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ORIGINAL ARTICLE

Metal vapor-induced arc instability in stationary TIG-welding

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Abstract

The stability of the arc in arc welding processes is primarily relevant to the joint quality. However, the influencing factors which determine the arc stability are still partly unknown. Combining arc welding with laser welding enhances arc stability. The laser-induced metal vapor is often named as one stabilizing factor. But this contradicts the presumptions of arc welding researchers who mentioned the metal vapor as a destabilizing factor especially when high amounts are present in the arc. This investigation analyzes the specific influence of metal vapor on arc conductivity as one aspect of arc stability by producing metal vapor using a laser process on a separately placed substrate material. Furthermore, the arc current was varied at a constant metal vapor amount. The investigations show that the metal vapor presence increases the arc voltage by at least 20% and its fluctuation amplitude by at least 51% which was presumed to mean a decreased electrical conductivity and therefore decreased arc stability. The arc instability was lower for higher arc currents at constant metal vapor amounts. Therefore, higher arc currents increase the arc stability of welding arcs in the presence of a constant metal vapor amount.

Keywords Laser welding · Arc welding · Metal vapor · Arc stability · Laser-arc-hybrid welding

1 Introduction

The welding result in arc welding depends on the arc stability. The arc stability influences arc behavior, droplet transfer, molten pool behavior, and seam formation [1]. The stability of the arc can be assessed using various factors. One optical method is to observe the arc base point [2]. A stable arc root remains stationary or progresses linearly without fluctuations transverse to the welding direction [3]. Fluctuations of the arc foot point lead to fluctuations of the weld seam or inconstant seams and consequently changes in the seam geometry [2]. Another optical method is the observation of the arc plasma [4]. A stable arc plasma has a constant geometry, area [4], and deflection angle [1].

A widely used non-optical quantitative method is the measurement of arc voltage and arc current [5]. These describe the resistance in the arc, which can also be expressed as conductivity. A low arc resistance and therefore high arc conductivity are associated with high arc currents and low arc voltages. The arc conductivity influences the current flow in the arc, which is crucial for the melting process of the substrate material [6]. High conductivity in the arc facilitates the current flow and thus the melt pool depth. Low arc voltages or currents and therefore low arc resistances and high conductivities are presumed with high stabilities. Another stability criterion related to voltage measurement is the fluctuation of the voltage or current [7]. Fluctuations in arc voltage or current indicate fluctuations in current flow. Small fluctuations in the arc voltage or current therefore mean a constant current flow and thus high arc stability. A stable arc results in a uniform depth of welding seams.

One influencing factor on the arc stability amongst others is the presence of metal vapor. Metal vapor is produced during the arc welding process due to the high arc temperatures which result in a partial vaporization of the metal [8]. Simulations showed the importance of considering the influence of vaporized substrate material on the arc properties [9]. The metal vapor amount is enhanced when combining arc welding with laser welding to laser-arc-hybrid welding [10]. This applies especially in laser deep penetration welding, where the metal is vaporized systematically to form a vapor capillary which enhances the absorption of the laser beam due to multiple absorptions [11]. The hybrid welding process enhances the welding

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speed and penetration depth in comparison to the arc welding process and the gap bridging ability in comparison to laser welding [12]. It is also known to increase the arc and laser stability due to synergic effects in the process zone [12]. This leads to a decreased arc voltage due to the laser beam and an increase in the melting pool area [2]. Reisgen et al. for example reported for their experiments a minimum melting pool area increase of 1.8 times of the sum of the single melting pools [13]. Thomy reported a higher welding velocity in the hybrid process due to the higher arc stability [14]. Laser-induced metal vapor is discussed as one of the stabilizing factors and the findings are summarized in the following.

The influence of the metal vapor on the arc stability is not finally clarified. An often-discussed measurable factor regarding the stability of the arc is the arc voltage and the related arc resistance [5]. Already in 1980, a decreasing arc voltage was reported by Steen et al. for laser-arc-hybrid welding, who presume that this finding is connected to a decreased arc resistance [7]. They also discussed the meaning of arc stability in this context and presented that when an unstable arc with a temporal fluctuating arc voltage is combined with a laser beam, the amplitude of the fluctuations is decreased, and the arc is stabilized. For a stable arc without a fluctuating arc voltage, the arc voltage and therefore the arc resistance was reduced. The first correlation of a decreased arc resistance to the presence of metal vapor was assumed by Cui et al. in 1992 [15]. Thomy mentioned partly ionized metal vapor as one important factor for the enhanced electrical conductivity in the welding arc [14]. The laser-induced plasma plume provides a favored contact point for the arc by reducing the resistance in the arc column thus maintaining the arc and facilitating arc striking [16]. This enabled a stable melting pool flow and droplet transfer in laser arc hybrid welding [1].

