence a process window of around 2.5 kW was possible. Such big process windows are in general known from welding with 10 µm CO_2 lasers.

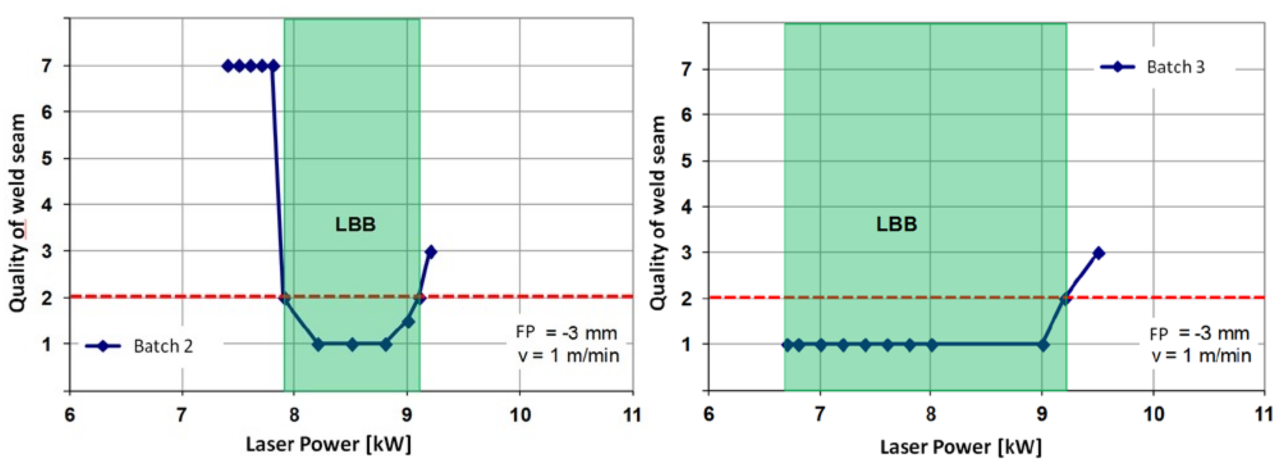

Figure 8: The influence of laser power on full penetration welds on 12 mm sheets at v = 1 m/min.
Left side: Batch 2, Supplier 1; Right side: Batch 3, Supplier 2
The quality is rated in school grades, where 1 equals very good quality

Visual inspection during the weld process showed slight spatters to the bottom side which lead to the assumption that the key hole is open throughout the entire welding process. At other batches a different behavior is seen. The melt flow is redirected to the workpiece and almost no spatters are ejected to the bottom side [14].

Figure 9 shows the weld seam qualities of batch 3, supplier 2 at different power levels. One can see a full penetration weld at 6.8 kW with very good weld seam qualities.

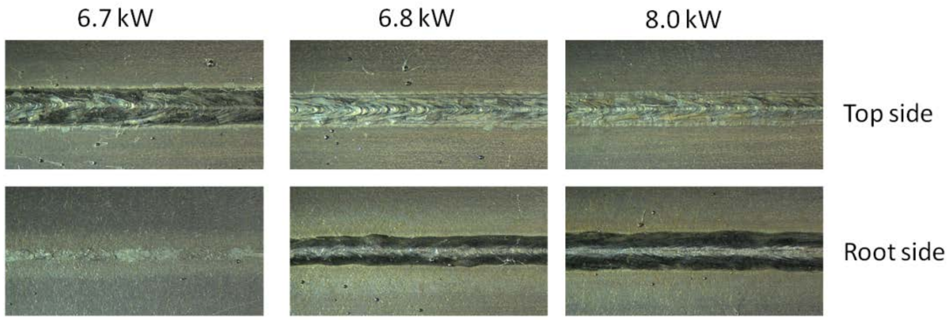

Figure 9: Weld seam qualities of Batch 3, Supplier 2

3.0 Thick sheet welding of copper

Beside welding of thick sheets in mild and stainless steel copper is gaining more and more interest due to the trend in e-mobility and electricity. Hence high power welds with a TruDisk 16002 and laser powers between 6 to 16 kW have been performed. Due to its high heat conductivity, its low absorption of the infrared wavelength and the low viscosity of the copper melt there are some challenges when welding thick copper materials. To overcome the heat conductivity typically high power levels at high feed rates are used. Figure 10 shows Cu-ETP welds at thicknesses of 6 mm and laser power levels of 7.5 to 12.5 kW. Focal position was set to + 2 mm at a spot size of 200 µm.

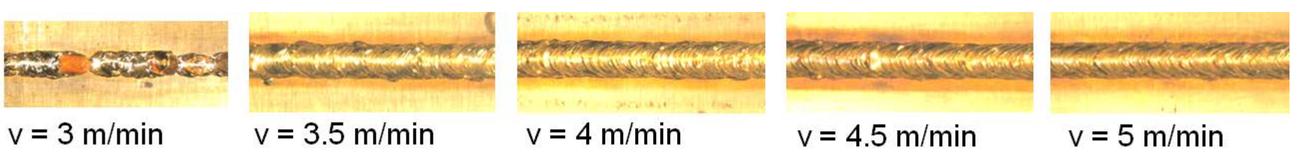

Figure 10: Weld seam of CU-ETP at different feed rates and different power levels (7.5 – 12.5 kW)

One can see a smoother weld with increasing feed rates. On the other hand measurements show that the welding speed does not have a significant influence on the penetration depth. Additionally to Cu-ETP we investigated CuSn6 having a 5 times lower heat conductivity. Hence 80 % more energy is needed to fully penetrate Cu-ETP (Figure 11).

