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RESEARCH PAPER

Plasma welding with a superimposed coaxial fiber laser beam

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Abstract A new laser-assisted plasma arc welding process with a coaxial arrangement of arc and plasma was developed. A low-power fiber laser beam (λ_{Yb}=1.07 μm) with maximum power of 300 W is guided through a hollow cathode. This combined process is of special interest regarding the costs and power input. Experiments show higher arc stability and welding efficiency due to the additional laser power. Of special interest for the investigations were the reasons for the synergic effects. Therefore, the experimental setup was enhanced by a laser displacement inside the hollow plasma cathode. The laser spot can lead or trail the arc, but the laser beam remains virtually coaxial to the arc. The different spot positions influence laser absorption on the surface and the creation of the weld seam. In order to maximize the effect of different temperature distributions due to the laser, stainless steel AISI 304 (X5CrNi18-10) was used as base material. Different plasma nozzle diameters were investigated on their influence on arc stabilization and melting efficiency by additional laser radiation. Hypothesis of the work presented is that higher arc stability and weld efficiency is caused by effects at the work piece and not in the arc column.

Keywords Laser enhanced plasma welding · Hybrid laser arc welding · Laser-arc interaction · Arc stabilisation · Hollow cathode

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1 Introduction

Arc joining processes as well as laser joining processes have specific advantages and disadvantages. Hybrid processes aim to combine both processes in order to compensate disadvantages and create synergies. Most of the literature as well as industrial applications refer to hybrid processes with comparable power inputs of laser and arc processes, which produce one energy source. Aim of these works is to influence metallurgy of the weld seam, to reach higher welding speeds and deeper penetration [1]. Industrial applications of today are mainly focused on GMAW hybrid processes, which are an important process especially in today's shipbuilding industry. Here, hybrid processes show good welding performance, high process stability, and weld seam quality. Overviews are given by Seyffarth and Krivtsun [6], Bagger and Olsen [7], Mahrle and Beyer [8], and Olsen [9].

Interactions between a gas tungsten arc welding (GTAW) (TIG) process and a CO_2 laser were investigated first by Steen and Eboo [2] and Steen [3]. It was found that the arc root point can be influenced and stabilized by a laser spot. Constricted arc root points (anodic) as well as more steady current and voltage runs could be observed. Welding speed and penetration were increased by adding the laser beam. Combined laser–GTAW process were investigated by Beyer et al., and differences using a Nd:YAG or CO_2 laser are documented [4, 5].

Another field investigated is the interaction of low-power laser beams and arcs. Here, the laser is used to stabilize the root of a GTAW arc, the main heat source is the arc. Such processes were investigated, mainly based on Steen's first works, by Cui et al. [10, 11], Finke et al. [12], and Decker et al. [13] in the late 1980s and early 1990s. It could be shown that even little additional laser power in the range of some 100 W can increase welding speed and penetration. This could be led back to significantly increased current densities compared to conventional arc processes. Hermsdorf [14] and

Kling [15] used a Nd:YAG laser with a wavelength of 1064 nm and a diode laser with a wavelength of 808 nm and demonstrated interactions independent of the wavelength used.

First experimental investigations on laser-assisted plasma welding (LA-PAW) were presented by Fuerschbach [16]. He found significantly deeper penetrations for the LA-PAW process than for single laser or plasma welds. The authors' previous studies of laser-assisted plasma welding using a fiber laser was carried out with two different experimental setups. The results using separate arrangements of plasma and laser process (both inclined) are published in [17]. The results show that weld efficiency can be increased for all materials. Especially for aluminum work pieces, the arc root point can be guided by the laser. It could be shown that the arc can be moved more than 3 mm away from the axis of the plasma torch by moving the laser spot. Using a highly focused laser spot on the work piece, the voltage drop on aluminum decreased considerably, when the laser beam is switched on. For mild steel and stainless steel, the voltage rises slightly [18]. Nevertheless, maximum effects on stability and melting efficiency were achieved by using a moderately defocused laser.

In subsequent studies, a new coaxial experimental setup of arc and laser process using a hollow cathode was developed. First results of experiments with aluminum, mild steel, and stainless steel were done [20, 21]. The new coaxial setup showed even better results due to the optimal angle of arc and laser beam perpendicular to the work piece. Even with very high welding speeds up to 40 m min^{-1}, unstable arc attachments could be prevented by little additional laser power. Figure 1 presents the top views of the plasma process and the laser-assisted plasma process on stainless steel.

Nevertheless, the mechanism of the interaction between arc and laser process is not well-understood yet. In some publications, the optogalvanic effect (OGE) is claimed to cause the synergic effects by increasing the electric conductivity of the arc plasma [22]. However, most experiments of OGE were carried out in glow discharges, e. g., [23], where laser-excited ionization can occur.

By the results of our own former investigations, the hypothesis was provoked that the synergic effects are actually caused by a changed temperature distribution on the workpiece surface. Higher surface temperatures raise the level of laser absorption on metals, e. g., for aluminum about 4 % at 0 °C to 13 % at 1,400 °C [24], and influence the arc attachment as well.

