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Laser-Plasma-Hybrid-Cladding: Possibilities in the combination of arc and laser for deposition welding

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Abstract

Plasma-Transferred-Arc (PTA) welding is a process that enables high deposition rates, but also causes increased thermal load on the component. Laser based Direct Energy Deposition (DED) welding, on the other hand, achieves a high level of precision and thus comparatively low deposition rates, which can lead to high processing costs. Combining laser and arc energy aims to exploit the respective advantages of both technologies.
In this study, different possibilities of this process combination are presented using a PTA system and a 2 kW disk laser. This includes the combination in a common process zone as a highspeed plasma laser cladding technology (HPLC), which achieves process speeds of 10 m/min. Besides that it is being examined whether a pre-running plasma arc can be used to coat difficult-to-weld rail steel with a carbon content of 0.8 % due to a preheating effect. Furthermore, a smoothing of the coating by a plasma arc following the laser is investigated.

Keywords: Plasma-Transferred-Arc, Direct Energy Deposition ; highspeed plasma laser cladding; deposition welding

1. Introduction

The idea of combining the complementary welding processes arc and laser beam in a common process zone to overcome the disadvantages of each individual process, dates back to the 1970s. [1, 2] Laser hybrid welding is nowadays a state-of-the-art process, used, in the shipbuilding industry to join ship panels, for example [3]. To perform a metal deposition welding process, the described technology in this paper is

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designed as a Hybrid-Metal-Deposition Technology [4]. In this context, the following three different approaches for the combination of the energy sources laser and plasma arc in the field of deposition welding are presented:

- Highspeed-Plasma-Laser-Cladding (HPLC), with a joint process zone, for high process speeds
- Laser-DED with plasma arc preheating, to enable coating of carbon-rich steels.
- Laser-DED with plasma arc remelting, to smooth the coating, e.g. on cutting tools

2. State of the Art

Laser based Direct Energy Deposition (DED) welding achieves a high level of precision, but can lead to high processing costs, due to comparatively low deposition rates. A process that enables high deposition rates is Plasma-Transferred-Arc (PTA) welding. However, PTA also causes increased thermal load on the component. Combining laser and arc energy aims to exploit the respective advantages of both technologies.

The approach of using a hybrid welding process as a cladding process or in additive manufacturing is being pursued by Wilden et al. [5, 6], Barroi and Hermsdorf et al. [7–11], and also Som et. al. [12].The investigated concepts pursue a combination of one transmitting arc and one laser beam. Together with a high-energy efficiency and a low thermal load for the component and a low dilution, deposition rate and welding speed represent key industry relevant parameters for coating processes by deposition welding. With a hybrid process the published works can gain deposition rates from 1.83 kg/h [6] to 2.7 kg/h [12] at welding speeds of 0.2 m/min [13] to 0.8 m/min [12]. A more complex approach by Barroi and Hermsdorf et al. [7, 9, 10] that works with a non-transmitting arc between two burners (tandem burners) and two consumable wire electrodes can result in higher deposition rates. The tandem burners provide already molten deposition material and an oscillating diode laser in front of the smelting line ensures a metallurgical bond between the substrate and the deposition material. By decoupling the deposition material melting process from the actual deposition of the material, low thermal stress and dilutions of <5 % at depositions rates of 7.5 kg/h can be achieved at welding speeds of only 0.3 m/min, resulting in limited area rates [10].

High process speed by a hybrid process combination however is demonstrated by Serres et al. [14], for example, the deposition of NiCrBSi+WC coatings using a hybrid plasma spraying process based on the coupling of a plasma spray gun and a diode laser. Wear protection layers can be applied crack-free at spray velocities of 75 m/min, with this process. But a soft decarburization or dissolution of WC particles to precipitate carbon in the layers is caused by the Lasers remelting process. In addition, the exposed area to combined treatment is only 1.6 mm^2, resulting in limited deposition rates. Especially in wear protection applications, a high application rate as well as high process speeds are decisive. A hybrid coating process that addresses both properties is presented among other tasks in the following.