Decker et al. explained the stabilizing influence of the laser-induced metal vapor with the lower ionization energy in comparison to the ionization energy of the process gas [17] as illustrated in Fig. 1 [18]. This results in a more probable ionization which leads to a higher electrical conductivity [17]. The influence of the easier ionization of laser-induced vaporized substrate material onto the electron density was investigated by Hao and Song [19]. The vaporized atoms of the magnesium substrate material were ionized more easily due to their low ionization energy in comparison to the used process gas argon which enhanced the intensity of the detected magnesium ion wavelengths in the arc spectra and decreased the detected intensity of the argon ion wavelength. Calculations showed a resulting increased electron density in the arc during the laser-arc-hybrid welding process in comparison to the TIG-arc welding process. This was assumed as one reason for the improved energy density of the arc plasma and improved welding quality [19].

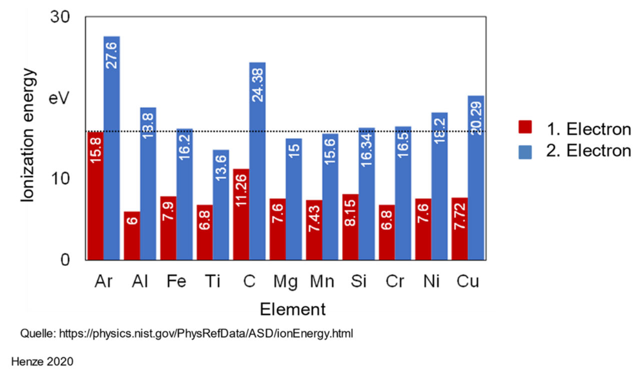

Fig. 1 Ionization energy of commonly used materials and alloying elements in comparison to the process gas argon

Wang et al. assumed that the lower required ionization energy of the metal atoms in laser-arc-hybrid welding results in a reduction of the energy for the maintenance of the arc [20]. The effective ionization potential decreases which leads to a more conductive and stable plasma channel whereas the keyhole is the favored contact point for the thermionic emission and the stability of the arc plasma and therefore arc increases. Henze et al. showed an influence of the composition of the metal vapor and therefore ionization energy of the elements in the metal vapor onto the arc stability [21]. The conductivity and therefore stability of the welding arc increases with decreasing average ionization energy of the metal vapor.

Möller and Thomy assumed that the positive influence of the laser-induced metal vapor on the arc conductivity is higher when welding aluminum in a DCEP (direct current electrode positive) configuration [3]. The indicator for the stabilization was a decrease in the arc voltage due to the addition of a laser process. This decrease of the arc voltage is reduced with increasing the arc current and increased with increasing laser power. In the DCEN (direct current electrode negative) configuration, the positive effect of the breaking of the oxide layer by the laser beam prevails whereas this is done in the DCEP configuration already by the arc due to the higher temperature on the cathode. Together with the observation of an increasing voltage decrease at laser deep penetration welding, it was assumed that the laser-induced metal vapor decreases the arc voltage due to an increase of the conductivity in the arc [3].

In arc welding as well as in laser-arc-hybrid welding also, negative influences of the metal vapor are discussed. Due to the presence of metal vapor, the arc temperature decreases [9] because of the higher radiative emission of metal ions in comparison to the process gas ions [22]. Therefore, the metal vapor causes a local reduction in the temperature and current density distribution [23] which increases the arc voltage and decreases the arc power in comparison to an arc without metal vapor [24]. The increase in arc voltage depends on the metal vapor amount and the arc current because of two conflicting influences of the metal vapor [8]. Metal vapor increases the radiative emissions of the arc which decreases the arc temperature [8] and increases the brightness of the arc [19], especially for high metal vapor amounts. This cooling effect of metal vapor is assumed to be dominant in high current arcs as well as in helium arcs because of the higher temperatures and therefore higher metal vapor amounts [8]. For low amounts of metal vapor, it is assumed that the decrease in arc voltage due to the easier ionization of the metal vapor atoms [22] and the higher electrical conductivity of the metal vapor at lower temperatures dominate the cooling effect which facilitates the conduction in the low-temperature regions [8]. In welding arcs with comparatively high metal vapor amounts, the temperature lowering overrides the higher electrical conductivity of the metal vapor [8]. For welding arcs without metal vapor generation, the arc stability increases with the arc current [25]. The influence of destabilizing effects is significantly lower for arc currents of at least 100 A. Therefore, low current arcs of up to 50 A are used for investigations of the arc stability [25] whereas high current arcs are used in the application to overcome arc instabilities [26]. Higher arc currents and arc voltages also increase the tensile strength of joints welded with industrial-applied welding parameters [27]. This is especially applicable for TIG welded joints [28].

The metal vapor is not distributed equally inside the welding arc. The distribution of the metal vapor in the arc is mainly influenced by the diffusion due to the mole fraction gradient and the temperature [9]. The diffusion due to mole fraction gradients results in an agglomeration of the metal vapor in the low-temperature electrically conducting regions of the arc [9]. Due to the lower required energy for ionization, the elements with the lower ionization energy agglomerate in the low-temperature region and are still ionized there in comparison to elements with higher ionization energies [29]. This additionally decreases the arc temperature.

