Influence of external magnetic fields on the coatings of a cascaded plasma generator

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Abstract. Cascaded single cathode single anode plasma generators represent a novel design in plasma spraying. They promise to combine the advantages of cascaded plasma generators, e.g. a higher plasma enthalpy and stability, with the simple design of the well-established non-cascaded single cathode single anode generators. In this paper, the electric arc of such a cascaded plasma torch (SinplexPro™-90, Oerlikon Metco) is manipulated by magnets mounted on the torch casing with the aim of moving the anodic attachment point. To analyze the effect on the coating properties, alumina (Amdry™ 6062) coatings are deposited using two operating parameters and two magnets of different remanences. The resulting coatings and their porosity, microhardness as well as phase composition are presented. Furthermore, measurements of the height profile of the spray spot, exhibiting an asymmetric shape, are shown. Consequently, the influence of the different process parameters and applied external magnetic fields on the coating properties is discussed.

1. Introduction

The development and application of plasma torches has gained importance in recent years. In atmospheric plasma spraying, plasma torches are used to generate thermal plasmas. The high temperature of the resulting plasma jet allows to process nearly any congruently melting material [1]. The most commonly used plasma torches have a single cathode and a single anode [2]. This design leads to a rather unstable behavior of the electric arc [3] and thus, the plasma jet [4], which, in turn, results in varying particle in-flight properties [5, 6]. Novel plasma torch designs utilize a cascaded neutrode between the cathode and anode to increase the enthalpy of the plasma jet and to reduce its fluctuations [7, 8]. Examples of such torches are the TriplexPro™ (Oerlikon Metco), Delta (GTV), KK (AMT) and the SinplexPro™ (Oerlikon Metco). In contrast to the first two, the SinplexPro™ and the KK have only one anode and one cathode, thereby combining the simplicity of a single cathode single anode plasma torch with the expected benefits of a longer and more stable electric arc due to the cascaded design.

It is not conclusively investigated whether the position of the anodic attachment point of the arc stays constant during the process or a movement of the attachment point applies for different process parameters. If the arc attachment point is fixed, it can be expected, that the increased length of the arc in case of the cascaded design leads to a higher intensity of the thermal loads on the anode and consequently to an increased thermal degradation. If this assumption applies, one possible method to reduce the thermal load on the anode might be to force the attachment point to change its position by...
applying a magnetic field, which induces a Lorentz force on the electric arc \([9–12]\). With the utilization of a permanent magnet to apply magnetic fields, as proposed in this study, it is expected that another position on the anode will be physically more favorable for the electric arc to attach on. Such a manipulation could affect the plasma jet and thus, the particle injection, the deposition rate and the coating properties. In the current state of the study, the investigations focus merely on the feasibility of such a manipulation and its possible effects on the coating properties. To the knowledge of the authors, there has not been any study regarding the influence such a manipulation on the coating properties in case of cascaded single anode single cathode plasma generators, so far. Here it must be noted that, Guggenheim et al. have already reported a possible movement of the arc attachment point by means of permanent magnets in \([13]\).

Therefore, the effects of an external magnetic field on the coating properties applied using a cascaded single anode single cathode plasma torch were investigated with the aim of proving the feasibility of moving the electric arc and its attachment point in such a plasma torch. The possible influence of a manipulation of anodic arc-attachment point on the resulting coatings properties, i.e. porosity, microhardness, thickness and phase composition, is the main focus of this study.

2. Experimental and materials
To manipulate the electric arc and anodic arc root, permanent magnets were mounted on the plasma torch (SinplexPro™-90; Oerlikon Metco, Pfäffikon, Switzerland) as shown in Figure 1. The magnets were placed outside of the plasma torch on top of its anode. The setup results in a magnetic field which is aligned perpendicular to the current flow. This leads to a Lorentz force \((F_L)\) acting on the electric arc, which directs it towards the permanent magnet and should move the attachment point in the same direction. Permanent magnets with different remanences of \(B = 680\) mT and \(1,200\) mT were used for the manipulation. As the aim of these investigations was proving the feasibility of this setup, the chosen remanences were not adapted to the process parameters.

![Figure 1. Setup of the plasma torch and the permanent magnet for the manipulation of the electric arc (conventional current direction)](image1)

As a first step, the attachment point of the electric arc was determined by head-on images of the plasma torch. This procedure is comparable to investigations conducted in \([4, 14]\). The setup used in this work is shown in Figure 2. To capture the highly dynamic events in the plasma torch, a high-speed camera (dimax HD; PCO AG, Kelheim, Germany) with a framerate of \(f = 34,473\) Hz \((\Delta t = 29\) µs\) was used. Thermal plasmas exhibit strong emissions. To attenuate the brightness of the
resulting images, a stack of neutral density filters (OD0.9+OD0.5+OD0.4) were mounted on the lens, which were combined with a bandpass filter for a wavelength of 694 nm (FWHM: 10 nm). Prior to the recordings, an alignment image was taken as shown in the upper right part of Figure 2. This image was used to determine the position of the nozzle in the following head-on recordings of the plasma column.