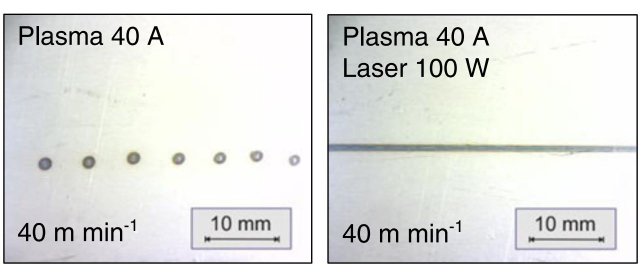


Fig. 1 Stabilization of arc root point on 6-mm stainless steel AISI 304 by additional laser power

In order to differentiate the influences inside the arc column and on the workpiece surface, we modified our coaxial plasma-laser torch to switch the laser spot position slightly related to the electrode axis. Any interaction inside the arc column such as increased electric conductivity should not be influenced, but the temperature distribution is influenced by the relative movement of the laser spot and the arc.

2 Experimental setup

The experiments were carried out using a modified plasma torch ABIPLAS WELD 150 with coaxial laser transmission of laser radiation, Fig. 2. This setup reaches best stability for the plasma arc and best absorption at the surface for laser radiation. In order to enable laser deflection in direction of feed, the previous coaxial setup was developed further with a wider drilled hole in the tungsten electrode. Therefore, leading or trailing positions of the laser spot on the surface of the workpiece could be adjusted.

Plasma nozzles of Ø 1.2 and Ø 2.6 mm were used. The working distance between plasma nozzle and workpiece was constant at 6 mm. Argon was used as plasma gas and shielding gas.

An EWM plasma power source Tetrix 400 was used in DC–EN mode with a current of 40 A. The applied laser source was an IPG single-mode fiber laser IPG YLS 400 (400 W, focal length 1254 mm, Rayleigh length 32 mm), with a wavelength of 1.07 µm. Laser power was varied between 50 and 200 W. The laser spot on the surface had a diameter of 300 µm. This adjustment was necessary due to the guiding of the laser beam through the hollow cathode. Nevertheless, previous investigations showed best synergy with a moderately defocused spot [18].

The welding trails were carried out with fixed torch and laser optic. The workpiece is moved with velocities of 0.75 and 1.25 m min^{-1}. To realize different laser positions, the direction of feed is changed. The experiments were carried out in the following way: First, the plasma process is established for 100 mm alone, after this, the laser is switched on and the combined LA-PAW process works for another 100 mm. At the end, the plasma process is switched off, and the laser beam is active for the final 100 mm. This setup allows the direct comparison of process parameters, weld seam appearance, and quality as well as the comparison of cross-sections on one single plate without influences by changing boundary conditions. The base material investigated was stainless steel AISI 304 (X5CrNi18-10) of 1 and 2-mm thickness.

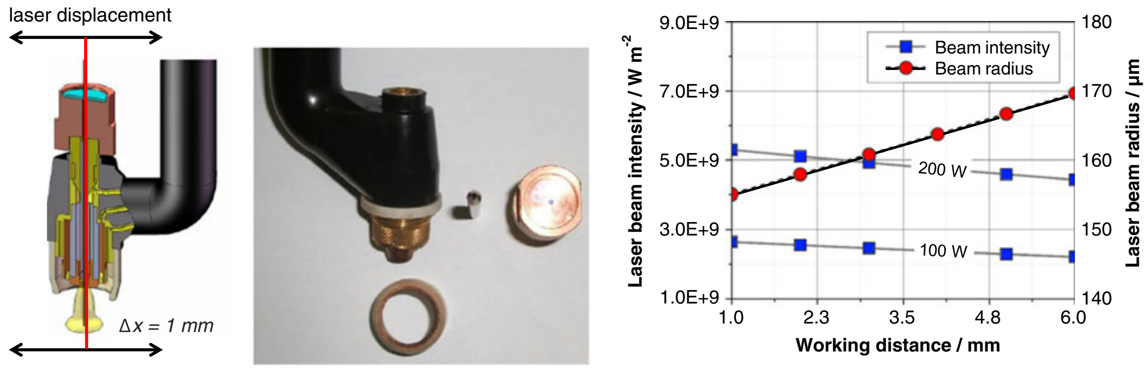


Fig. 2 Experimental coaxial setup of the plasma torch with a hollow cathode

For documentation of the experiments, a high-speed camera Photron SA4 with a frame rate of 5 kHz and a synchronized data acquisition system Dewe-30-8 with a sample rate of 100 kHz were used. A photodiode with a central wavelength of 520 nm and a full width at half maximum of 10 nm was used to measure the radiation of iron (without local resolution).

3 Results with Ø 2.6-mm plasma nozzle

Welding trials on 1-mm stainless steel with leading and trailing laser spot were carried out. Figure 3 shows the results of a change of 1-mm laser spot deflection relative to the plasma axis (dotted line in Fig. 3, very left). The laser spot was moved in the direction of feed or in the opposite direction by changing the feed direction on the workpiece. The welding speed was 0.75 m min^{-1}.