The hybrid welding process changes the metal vapor flow. The addition of the laser beam increases the metal vapor amount [19]. Mu et al. showed a fluctuation in the plasma area due to the fluctuation of the flow of the laser-induced metal vapor using a high-speed camera with an 808-nm narrow-band filter [4]. The metal vapor flow from the keyhole has a higher velocity and density than the arc plasma flow which causes a unique flow pattern in hybrid arc welding [4]. Additionally, the metal vapor inside the keyhole has a fluctuating flow velocity in combination with a fluctuating flow direction [30]. Combining the processes locating the laser and therefore keyhole behind the arc causes a strong vapor flow and therefore temperature decrease in the arc tail [4]. The fluctuation of the metal vapor flow disturbed the arc flow, especially in the regions with a high amount of metal vapor. The amplitude and frequency of the fluctuations of the plasma area are increased due to the laser process. The influence of the dynamic flow of the laser-induced metal vapor on the arc flow was called laser-induced arc dynamics destabilization (LIADD) [4]. The vapor flow and therefore LIADD effect was enhanced by increasing the laser power whereas a higher arc current increases the arc flow and therefore decreases the LIADD by decreasing the relative fluctuation amplitude. However, the authors also mentioned that the LIADD phenomena do not prevent the stabilization process of the arc by the laser.

2 Aim and scope

The specific influence of metal vapor on arc conductivity as one aspect of arc stability in arc welding as well as in laser-arc-hybrid welding has not been clarified yet. Stabilizing and destabilizing influences are discussed. The findings are mainly based on simulative studies since the metal vapor amount forming during welding cannot be adjusted independently from the welding parameters itself in the conventional arc welding process. In the investigations based on laser-arc-hybrid welding, further effects influenced the results, e.g., the laser-induced heating of the substrate or the laser-induced plasma plume.

In this study, the metal vapor generation and the welding arc are separated by a special setup for an experimental investigation. The metal vapor is generated by a laser welding process on a separately positioned substrate material next to a TIG arc between two not melting electrodes (cf. Fig. 2). By a perpendicular orientation of the laser beam and welding arc, the metal vapor is directly introduced into the arc. The interaction of the arc and laser welding processes is limited to the metal vapor. The process principle is described in detail in [31]. Further studies concentrated on the variation of metal vapor-related process parameters as its amount [31] and composition [21] on the arc voltage and plasma composition. This investigation deals with the arc stability represented by the arc voltage and arc voltage fluctuation. During the investigation, the arc current as an arc-based process parameter was varied to investigate the influence of higher arc currents and therefore arc stabilities on the arc-metal vapor interaction. The arc voltage changes and temporal arc voltage fluctuations when applying the metal vapor are analyzed regarding a change in arc conductivity. Hereby the specific influence of metal vapor on the arc conductivity representative of the arc stability is examined.

3 Experimental

The experiments are based on a special setup with a separate lateral laser generation of the metal vapor into a TIG arc between two tungsten electrodes. The arc axis is located vertically, and the laser beam axis is horizontally and was therefore arranged perpendicular to each other. The measuring setup is shown in Fig. 2. During the "laser-on" measurement, the metal vapor originating from the laser welding process is flowing in the arc due to the location of the laser welding process and interacts with the TIG arc [31]. For the measurement of the arc stability without metal vapor ("laser-off" measurement), the arc was ignited before the laser beam (see Fig. 3). The substrate material was moved in welding velocity whereas the arc and laser beam were stationary.

The experiments were carried out by using a Trumpf TruDisk 12002 laser with a maximum power of 12 kW in combination with an Abicor Binzel Abiplas MT 500 W welding torch and an EWM Tetrix 500 AC/DC Synergic welding power source. The laser beam had a spot diameter of 370 µm at the substrate surface, in which a bead-on-plate welding process was carried out. The aluminum alloy EN AW-5083 and the steel material S235 are used as substrate materials based on experiences from further experiments [21] and their utilization by other researchers [32]. The substrate material had a thickness b_M of at least 5 mm to prevent welding through. The chemical composition and thickness are shown in Table 1. A tungsten electrode (WLa 15 Ø 3.2 mm) was used as an electrode in the plasma torch and the water-cooled device as the counter electrode. A ceramic nozzle was positioned as a shielding nozzle around the counter electrode to avoid heating of the electrode which can influence the arc conductivity [7] by reflected laser beams from the substrate. Figure 2 shows the experimental setup. For every parameter set, four experiments were performed at room temperature and a relative humidity of 32%. The samples were cleaned with ethanol before welding and the electrodes were sharpened to an angle of 45° by grinding before every parameter set.