3. Experimental Setup

3.1. Highspeed-Plasma-Laser-Cladding (HPLC)

The process arrangement in which the two energy sources laser and plasma arc form a common process zone represents a hybrid process arrangement. Figure 1 shows the experimental setup of this process variant in the laboratory (a) and schematically (b). The plasma torch is arranged perpendicular to the workpiece and the laser with a defined angle α in a forward trailing position. Due to this constellation of the two energy sources, both the plasma arc and the laser radiation are focused in a common process zone. The laser spot is positioned a few millimeters in front of the electrode perpendicular of the plasma torch so that the laser assumes a leading position. The plasma torch is a commercially available torch that has been adapted in the front area through an opening for the laser beam. The torch has an electrode with a diameter of 4 mm and conducts the metal powder through six powder feeds arranged around the arc.

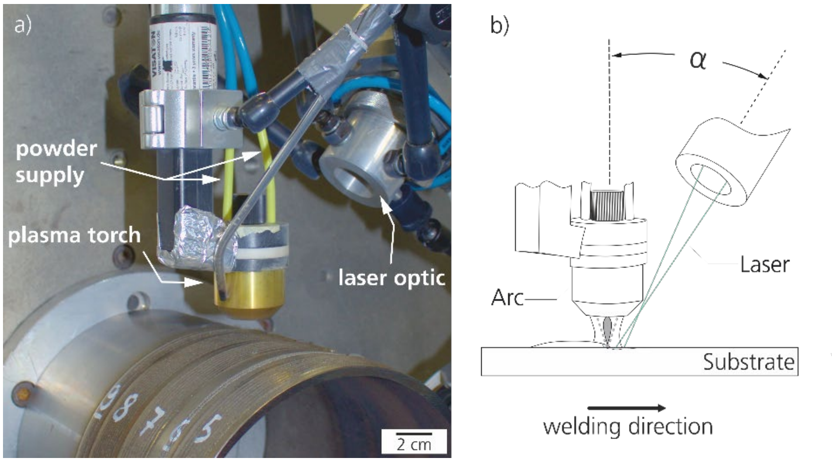

Fig. 1. a) Experimental setup of the plasma laser hybrid deposition welding process in the laboratory b) Schematic diagram of the arrangement of the energy sources

To perform the investigations, the PTA system is integrated into a laser processing workstation. The laser processing workstation is equipped with a 2 kW Yb:YAG disk laser and optics with a nominal focal length of 200 mm. Both, the carrier gas and the plasma gas are argon, at gas flow rates of 2 l/min and 3 l/min respectively. For the process investigations with regard to wear protection layers, a filler material is selected which contains 60 % cast tungsten carbide (WC) in crushed form. The tungsten carbides are embedded in a NiCrBSi matrix. S235JR mild steel is used as the substrate material. Individual weld tracks were applied to a piece of pipe or sheet metal to form single-layer surface coatings. In order to achieve high welding speeds, a speed of 10 m/min is selected for the experiments. Compared to conventional methods such as the PTA [15] or the DED method [16], this is a speed at which conventional arc-based methods do not work at a stable state.

3.2. DED with plasma arc preheating

The process configuration in which the DED process is supported by a leading plasma arc is shown in Figure 2 as an experimental setup in the laboratory (a) and schematically (b). The two energy sources do not form a common process zone. Rather, the plasma arc is intended to fulfil a supporting function for the DED process. Depending on the direction it is welded, the plasma arc assumes a preheating or remelting function. In a preheating process arrangement, the welding direction in Figure 2 runs from right to left.