It can clearly be seen that different laser spot positions (100 W, Ø 300 µm) on the workpiece lead to a tremendous effect in penetration and weld seam appearance. While with a leading laser spot, less than half of the sheet thickness is melted; with a trailing laser, it leads to a complete root penetration. The cross-section area is more than doubled with the very same laser power (0.49 to 1.14 mm^2). The efficiency rises from 0.58 to 1.33 mm^{-2} kW^{-1} (cross-section area to power of arc and laser). The top views of the weld seams (Fig. 3, right) show a uniform and symmetric weld seam for the leading laser; whereas for the trailing laser, the seam of the arc is more independent from the laser seam.

In trailing position, additional welding trails with 50-W laser power (Fig. 4) were carried out. Compared to the results

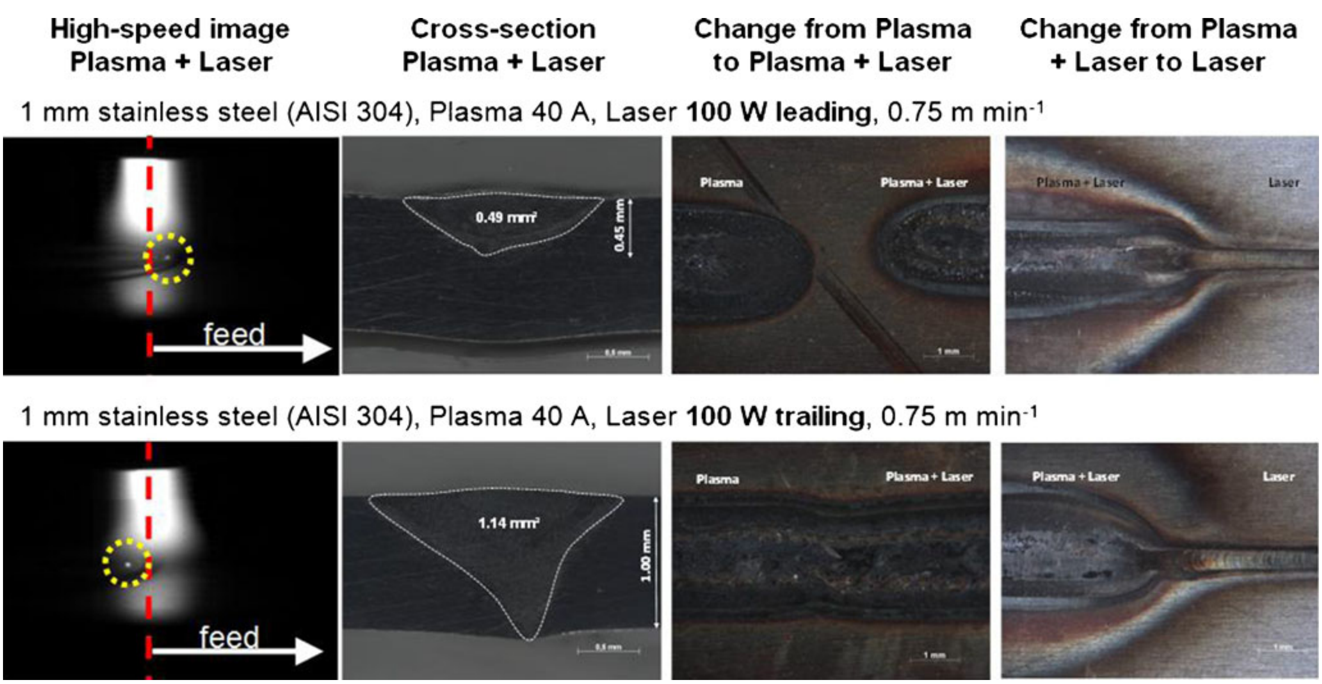


Fig. 3 Influence of laser positioning (leading or trailing) on the arc, the penetration, and the weld seam appearance (100-W laser power, plasma nozzle Ø 2.6 mm)