During the experiments, the arc voltage is monitored as a measure of its conductivity and therefore stability [5]. The

Fig. 2 Experimental setup for the arc stability measurements

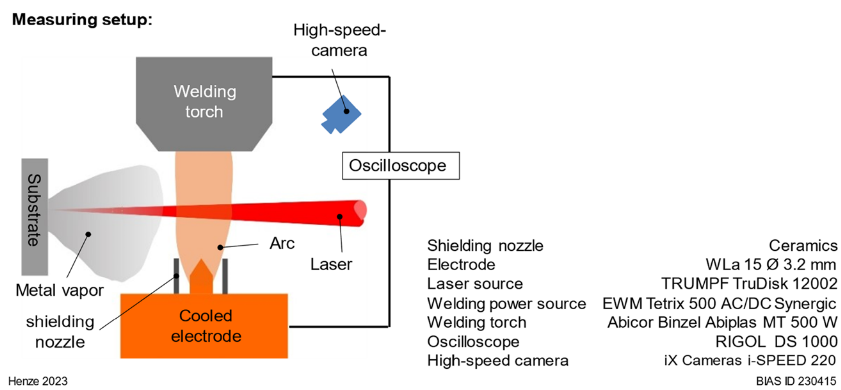

Fig. 3 Process principle of the arc stability measurements

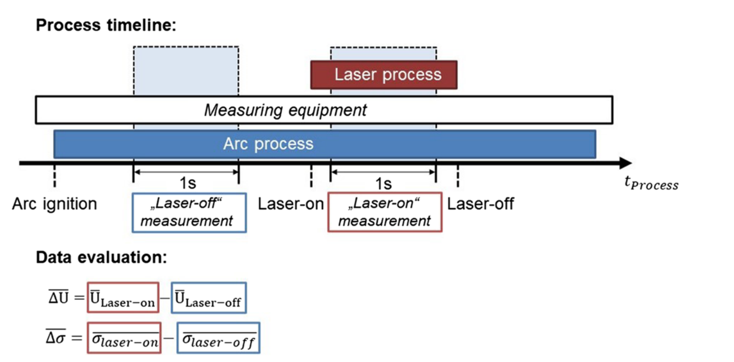

Table 1 Composition of the used aluminum alloy EN-AW 5083 and steel material S235

Material	C [%]	Fe [%]	Cu [%]	Mn [%]	Mg [%]	Cr [%]	Zn [%]	Other [%]	b_M [mm]
EN AW-5083		0.4	0.1	0.4–1	4.0–4.9	0.05–0.25	0.25	Ti: 0.15 Si: 0.4 Al: rest	5
S235	0.17	Rest	0.55	1.4				P: 0.035 S: 0.035 N: 0.012	6

average voltage $\bar{U}$ of a signal is defined as the arithmetic average of a duration of at least one second of the “laser-off” respectively “laser-on” measurement. Additionally, the standard deviation of the same arc voltage measurement was calculated as representative of the fluctuation of the arc voltage signal. At least 25,000 data points were taken for the calculation. The process was recorded using an “iX Cameras i-SPEED 220” high-speed camera. The measuring and welding parameters are summarized in Table 2. The laser process is kept constant during the investigation. Therefore, the metal vapor amount is presumed to be constant. The arc voltage was varied between 5 and 25 V because of the higher susceptibility of low currents arcs to arc instabilities [25].

4 Results

Figure 4 shows an example of a voltage measurement and its evaluation. After switching on the laser process, the metal vapor flowed in the arc which increased the average arc voltage by 28% from 18.49 to 23.73 V. During the “laser-on” measurement, the arc voltage showed higher temporal fluctuations in the signal path.

Figure 5 shows the results of the variation of the arc current. The arc voltage increased for all tested parameters during the “laser-on” measurement by at least 20% for both tested materials. The voltage difference and therefore increase of the arc voltage decreased with increasing arc current. The highest voltage increases were measured for the lowest tested arc currents of 5 V for the aluminum alloy EN AW-5083 by 36% of the arc voltage of the “laser-off” measurement respectively the lowest measurable arc current of 10 V for the steel material S235 by 38%. For the steel material S235, higher voltage differences were measured than for the aluminum alloy EN AW-5083. In some experiments especially when using steel material as substrate material, the arc extinguished for low arc currents during the metal vapor influence. The average arc voltage of the measurement without metal vapor decreases with increasing arc current.

Figure 6 shows images of the high-speed recordings of the process using the aluminum alloy EN AW-5083 at an arc voltage of 15 A. Both measurements showed the welding arc. The “laser-on” measurement also shows spatters and a plasma plume which is not reaching up to the welding arc in the laser welding process. The temporal arc plasma dynamics are small during the “laser-off” measurement. During the “laser-on” measurement, the arc plasma size increases as well as the temporal arc plasma area dynamics. The arc also showed a higher brightness than during the measurement without laser.