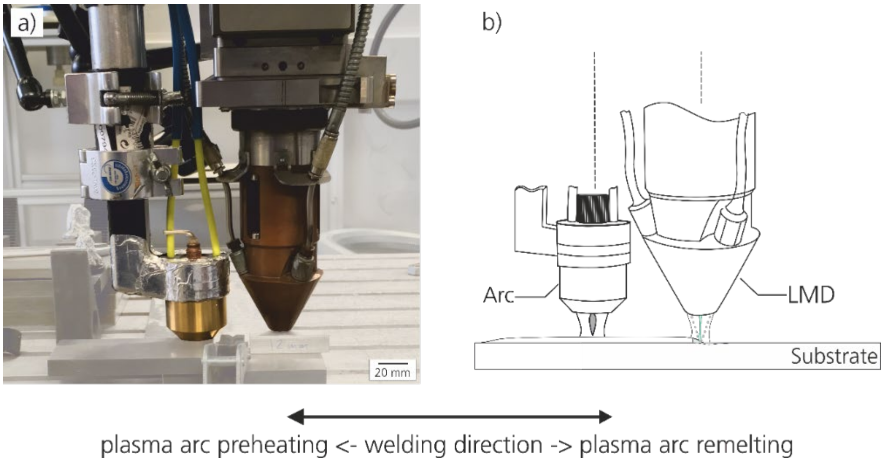

Fig. 2. a) Experimental set-up of the DED process in the laboratory with a plasma torch arranged in a leading or trailing order, depending on the welding direction b) Schematic diagram of the arrangement of the energy sources

For these investigations only the parameters of the plasma process were varied. The plasma torch is operated without powder supply and is supplied with protective gas (argon) and plasma gas (argon). The range of parameters to be tested during the investigations is given in Table 1. The parameters are determined on the basis of a full factorial design on single tracks. To check the preheat effect of the plasma arc, a steel that is difficult to weld was chosen as base material. The base material used in these investigations is a fine-pearlitic heat-treated R350HT rail steel with a carbon content of approx. 0.8 % and a minimum hardness of 350 BHN. The detailed chemical composition and further information can be found in [17]. The filler material used is 20NiCrMo2-2 case-hardening steel in gas diffused powder form with a grain fraction of -150+53 µm. In addition to metallographic cross sections, the evaluation is carried out via a hardness measurement according to Vickers (HV1). The hardness measurement is performed in the middle of each track and is performed in such a way that three measuring points are set in the weld deposition (WD), in the heat-affected zone (HAZ) and in the base metal (BM).

Table 1. Range of investigated process parameters for the DED plasma preheating process

Parameter	Velocity	Laser power	Powder mass flow	Main arc current	Plasma gas flow	PTA-working distance
Unit	mm/min	W	g/min	A	l/min	mm
Value	400-600	1400	13	60-160	1-3	8-12

3.3. DED with plasma arc remelting

The experimental setup for the process configuration with a plasma arc following the DED process is the same as shown in Figure 2, but with the corresponding welding direction from left to right. The aim of this process arrangement is to remelt the surface of the coating applied by the DED process by means of a trailing plasma arc, thus producing a smoother surface.

The plasma torch is also operated without powder supply and is supplied with protective gas (argon) and plasma gas (argon). The range of parameters to be tested during the investigations is given in Table 2. The parameters are determined on the basis of a full factorial design, first on single traces, then on promising parameters on flat single-layer coatings. As in chapter 3.1, a metal matrix composites (MMC) of 60% WC in a NiCrBSi martix is used as filler material. The base material is mild steel type S235. The evaluation of the surface roughness is carried out by the optical measuring device MircoProf of FRT GmbH according to the standard ISO 4287. For the evaluation of the surface coatings, three surface measurements are performed on a square measuring surface of 6.25 mm^2 for each sample. The average roughness value S_a is used as the comparison parameter.

Table 2. Range of investigated process parameters for the DED plasma remelting process

Parameter	Velocity	Laser power	Powder mass flow	Main arc current	Plasma gas flow	PTA-working distance
Unit	mm/min	W	g/min	A	l/min	mm
Value	700	1300	13	50-280	0.75-3	8-12

4. Results and Discussion

4.1. Highspeed-Plasma-Laser-Cladding (HPLC)

Figure 3 b) shows a single-layer coating with 20 tracks of NiCrBSi+60%WC next to each other. On the side edges of the welding beads, powder particles still adhere which have not completely melted and can be seen in the overlap area of the sheets. The cross section of a single-layer coating with this material is shown in Figure 3 a). The carbides of the coating are well distributed in the thin layer. Particularly noteworthy is the small HAZ with a depth of less than 0.2 mm. It is assumed that the stabilization effect of the laser radiation is mainly due to an improvement of the surface properties of the workpiece for the coupling of the plasma arc [18]. The laser spot provides a preferred location for coupling the arc to the workpiece surface. This type of stabilization allows the plasma arc to apply the filler material even at very high speeds.[18]