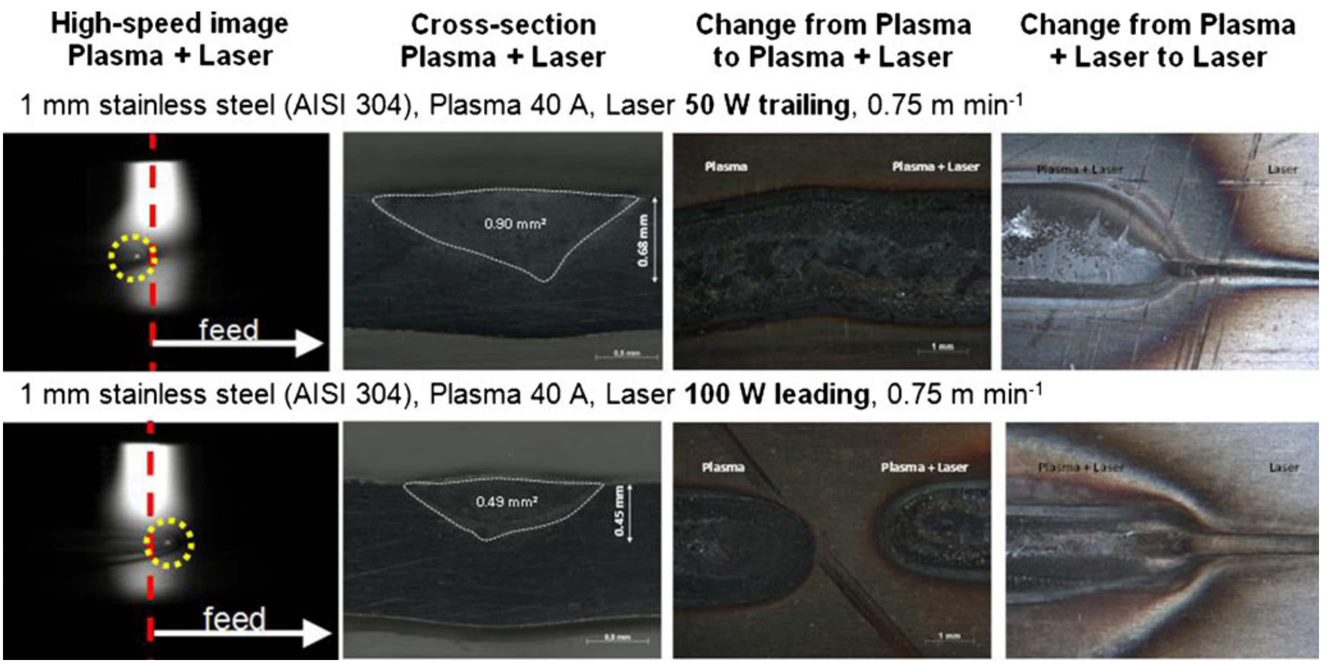


Fig. 4 Influence of laser positioning (leading or trailing) on the arc, the penetration, and the weld seam appearance (50 and 100-W laser power, plasma nozzle Ø 2.6 mm)

for a 100 W leading laser, it can be seen that even with half the laser power but a trailing position, a much wider (0.90 to 0.49 mm^2) and deeper (0.68 to 0.45 mm) weld pool is achieved. The efficiency rises from 0.58 to 1.07 mm^{-2} kW^{-1}. Regarding the surface of the weld seam, the asymmetric appearance is even more obvious with the reduced laser power of 50 W. A much wider weld pool occurs with a trailing 50-W laser spot than with a leading laser spot of 100 W.

It can be concluded that the leading laser has a big influence on the arc attachment. This effect should be visible in the voltage run. In fact, the analysis of the voltage runs confirms that the voltage drop due to the leading laser positioning is three times as much as the voltage drop due to the trailing laser position (1.8 to 0.6 V), Fig. 5. Furthermore, the voltage drop with the trailing laser is almost the same for 50 and 100-W laser power.

Welding trails on a 2-mm plates show considerably smaller penetration with trailing laser than on 1-mm plates with trailing laser (0.46 mm to complete penetration), Fig. 6. Furthermore, a more symmetric surface of the weld seam of laser and arc is achieved than on 1-mm plates. A decrease in arc voltage of about 1.2 V was measured when the laser was switched on; on 1-mm plates, the voltage drop was about 0.6 V, Fig. 7.

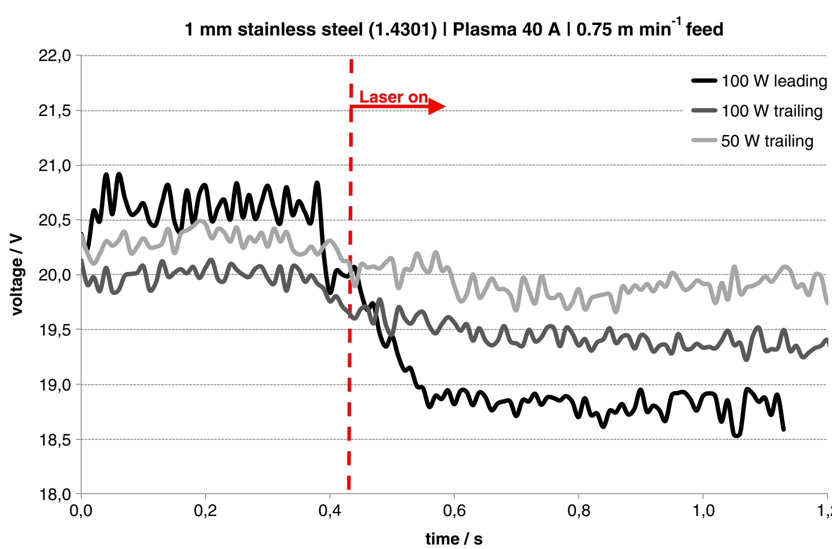


Fig. 5 Influence of laser positioning (leading or trailing) on the voltage run (laser power 100 W, plasma current 40 A, linear feed 0.75 m min^{-1}, and plasma nozzle Ø 2.6 mm)