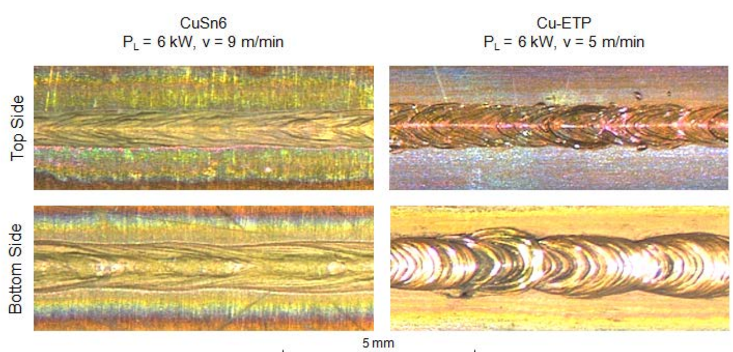

Figure 11: Comparison of CuSn6 and Cu-ETP

Having this knowledge we developed different process strategies which are shown in figure 12.

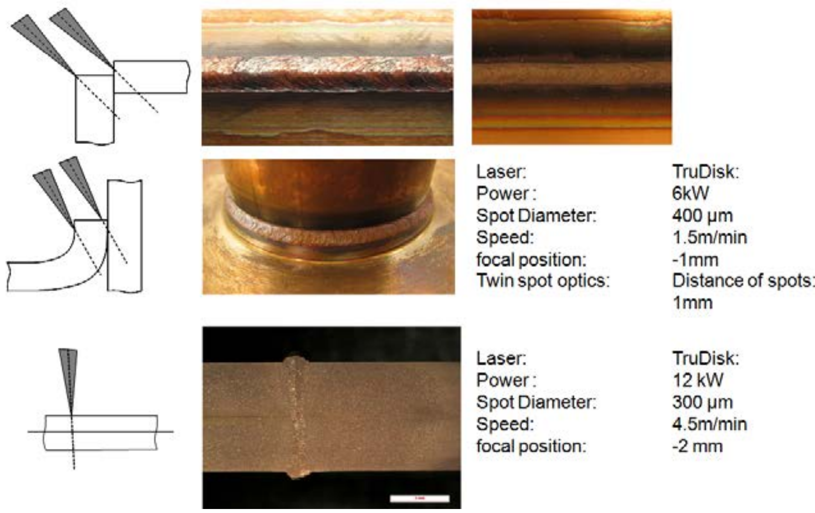

Figure 12: Different welding strategies at copper welding

4.0 Welding and weld preparation of hot formed steel

While the cutting of already formed parts is the most wide spread application, there are a variety of other laser applications when processing hot formed steel which either enable processes like welding or help to be more efficient compared to other processes. A new trend in the hot forming market is the use of tailor welded blanks to further reduce weight or to combine two different material properties in one blank. AlSi coated material (see figure 13) is the most wide spread material in this industry. The aluminum content of the coating poses challenges to weld the blanks. When aluminum gets into the weld seam the mechanical properties of the weld are weakened. Therefore the objective is an efficient elimination of the AlSi coating on the one hand and to assure corrosion prevention in the welding area on the other hand. Mechanical processes cause significant wear on the grinding tool and leave significant amount of aluminum. However laser ablation is a solution for this application allowing an efficient and repeatable process. The use of disk based ultra short pulse nano-second lasers and the development of new parameters allow so far unknown processing speeds and ablation rates for this application. The high processing speeds make short pulse nano-second lasers the most efficient tool to remove the AlSi coating.

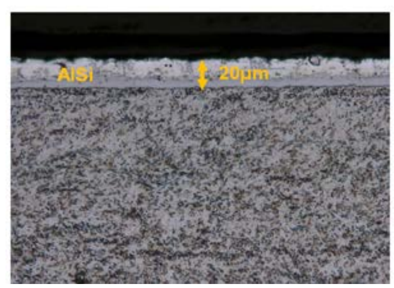

Figure 13: AlSi layer on base material

The experiments have been performed with a TruMicro 7050 laser at pulse durations of 30 ns and average power of 750 W. Different pulse shapes (round spot, square spot, line spot) have been investigated and compared. We have shown that a line focus lead to highest process efficiencies and - with adapted parameters - to a full removal of the AlSi coating. The results have been verified with SEM and EDX measurements (see figure 14).

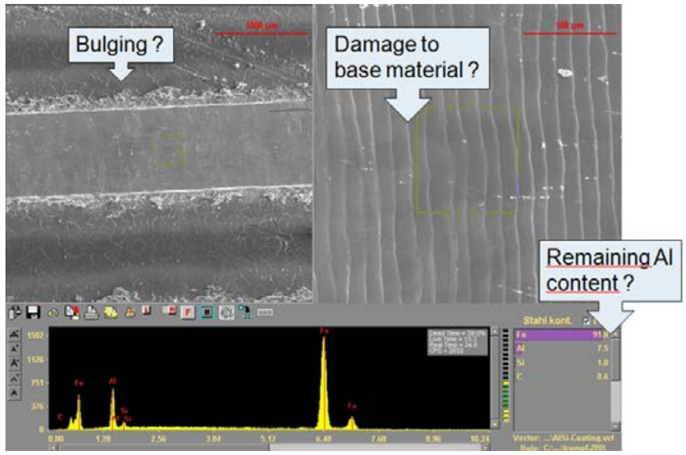

Figure 14: SEM and EDX measurements of removed AlSi layers

3.0 Conclusion

In this paper we demonstrated the important link of process understanding, continuous development of accessories and laser sources leading to economical solutions for industrial 24/7 applications. Thick sheet welding of mild and stainless steel as well as thick sheet welding of copper was demonstrated with high power cw disk lasers. Additionally the trend in light weight constructions lead to the use of hot formed steels. With short pulsed laser systems in addition to an optimized line focus an efficient removal of AlSi layers was performed and hence successful welds can be obtained.

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