In the lower right part of Figure 2, an image recorded during the process is shown. The point with the maximum intensity is assumed to represent the center of the electric arc, as the light emissions are higher in this region due to the elevated temperatures. Additionally, this point indicates the direction of the arc attachment point. To establish a statistical basis for the determination of the arc attachment point, 256 consecutive images were recorded and evaluated. Subsequently, the points of maximum intensity were determined for all images using a custom image processing tool.

The influence of the external magnetic field was investigated using the parameters given in Table 1. With each parameter set, alumina coatings were applied on two specimens to observe the effect of the external magnetic fields on the coating properties. The feedstock powder (Amdry™-6062; Oerlikon Metco, Pfäffikon, Switzerland) consists of Al2O3 particles with a nominal size distribution of -45+22 µm. Round specimen with a diameter of 25 mm and a thickness of 7 mm made of S235JR structural steel were used as substrate material. Prior to the coating deposition, the substrates were grit blasted to a roughness of Rₐ ≈ 8.5 µm and a preparation grade of Sa 3. During the deposition, the plasma torch was moved in a meander shape at a standoff distance of dₛ = 100 mm over the substrate material with a transversal speed of v = 1 m/s, a gap of d₉ = 5 mm between the meander for n = 20 passes in total. The powder was injected with a carrier gas flow of V₉ = 5 SLPM at a powder feeding rate of mₚ = 17 g/min through an injector head with an internal diameter of 2 mm.

To observe the influence of the magnetic field manipulation on the coating thickness, it was measured at ten positions at two specimens using the eddy current method (DUALSCOPE® MP40 EAW3.3; Helmut Fischer GmbH, Sindelfingen, Germany). The hardness of the coatings was determined by microindentation (MICROMET™ 1; Bühler Ltd. Illinois, USA) in the cross section with a load of mᵢ = 100 g, which was held for a period of t = 15 s. For each parameter set, nᵢ = 20
points on two specimens were investigated to achieve a statistically relevant database. Furthermore, the porosity of the coatings was measured at these cross sections by optical analysis of ten images with the software ImageJ. Phase identification of the specimen were conducted using an X-ray diffractometer (XRD 3000; Seifert, Ahrensberg, Germany), which is equipped with a Cu-Kα X-ray source generating a wavelength of 1.540598 Å. The incidence angle was kept constant at 𝜔 = 10° while 𝛛 was measured between 20° and 80° in steps of 0.05° holding each position for 5 s.

Table 1. Designation of the investigated process parameters and the applied external magnetic flux density.

| Designation | Current [A] | Gas flow rate Ar/H₂ [SLPM] | Magnetic flux density B [mT] |
|-------------|-------------|----------------------------|-----------------------------|
| A₀mT        | 540         | 52 / 8                     | 0                           |
| A₆80mT      | 540         | 52 / 8                     | 680                         |
| A₁₂00mT     | 540         | 52 / 8                     | 1,200                        |
| B₀mT        | 360         | 52 / 8                     | 0                           |
| B₆80mT      | 360         | 52 / 8                     | 680                         |
| B₁₂00mT     | 360         | 52 / 8                     | 1,200                        |

To gain a further insight in the influence of the manipulation on the footprint, spray spots were applied on S235JR substrates, with the dimensions of 50 x 50 x 5 mm³, by keeping the plasma torch in front of these specimen at a stand-off distance of 100 mm for a duration of 3 s. The height profile of these spray spots was measured by confocal laser microscopy (VKX 210; Keyence Deutschland GmbH, Neu-Isenburg, Germany).

3. Results and discussion

In Figure 3, the results of the head-on recordings are displayed for the parameter set A. The accumulated red dots represent the points of maximum intensity for 256 consecutive head on images. The dashed lines are the center lines of the anode nozzle, the dotted line is an auxiliary line used to follow the movement of the arc attachment point. Without an external magnet field, the 256 points of maximum intensity are located in a restricted area at the top right of the center of the nozzle. This indicates a preferential azimuthal attachment point of the electric arc for this parameter even without any manipulation by an external magnetic field. It must be note that further investigations are necessary to conclude, whether this preferential azimuthal attachment point is valid for a longer time and if they apply for other process parameters as well.