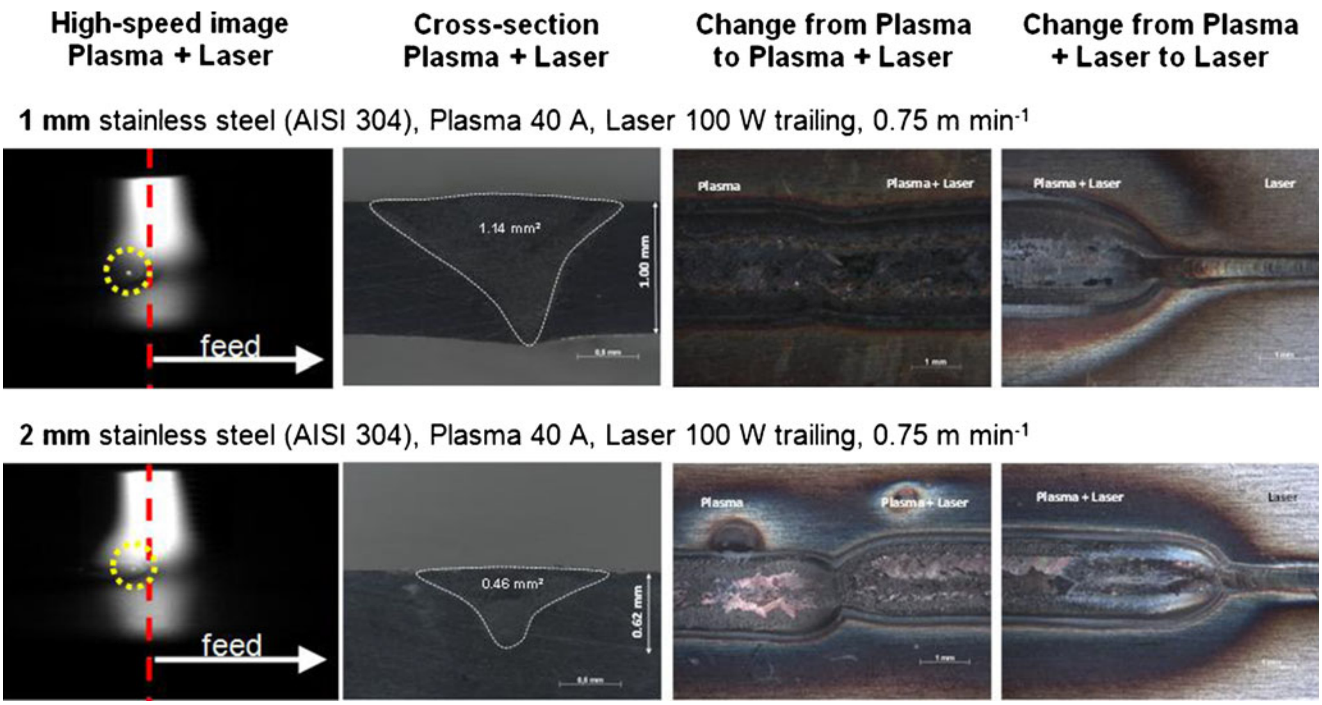


Fig. 6 Influence of sheet thickness on arc, penetration, and weld seam with a trailing laser position (plasma nozzle Ø 2.6 mm)

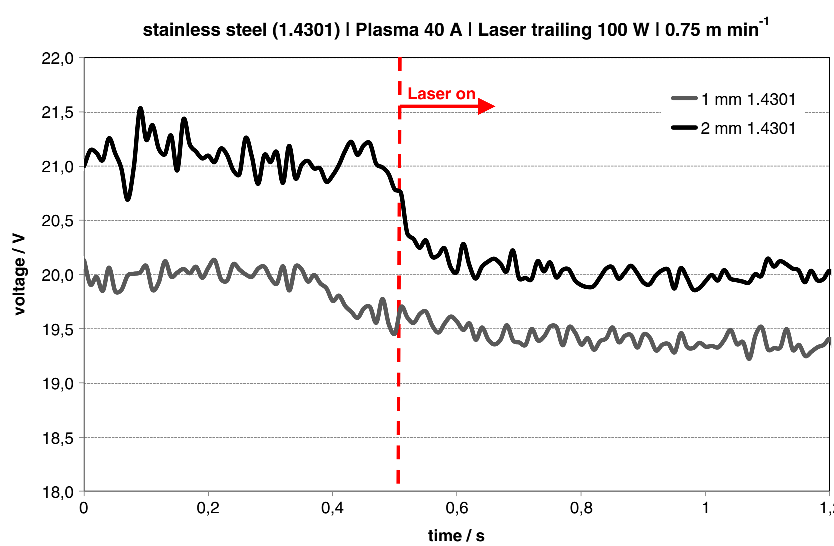
At first, it can be seen that the decrease in the arc voltage corresponds to the guiding effect of the laser, respectively, to the arc stabilization. But secondly, it can be seen that the decrease in the arc voltage does not necessarily lead to an increase in penetration, respectively, weld efficiency.