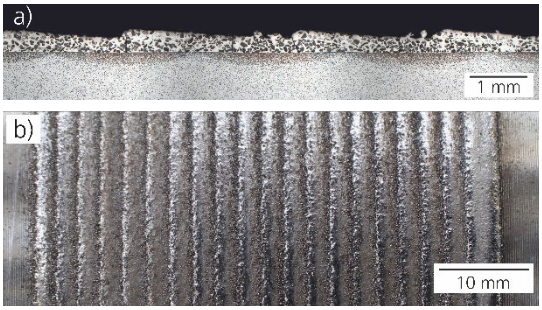

Fig. 3. a) Cross section of a single layer coating of NiCrBSi+60%WC on mild steel type S235, manufactured by HPLC. b) Top view of a single-layer coating of NiCrBSi+60%WC on mild steel type S235 with 20 tracks next to each other on a pipe section, manufactured using HPLC.

With a powder mass flow of approx. 6.6 kg/h, a volume deposition rate of 508 cm^3/h can be achieved, which leads to a deposition rate of 6.5 kg/h for the alloy investigated here, at a calculated density of approx. 12.8 g/cm^3. The track offset or the step width of 2.5 mm was chosen in order to keep the overlap of the individual tracks small. This results in an area rate of 1.6 m^2/h. In comparison with the above-mentioned literature values for hybrid coating processes, these figures represent a significant increase. The process speed, for example, can be increased by a factor of 10. With a laser power of only 2 kW, this results in a considerable increase in productivity, which would otherwise only be possible with a significant increase in laser power.

4.2. DED with plasma arc preheating

The results of the hardness measurement of all welding tests are shown in Figure 4. The hardness curve is as expected for the welding tests without preheating by the plasma arc (Figure 4 a)). The hardening in the HAZ takes place at a level of 800 HV1 – 900 HV1, which corresponds to a hardness range of martensite at a carbon content of approx. 0.8 % [19]. The HAZ of the high carbon rail steel becomes martensitic and hardens due to the high cooling rates of the DED process and the lack of preheating. The results of the hardness measurements of all welding tests with preheating by the plasma arc at different parameter settings (see Table 1) are summarized in Figure 4 b). In principle, the hardenings in the HAZ are comparable with the DED process without preheating (Figure 4 a)). Five samples show a slight tendency to less high hardenings in the range of 690 HV1 – 707 HV1. Since there are samples from all parameter ranges, no clear correlation between this tendency and the selected plasma parameters can be established. It can be assumed that only a partial transformation to martensitic structure has taken place in these samples within the HAZ.