Figure 4 shows higher fluctuations in the “laser-on” measurement than in the “laser-off” measurement. To quantify the influence of the metal vapor on the fluctuations, the standard deviation of the measured arc voltage was calculated as representative of the amplitude of the fluctuations for

Table 2 Welding and measuring parameters

Shielding gas [l/min]	Ar: 25
Arc current [A]	5, 10, 15, 20, 25
Distance between the electrodes [mm]	16
Welding speed [m/min]	1.0
Focal diameter [µm]	370
Laser power [W]	1300
Measuring frequency oscilloscope [Hz]	25,000
Recording frequency high-speed camera [Hz]	2000

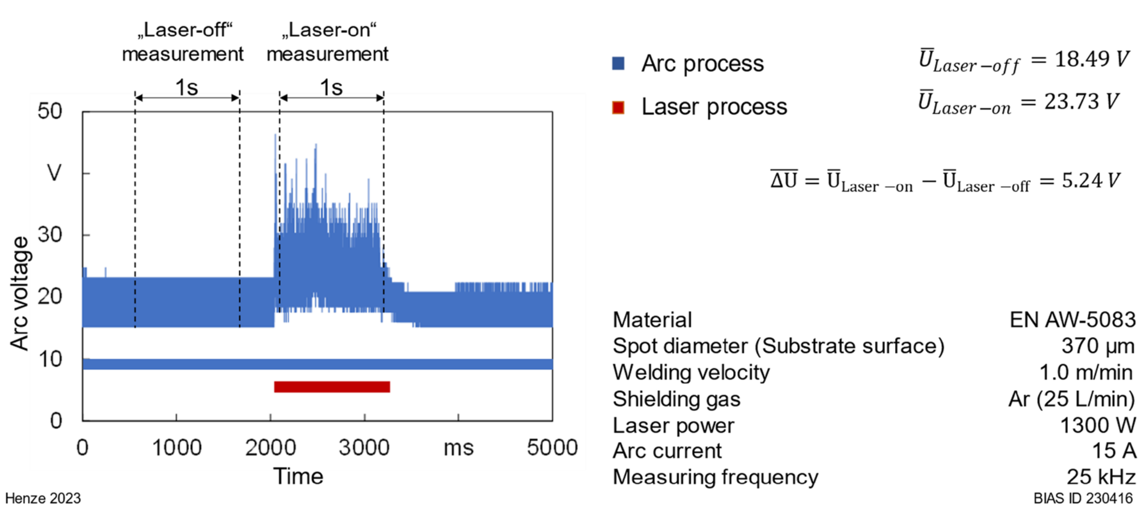

Fig. 4 Example for voltage measurement with the substrate material EN AW-5083

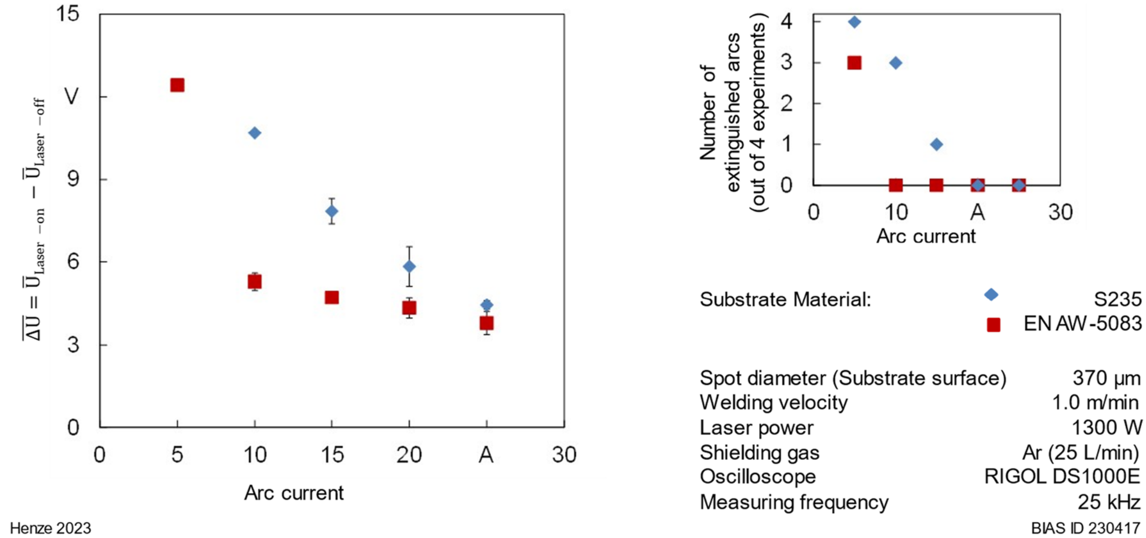

Fig. 5 Influence of the arc current on the voltage difference of the arc with and without metal vapor for the steel material S235 and the aluminum alloy EN AW-5083

the "laser-off" and "laser-on" measurements. An example of the calculation of the fluctuations is illustrated in Fig. 7 for the "laser-on" measurement of the aluminum alloy EN AW-5083. During the "laser-on" measurement, the standard deviation of the arc voltage increased by 64%. The calculations of the other measurements showed higher standard deviations for the measurements with metal vapor for all experiments.

The influence of the arc current on the fluctuations of the arc voltage is shown in Fig. 8 as the difference between the "laser-off" and "laser-on" measurements. The standard deviation of the measurements was increased by at least 51% of the "laser-off" measurement. The standard deviation difference decreases with increasing arc current. The highest standard deviation increases were measured for the lowest tested arc current of 5 V for the aluminum alloy EN AW-5083 by 123% of the standard deviation of the arc voltage of the "laser-off" measurement. The highest measured increase of the standard deviation of the arc voltage for the steel material S235 was measured for the lowest measurable arc current of 10 V by 130% of the standard deviation of the "laser-off" measurement. For the measurement without metal vapor, the fluctuations were also decreasing with increasing arc current.