4 Results with Ø 1.2-mm plasma nozzle

Experiments with Ø 1.2-mm plasma nozzle and laser power of 200 W show equivalent results concerning the weld efficiency as with a Ø 2.6-mm plasma nozzle, Fig. 8. With a trailing laser of 200 W, full penetration can be achieved with a welding speed of 1.25 m min^{-1}. With a leading laser, less than half of the sheet thickness (0.50 mm) is melted. The cross-section area is about the double with trailing laser as well (1.24 to 0.63 mm^2). The weld efficiency rises from 0.5 to 0.99 mm^{-2} kW^{-1}.

Nevertheless, in contrast to experiments with the wide plasma nozzle of Ø 2.6 mm, the leading laser did not show a guiding effect on the arc, and the cross-section areas of arc and laser are separate. Therefore, it can be assumed that the guiding and stabilizing effect of the laser depends on the stability of the arc. With a smaller plasma nozzle, the arc is

Fig. 7 Influence of sheet thickness on the voltage run (trailing laser 100 W, plasma current 40 A, linear feed 0.75 m min^{-1}, and plasma nozzle Ø 2.6 mm)



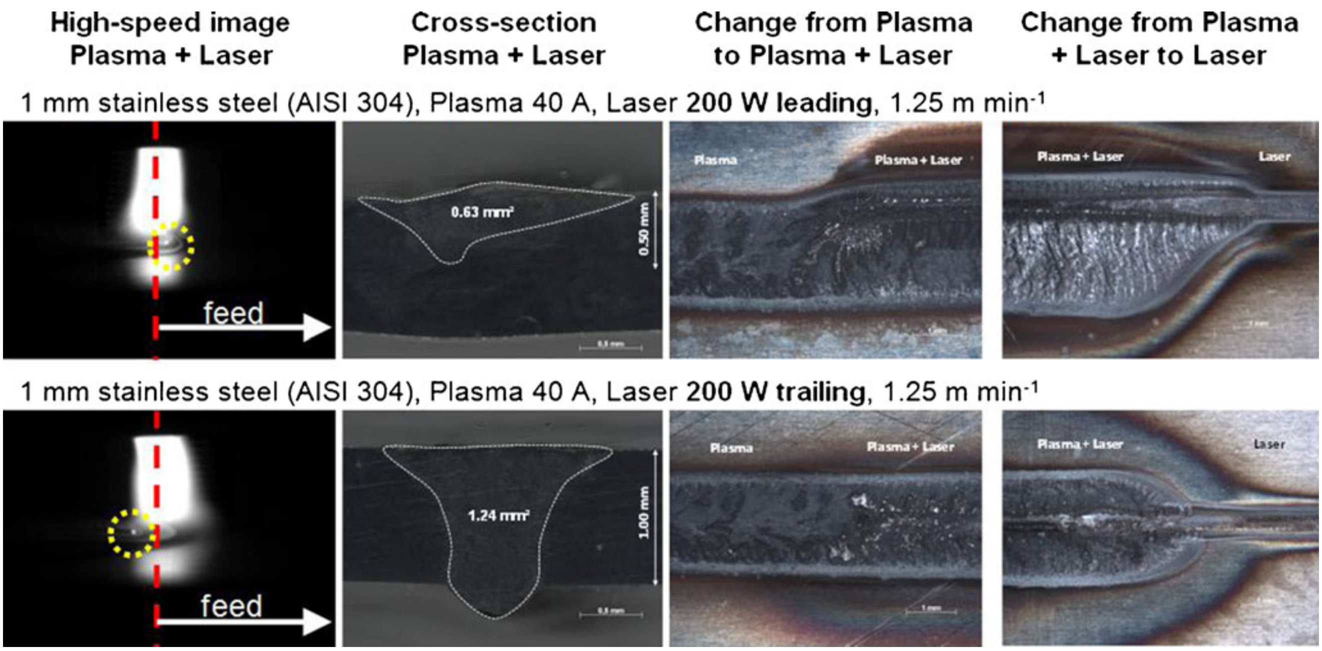


Fig. 8 Influence of laser positioning (leading or trailing) on the arc, the penetration, and the weld seam appearance (plasma nozzle Ø 1.2 mm)

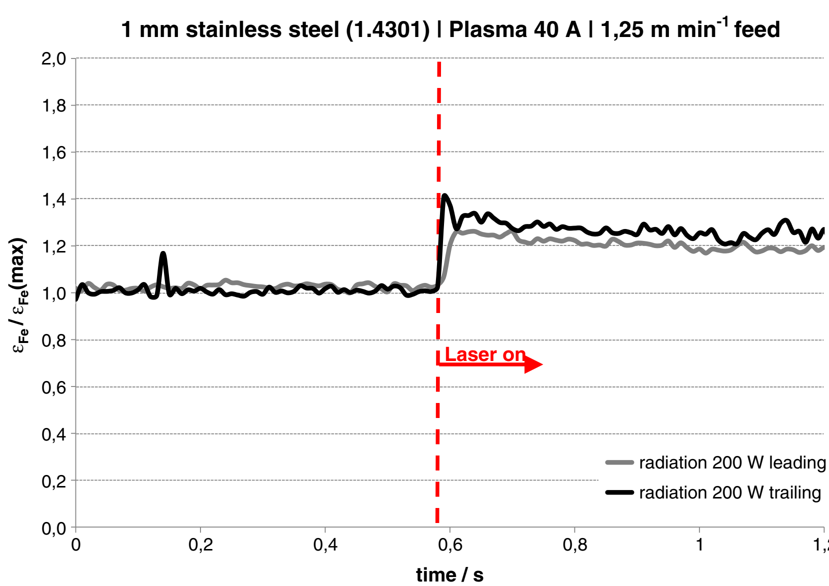
more stable and less influenced by the laser due to the higher current density.