Figure 3. Arc attachment points, determined by high-speed videography for the parameter A with no external magnetic field, A₀mT, and the same parameter manipulated by two magnets with different magnetic flux densities, A₆80mT and A₁₂00mT.
The manipulation by an external magnetic field of 680 mT led to an upward movement of measured maximum intensity, implying a position change of the arc attachment point. While moving upwards, the measured maximum intensity was shifted towards the vertical center line, which is ascribed to the circular form of the anode. A similar movement of the attachment point was observed for the process parameter A1200mT, even though this shift seems to be slightly smaller. The observed movement of maximum intensity corresponds to the expected direction for a movement of the attachment point. The external magnetic field induces a Lorentz force, which affects the electric arc and consequently moves the arc attachment point to a different position. For the parameter set B, which is not shown here, a similar but somewhat smaller movement of the arc attachment point was observed. These first results prove the feasibility of the proposed manipulation of an electric arc in a cascaded one cathode one anode plasma torch by an external magnetic field. However, these results need to be validated as the overall timespan of the consecutive 256 images was limited to trec ≈ 7.4 ms.

Figure 4 shows micrographs for the non-manipulated samples A0mT and B0mT. The parameter A0mT led to a coating thickness of about t = 236 µm. Parameter B0mT exhibits a coating thickness of t = 131 µm. Considering the relatively low powder feeding rate of mp = 17 g/min, these coating thicknesses are quite remarkable indicating a high deposition efficiency for the parameter set A. The porosities of these coatings were determined to be approx. P = 7.4 % for parameter A0mT and P = 10.9 % for parameter B0mT.

Table 2 shows the measured thickness and its standard deviation as well as the determined porosity of the coatings applied with the parameter sets A and B. While the thickness of the coating A0mT was about 236 µm, the manipulation of the plasma torch by the external magnetic fields led to an increased coating thickness of 285 µm and 284 µm. This indicates that there is an influence of the manipulation on the coating properties. However, this effect was only observed for the parameter set A. Parameter set B shows a rather constant coating thickness in the range of 124 µm to 131 µm. The same can be stated for the porosity of the coatings. In case of parameter set A, the porosity ranges between 7.2 % and 8.3 %. In case of the parameter B set, it varies between 10.2 % and 11.4 %. These values show no significant influence of the arc manipulation on the fraction of the pores. Yet, as this visual...
determination of the porosity is an imprecise procedure, capturing rather drastic effects, there could be an effect on the porosity which might not be detected by this method.

| Table 2. Thickness and porosity of the alumina coatings. |
|-----------------------------------------------------------|
| designation | thickness [µm] | standard deviation [µm] | porosity [%] |
| A0mT         | 236            | 23.1                      | 7.4          |
| A680mT       | 285            | 13.4                      | 7.2          |
| A1,200mT     | 284            | 13.6                      | 8.3          |
| B0mT         | 131            | 11.2                      | 10.9         |
| B680mT       | 127            | 13.3                      | 11.4         |
| B1,200mT     | 124            | 8.8                       | 10.2         |

In order to further investigate the influence of external magnetic fields, the microhardness values (HV0.1) of the coatings were determined. The results are displayed in Figure 5. The mean value of the hardness of the coatings applied with parameter set A ranges between 1,158 HV0.1 and 1,229 HV0.1, compared to the hardness of the coatings applied with parameter set B, which is in a range of 993 HV0.1 to 1,064 HV0.1. The difference in hardness between parameter set A and B is in accordance with the porosities of the coatings given in Table 2. The higher hardness of parameter A seems to be based on the less porous structure of these coatings. Yet again, there is no discernible difference between the microhardness of the coatings due the manipulation by different external magnetic fields detectable. The depicted differences are too small compared to the statistical variance to identify any trend.

Figure 5. Box-and-whisker plot of the microhardness (HV0.1) of the alumina coatings for the parameters A and B affected by the external magnetic fields.

Figure 6 shows the measured XRD spectra of the alumina feedstock powder (black) and the resulting coatings as well as the positions of the peaks for α-Al2O3 (JCPDS 01-088-0826) and γ-Al2O3 (JCPDS
The spectrum of the analyzed powder exhibits the peaks of \( \alpha-\text{Al}_2\text{O}_3 \), demonstrating that the feedstock material consists of the \( \alpha \)-phase only. In the spectra of the resulting coatings, the peaks of \( \alpha-\text{Al}_2\text{O}_3 \) are comparably small in case of the parameter set B and are barely visible for the coatings applied by the parameter set A. The dominant peaks of all coatings correspond to \( \gamma-\text{Al}_2\text{O}_3 \), which is the typically prevailing phase in thermally sprayed alumina coatings \([15, 16]\). The rapid solidification of the molten alumina particles during the impact on the substrate leads to the formation of the \( \gamma-\text{Al}_2\text{O}_3 \)-phase, while the formation of \( \alpha-\text{Al}_2\text{O}_3 \) is negligible for comparably low substrate temperatures \([17, 18]\).