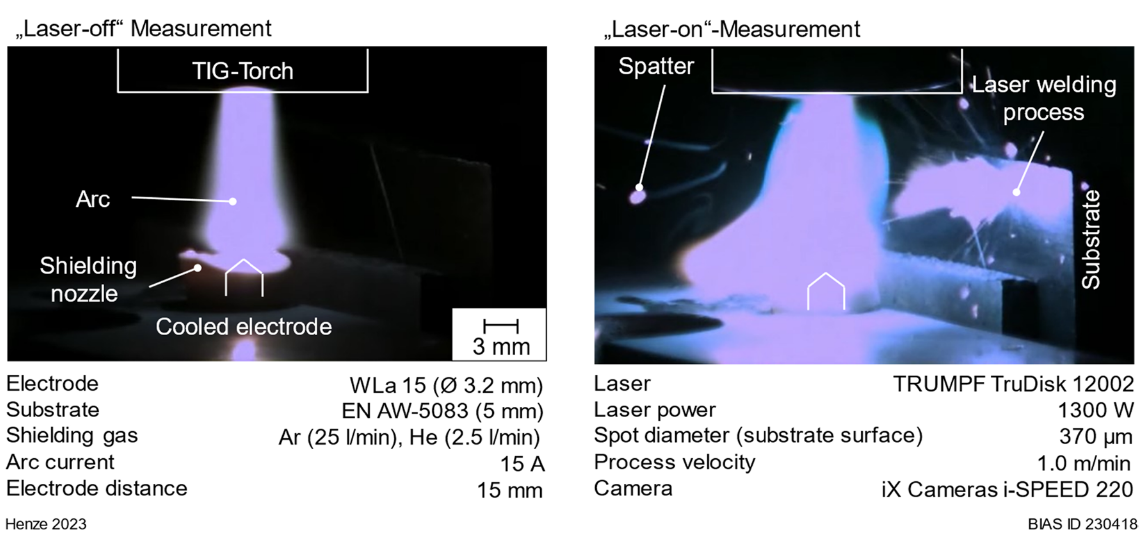

Fig. 6 Images of the arc during the "laser-off" (left) and "laser-on" measurement (right) of high-speed recordings of the process

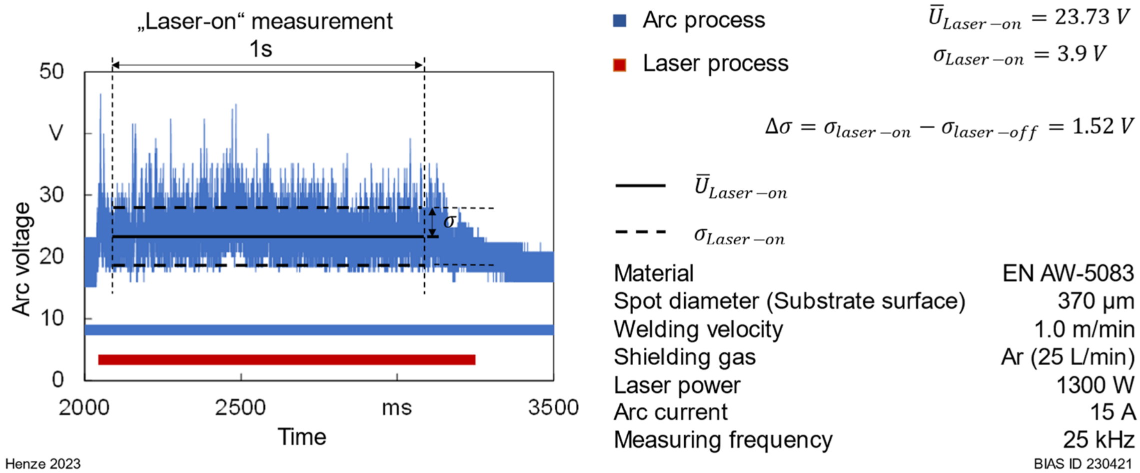

Fig. 7 Example for the evaluation of the amplitude of the fluctuation of the voltage signal. The “laser-off” measurement was evaluated equally

5 Discussion

The arc and laser welding processes were separated in this investigation. The laser welding process had a plasma plume as visible in the high-speed recordings which did not reach the arc plasma. Therefore, the direct interaction of the arc plasma and laser-induced plasma as in laser-arc-hybrid welding was not possible. It is therefore presumed for the used setup that the metal vapor is atomic and not ionized when entering the arc. The positive influence of the laser-induced partly ionized metal vapor [14] or laser-induced plasma plume [16] as in the hybrid welding process was not possible. For the industrially used laser-arc-hybrid welding process, a positive influence of the laser-induced metal vapor is not excludable because of its partial ionization.