To investigate the interaction of arc and laser more in detail, the radiation of iron (520 nm) was measured with a photodiode. This wavelength is well-separated from the laser wavelength and strong argon lines. Figure 9 shows the relative signal of the photodiodes in volt. The base level is different in both measurements due to the experimental setup with fixed torch and photodiodes. Therefore, in one experiment, the radiation is measured in the direction of feed, and in the second experiment, the radiation is measured behind the combined process. The level of the radiation increased in both setups by about 25 %. Therefore, it can be concluded that the evaporation of base material does not change significantly depending on the leading or trailing position of the laser spot.

Additionally, the analysis of the voltage signal shows that using the small Ø 1.2-mm nozzle no reduction of the voltage drop occurred, when the laser was switched on. It is assumed that with the smaller nozzle diameter, no stabilization of the arc occurs because the arc is very stable due to the high constriction by the nozzle.

In order to prove these results with quite low-signal level and the measuring method in general, an additional experiment with 300-W laser power in leading position was carried

Fig. 9 Influence of laser positioning (leading or trailing) on iron radiation (nozzle Ø 2.6 mm)



out. Here, the signal level rises from 0.13 to 0.29 V, Fig. 10 left. This can be considered as an increased evaporation of iron. Nevertheless, even with 300-W laser power, no complete root penetration could be achieved. The cross-section area is almost the same as for the trailing laser of 200 W (1.23 to 1.24 mm^2), but the shape of the cross-section area shows a separate molten area of the laser, Fig. 10 right top. Therefore, penetration is only 0.82 mm with a leading 300-W laser spot compared to a full penetration with a trailing 200-W laser spot.

5 Discussion of the results

The experiments using the laser-assisted plasma welding in the coaxial setup and laser displacement in the hollow cathode show special importance of the positioning of the laser spot on the workpiece concerning the efficiency of the combined welding process. With a trailing laser spot about 1 mm behind the arc axis, the cross-section area can be more than doubled, and full penetration can be achieved (e. g., cross-section Fig. 4: 0.49–1.14 mm^2). Identical welding parameters with a leading laser only achieved a penetration of only half of the sheet thickness. Nevertheless, a leading laser guides more distinctively and causes a more symmetrical weld seam (e. g., Fig. 4 very right). This guiding effect is also visible in the voltage signal, which is influenced considerably stronger. It can be assumed that the stabilization is more pronounced for the leading laser setup, which is therefore to the preferred for high-speed application of thin plates or foils.

Besides the question of practical applications, the differences demonstrate that the interactions between the arc and the laser spot do not take place inside the arc column. A significant influence of ionization inside the arc column by the laser beam can be excluded because if the interaction would take place in the arc column, the effect would have to be independent of the marginal movement of laser beam inside the hollow cathode. These experimental results using the hollow cathode setup confirm calculations of previous numerical studies [19] with different absorptions of laser power in the arc column (1 to 10 %). Due to the high temperatures in the arc plasma and little particle density, there is almost no influence of absorption on current density and temperature distribution.

The second interesting result is about the influence of metal vapor. The radiation of iron which should correlate to evaporation increases by the same value for a leading and trailing laser beam. Consequently, the observed increase of weld efficiency using a defocused laser spot does not correlate with changing evaporation. Hence, if the positive results cannot be explained by an interaction inside the arc column, the interaction has to take place on the surface. It is assumed that the synergy of the arc and the laser is caused by the preheating of the material, the better absorption of laser radiation, and the effect of deep penetration welding.

At first, the higher absorption of laser radiation increases on hotter surfaces due to the preheating by the arc. This assumption is strengthened by first experiments with different materials (aluminum and mild steel). These experiments showed the influence of thermal conductivity of the base material. The higher the thermal conductivity the lower is the influence of the laser position.