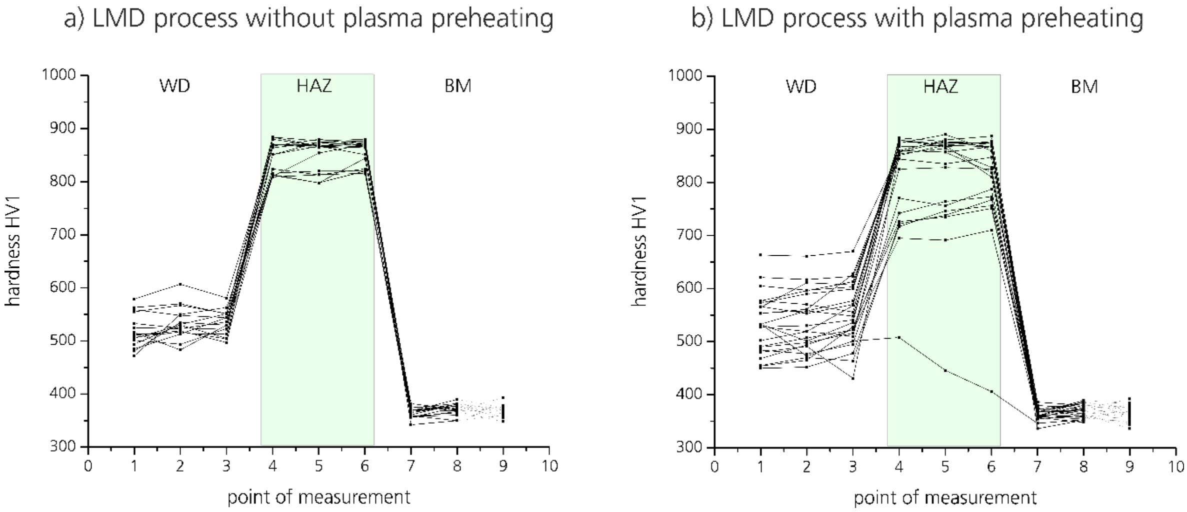

Fig. 4. a) Hardness profile HV1 of the DED build-up welds without leading plasma arc from the outer edge of the coating via the weld metal (WD), heat-affected zone (HAZ) to the base metal (BM) b) Hardness profile HV1 of the DED build-up welds with leading plasma arc

In order to further reduce the hardening effect and to further increase the heat input during preheating, one possibility is to further increase the power of the plasma arc. At a current strength of more than 160 A of the main arc, however, the arc pressure pushes melt out of the melt pool. This ejection, however, impedes the subsequent coating process, so that the process power of the plasma arc is limited. Figure 4 b) also shows a hardness curve that does not show any hardening in the HAZ area and thus represents the actual goal of the preliminary process configuration. A closer examination of this sample revealed that it was applied directly next to the edge of the workpiece. It is assumed that this edge position led to a strong heat accumulation and therefore sufficient heat was present in this zone, which could sufficiently reduce the cooling speed.

4.3. DED with plasma arc remelting

Figure 5 shows an example of the result of the tests with a trailing plasma arc. The smoothing effect can already be clearly seen in the top view of the sample. The optical surface measurement also shows a significant reduction of the mean roughness value when suitable parameters are selected. With an average mean roughness value of S_a= 2.45 µm, the roughness value of the coating can be reduced in comparison to the reference surface with S_a= 9.518 µm by approx. 76 %. A closer look still needs to be taken at the resulting quality of the embedded carbides. Due to the remelting process of the plasma arc, there is a risk that the carbides will melt and decompose. This process can lead to a decrease in wear resistance.

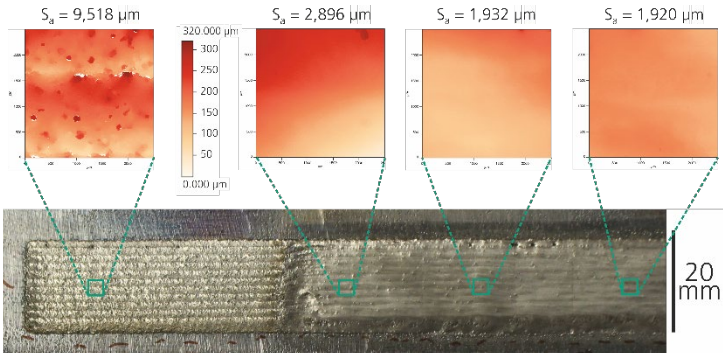

Fig. 5. a) Experimental set-up of the DED process in the laboratory with a plasma torch arranged in a leading or trailing order, depending on the welding direction b) Schematic diagram of the arrangement of the energy sources

5. Summary and outlook

In this paper different laser and plasma arc combinations for the application as deposition welding process were presented. The hybrid combination with a common process zone of laser and plasma arc shows promising results regarding the possible process speeds due to the supporting effect of the laser radiation. For the coating of large surfaces, the achievable feed rates of this hybrid approach can significantly increase the process speeds of the PTA-Process by up to factor 10. In addition, two process approaches were presented in which the plasma arc should support the DED process in a leading or trailing position. A sufficient preheating by a leading plasma arc could not be achieved. As a result, on the basis of this study, it can be concluded that a leading plasma arc is not sufficient to weld steels with high carbon contents without martensitic hardening. A trailing plasma arc, on the other hand, can contribute to a significant smoothing of the coating surface. One area of application is in the field of industrial cutting tools. An improvement in the surface quality of wear protection coatings could reduce the friction between two knives in cutting tools and thus improve tool life and cutting quality.

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