The results showed an increased average arc voltage during the “laser-on” measurement and therefore a metal vapor influence. The increased arc voltage is related to a higher arc resistance [7] and therefore lower arc stability [3]. The increased voltage due to the metal vapor corresponds with the simulative assumptions of [22] and [9]. The metal vapor increases the radiative emission from the welding arc and therefore decreases the temperature in the arc. The higher radiative emission is visible due to the higher brightness of the arc [19] as visible in the high-speed recordings of the process. This decreases the arc conductivity and therefore increases the arc resistance which is measurable due to an increased arc voltage during the metal vapor influence.

In this investigation, a laser welding process was used to generate the metal vapor. The metal vapor amount is therefore comparatively high [19]. High metal vapor amounts are presumed with a destabilized arc because the high radiative emission that cools the arc overrides the positive effects of the metal vapor as an increased electrical conductivity [8]. Therefore, the presence of metal vapor increases the arc voltage and causes arc instability [24].

Additionally, to the results concerning the average arc voltage, higher arc voltage fluctuations were measured during the measurement with metal vapor. The high-speed videos of the process showed higher temporal arc dynamics for the “laser-on” measurement than for the arc without metal vapor. The higher arc dynamics due to laser-induced metal vapor are comparable to the LIADD known from laser-arc-hybrid welding [4]. The turbulence of the metal vapor flow when leaving the keyhole [30] is transferred to the welding arc and leads to a higher arc fluctuation as in the LIADD phenomenon [4].

Calculating the fluctuations of the arc voltage using the standard deviation of the measurements showed increased fluctuations for the measurements with metal vapor and therefore confirmed the presumption. Increased arc plasma fluctuations [4] and arc voltage fluctuations [7] are presumed with lower arc stabilities. Therefore, the measurement of the arc voltage fluctuations presumes a lower arc stability for the measurement with metal vapor which correlates with the results for the average arc voltage.

Figure 9 shows the correlation between the measurement of the fluctuations as well as the average arc voltage. With increasing arc voltage difference also, the standard deviation of the measurements and therefore fluctuation difference increases which are both presumed to decrease arc stability [7]. The values showed a linear correlation between the voltage difference and the standard deviation difference of the measurement with and without metal vapor. The arc stability is therefore lowered during the metal vapor influence. For some measurements, this lower arc stability was confirmed due to an extinguishment of the arc.

The arc current was varied during the investigation. Two conflicting effects were discussed in the introduction. On

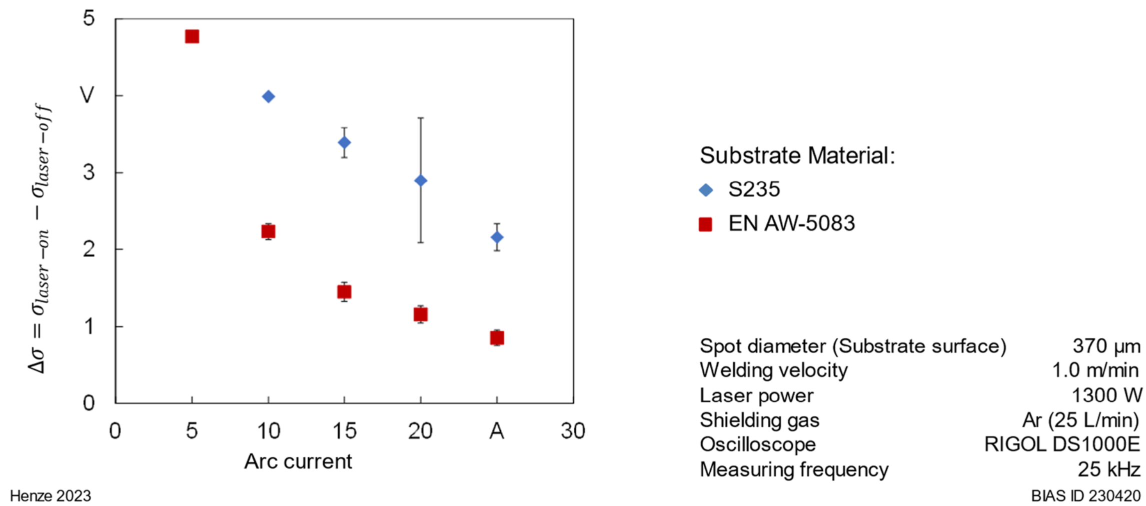

Fig. 8 Influence of the arc current on the difference of the amplitude of the fluctuations of the voltage measurement without ("laser-off") and with ("laser-on") metal vapor

the one hand, Murphy et al. assumed an increasing negative influence of the metal vapor for increased arc currents due to higher metal vapor amounts because of higher arc temperatures [8]. . On the other hand, it is assumed that higher arc currents increase the arc stability [25]. Thereby the influence of stabilizing effects is lowered with increasing arc current [3]. The first effect is neglectable in this investigation. The metal vapor was separately generated by a laser welding process and is therefore independent of the arc current. The metal vapor amount was presumed to be constant due to a constant laser process during the investigation.