Secondly, the cross-sections suggest that the leading arc (respectively the trailing laser) lead to a deep penetration welding process rather than a heat conduction welding. Normally, deep penetration welding requires much higher laser intensity than used here. But by a leading arc, the base

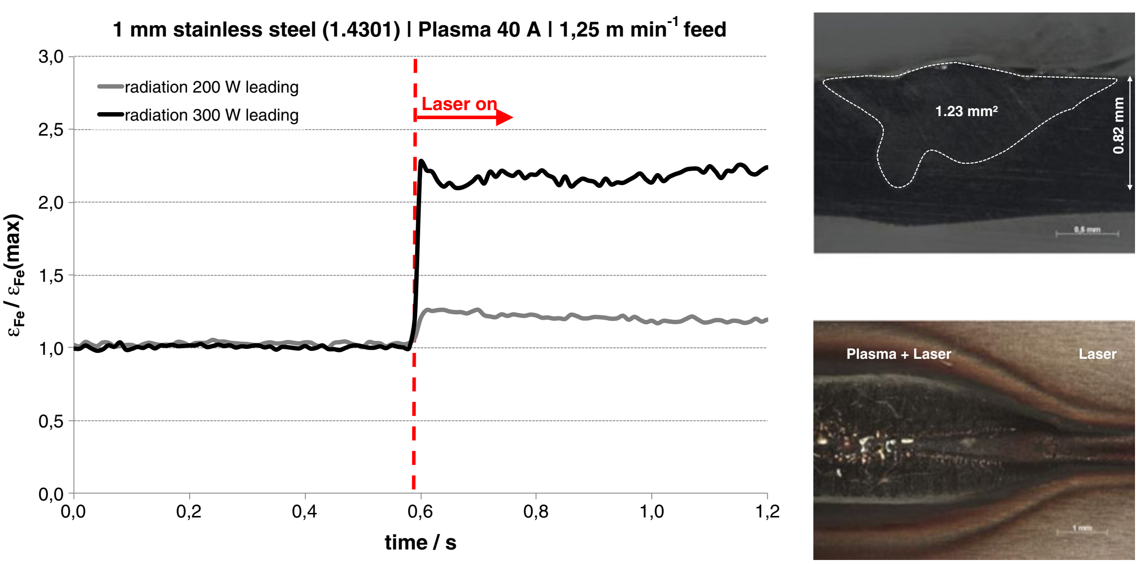


Fig. 10 Influence of laser power on the iron radiation with leading laser position (plasma nozzle Ø 2.6 mm)

material is preheated on the surface as well as inside the material. Furthermore, the plasma flow acts as a jet near the keyhole and pushes the evaporated material into the keyhole. Therefore, the keyhole cannot outgas, which increases the absorption of the laser beam. This assumption could explain why the iron radiation measured was rather small. Furthermore, it explains why high laser intensities are less efficient than moderately defocused laser spots—the keyhole velocity would be too high for a high-focused laser spot. In [19], it could be shown that only low vaporization rates are able to stabilize the arc. High vaporization rates on the other hand would destabilize the arc and increase the voltage drop. This fact also explains why best weld efficiencies are achieved with a defocused laser spot as used in the experiments. Furthermore, by deforming the laser spot in the weld seam, the arc can attach in a more constricted manner.

The results demonstrate that a better understanding of the temperature distribution and the fluid flow inside the work piece is necessary for a complete understanding of the effects in combined laser–arc processes. First numerical efforts with given temperature distributions on the workpiece surface show the highest voltage drop for wider temperature distributions and prove the importance of the surface temperature.

6 Summary and conclusion

LA-PAW of stainless steel was carried out using a coaxial setup of DC EN plasma torch with 40-A current and low-power single-mode fiber laser with laser power of 50 to 300 W. The new coaxial setup shows high synergic effects due to the optimal angle of arc and laser beam perpendicular to the workpiece. With the new LA-PAW-torch used, the laser beam can be displaced inside the hollow cathode. In previous measurements, it was found that with this setup, a stable arc attachment is achieved even with very high feed rates (40 m min^{-1}) and limited current. Best results were achieved with a defocused laser spot of 300 μm on the workpiece surface, when almost no additional metal vapor is created.

In this paper, a setup of LA-PAW is presented, which allows marginal longitudinal adjustments of the laser beam inside the hollow cathode, which causes a leading or trailing position of the laser spot related to the arc axis (± 1 mm). Using this setup, important indications for the synergy of the arc and laser were found: the main interaction takes place at the base material. To find optimal synergic effects, the laser spot on the workpiece has to be displaced. Maximum stabilization of the arc attachment and higher melting efficiency are not to achieve in one single setting.

By a trailing laser spot behind the axis of the plasma process, the melting efficiency can be doubled compared to a leading laser spot. Due to the heating of the base material, the absorption of the laser beam is improved, and wider weld pools occur. On the other hand, there is only a limited guiding effect of the laser to the arc, which causes separate weld seam tracks on the surface. A more pronounced guiding of the arc attachment is caused by a leading laser, which causes the creation of a single-weld seam tracks. It is assumed that the leading laser leads to an increase of surface temperature, which constricts the arc. With a trailing position of laser, the arc is not that strongly influenced, but the laser absorption which leads to an intense heating of the weld seam surface and changed flow inside the melt can be supposed by cross-sections. The influence on melt pool flow by the interaction of arc and laser is the subject of the current research. Furthermore, more detailed investigations concerning the influence of microstructure especially of stainless steel are of special future interest.

For practical application, this means that for high welding speed, the laser should lead the arc. The arc is more stable, but the efficiency of the combined process is limited. If maximum penetration is needed, the laser should trail the arc. Here, the arc has to attach stable by itself, which is not too hard to realize on stainless steel with limited welding speeds. The arc stability can be increased by a plasma nozzle with smaller diameters.

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