![Figure 6. XRD spectra of the alumina feedstock powder (Amdry™ 6062) and the applied coatings as well as the positions of the peaks for \( \alpha-\text{Al}_2\text{O}_3 \) (JCPDS 01-088-0826) and \( \gamma-\text{Al}_2\text{O}_3 \) (JCPDS 00-056-0457). The spectra were normalized to their respective highest peak.](image)

The high contents of \( \gamma-\text{Al}_2\text{O}_3 \) for parameter \( A_{0\text{mT}} \) indicate, that the alumina particles were nearly fully molten during the flight. As a result, it can be stated that the cascaded single cathode single anode plasma torch operating with parameter set A is capable of fully melting and thus effectively processing alumina. The spectra of the coatings \( A_{680\text{mT}} \) and \( A_{1,200\text{mT}} \) exhibited little difference to the
spectrum of the $A_{0\text{mT}}$ coating. Similarly, for parameter set B there is no significant difference in the XRD spectra caused by the influence of external magnetic fields.

To visualize the influence of the magnetic manipulation on the deposition of the particles on the substrate, spray spots were applied for parameter set A. Spray spots are a simple and comparatively fast way to detect the local distribution of molten particles in the free jet. The upper part of Figure 7 shows the measured height profiles of the spray spots for the parameter $A_{0\text{mT}}$ as well those of the manipulated parameters $A_{680\text{mT}}$ and $A_{1,200\text{mT}}$. The direction of the particle injection is also illustrated. The particles are injected in top-down direction. For all three cases, the spray spot of the SinplexPro™-90 exhibits an asymmetric shape. Two effects are most likely responsible for this shape. The first might be the swirl of the plasma flow which deflects the particles injected from above and thus, prevents the formation of a circular spray spot. The second reason might be the fixed position of the arc attachment point leading to an asymmetric distribution of temperatures and velocities in the cross section of the plasma jet. It is known that a fixed anodic arc attachment greatly affects the plasma gas properties in the region of particle injection thus having a huge impact on the particle in-flight properties [7]. Consequently, a fixed and decentered attachment point could promote the asymmetric distribution of the injected powder in the plasma jet resulting in an asymmetric spray spot.

![Figure 7. Influence of the arc manipulation on the shape of the spray spot. Top: Height profile of the spray spots for the process parameter $A$ under influence of the external magnetic fields. Bottom: Corresponding contours for a height of 400 µm and above.](image)

If the preferential attachment point of the electric arc is manipulated by external magnetic fields, it should have an influence on the shape of the spray spot as well. This effect can be observed by comparing the height profiles shown in Figure 7. To facilitate a comparison, the contours for a height of 400 µm and above were drawn. They visualize the effect of the shift in the arc attachment position due to the magnetic manipulation on the shape of the spray spot. The shape of the spray spot becomes slightly broader with increasing magnetic remanence. Although this qualitative comparison shows only slight differences, it is in accordance with the measured maximum intensities shown in Figure 3. It can be expected to observe a more pronounced effect by using magnets with higher magnetic remanences or at different positions.
4. Conclusions
This study investigated the possible effects of external magnetic fields on a cascaded plasma torch. The position of the arc attachment point was determined and its change due to the manipulation was observed. Subsequently, the effect of this position change on the spray spot was visualized. The influence of anodic attachment manipulation on the applied coatings and their properties was examined. The results can be summarized as follows:

- Cascaded single cathode single anode plasma torches, like the SimplexPro™-90, can exhibit a preferential arc attachment point for certain parameter sets
- It is possible to manipulate the anodic arc root in such plasma torches by external magnetic fields
- This manipulation has an influence on the particle deposition leading to different shapes of the spray spot
- The effect on deposition showed, so far, no pronounced influence on the resulting coatings’ porosity, phase composition and hardness

As the presented results are first investigations, further research is needed especially using magnets with adjusted magnetic flux densities and at different positions to confirm these results and to evaluate the effects of the manipulation by magnetic fields in plasma spraying in detail. Supplementary measurements of the coating hardness and its porosity are necessary to improve the statistical basis and to detect a possible effect of the manipulation on the coating properties. The authors aim to investigate the effect of the arc attachment position on the temperature and velocity distribution of the plasma jet. For this purpose, simulations of the plasma torch as well as the resulting plasma jet will be conducted and supplemented by computer tomographic measurements of the plasma jet temperatures.

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