The measurements showed an increased arc voltage and arc voltage fluctuation which is presumed with an arc instability during the measurements with metal vapor. Both evaluated values and therefore the arc instability decreased due to an increasing arc current at a constant metal vapor influence. Increasing arc currents are presumed with higher arc stabilities [7]. The higher arc current increases the arc power and therefore the arc stability by increasing the electrical conductivity. Therefore, high arc currents are industrially applied to overcome arc instabilities whereas research studies that focus on the investigation of factors influencing the arc stability are using low arc currents [25]. Higher arc currents are therefore lowering the influence of stabilizing effects, e.g., by reducing the laser-induced arc voltage decrease in laser-arc-hybrid welding [3]. Also, the influence of negative effects on the arc stability is lowered by an increased arc current as reported in [4]. The lowering

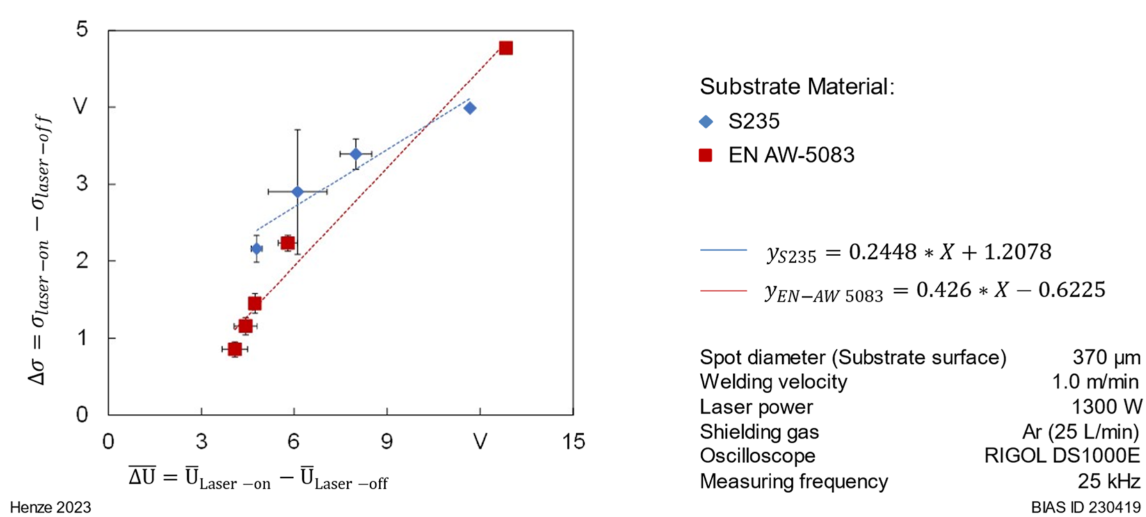

Fig. 9 Arc voltage difference and corresponding fluctuation amplitude difference of the arc voltage measurement

of the arc voltage and arc voltage fluctuation difference by an increased arc current is therefore related to the increased arc stability at increased arc currents. Therefore, it can be concluded that higher currents increase the arc stability in a welding arc with a constant metal vapor amount.

Mu et al. reported a decrease in the influence of the LIADD on the fluctuations of the arc plasma area with increasing arc current [4]. The amplitude of the fluctuations is decreased with increasing arc current due to the higher arc flow. An evaluation of the standard deviation of the arc voltage showed a decreasing standard deviation and therefore decreasing fluctuations of the measurement with increasing arc current. This corresponds with the findings of Mu et al. concerning the fluctuations of the arc plasma area [4]. This confirms the assumption of a decrease in the fluctuations in the arc voltage with increasing arc current. The higher arc current stabilizes the arc which decreases the destabilizing influence of the fluctuating metal vapor flow.

6 Conclusion

The investigation showed the specific influence of separately laser-induced metal vapor on the arc voltage and therefore conductivity and fluctuations of the arc voltage as aspects of the arc stability by the separation of the metal vapor generation from the welding process. The average arc voltage as well as the arc voltage fluctuations were increased due to the metal vapor influence by at least 20% respectively 51%. This is presumed to be a decreased arc stability. The increased radiative emission by the atomic metal vapor and therefore decreased temperature of the arc lowered the arc conductivity. Additionally, the turbulences of the metal vapor flow are transferred to the welding arc which increases the arc voltage fluctuation. The metal vapor therefore has a negative influence on the welding arc in this investigation.

The voltage difference as well as the fluctuation difference of the arc voltage were decreased with increased arc current at constant metal vapor amounts. The increase of the arc current therefore stabilizes the arc for a constant metal vapor amount. The increased arc stability lowers the destabilizing negative influence of the metal vapor. Because of the comparatively low used arc currents in this investigation, it is assumable that the arc instabilities due to the metal vapor are significantly lower respectively eliminated in technically used welding arcs.

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Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Insa Henze. The first draft of the manuscript was written by Insa Henze and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Data is available at the institution from the authors.

Code availability Not applicable.

Declarations

Ethics approval There are no ethical conflicts.

Consent to participate The study did not include humans or animals.

Consent for publication Included in submission.

Competing interests The authors declare no competing interests.

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