Letter

Anode spots of low current gliding arc plasmatron

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Received 16 April 2020, revised 10 July 2020
Accepted for publication 16 July 2020
Published 13 August 2020

Abstract

In this work a gliding arc plasmatron consisting of a filamentary discharge rotating in a nitrogen vortex flow at low DC current \( I = 100 \text{ mA} \) is investigated. The gas flow swirl of the plasmatron is produced by six tangential gas inlets. The Reynolds number of the nitrogen flow through these tubes at the flow rate of \( Q = 10 \text{ slm} \) amounts to about 2400, which is in the intermediate range. Under these conditions, the formation of micro-vortices can be caused by small gas flow disturbances like e.g. a tube edge. The operation of the GA plasmatron at these conditions is accompanied by the production of plasma spots at the anode surface, namely near the gas inlets. Melted and solidified metal is found in erosion traces left by plasma spots at the anode surface. It is established that melting of stainless steel cannot be caused by an axial current of \( I = 100 \text{ mA} \) of plasma spots and an helical current is supposed. This assumption is confirmed by microscope images of eroded traces with toroidal melting areas. These experimental results corroborate a hypothesis of previous studies, concerning the gliding arc physics, about the formation of plasma objects with an axial magnetic field by the interaction of micro-vortices with the plasma channel.

Keywords: gliding arc plasmatron, anode spot, gliding arc, micro vortex, plasma plume

(Some figures may appear in colour only in the online journal)
of the characterization of the GAP plasma conditions using optical emission spectroscopy and numerical simulation, it was supposed in [10] that the electric current through these plasma objects, named in [10] as ‘plasma plume’, flows in a helical direction in respect to the GA channel axis. Moreover, using measured rotational distribution of molecular nitrogen emission spectra, it was concluded, that positive ions inside of the plasma plume possess considerably higher kinetic energy than expected based on the measured electric field strength. It was assumed in [10] that, because of the diamagnetic behavior of a plasma far away from a conductive surface, an axial magnetic field of the plasma plume core causes the formation of the plasma plume with an helical electric current, magnetization of ions and high kinetic energy of neutrals ($T_g = 5500 \text{ K}$). To test this assumption, an influence of the plasma-diamagnetism must be excluded, so the formation of a plasma core with an axial magnetic field inside of the plasma spot near the electrode can be studied. Formation of a cathode spot inside of a GAP, a contraction of the plasma channel, a drastic increase of current density, overheating and erosion of the cathode material, which are correlated with an increase of the gas flow and thereby possible turbulence, was shown in [9, 23].

Despite the absence of a reliable theoretical model, the considered effect can be already applied for the optimization of gas flow conversion. As was shown in [9, 10] at specific conditions (gas flow, electric current and plasma reactor geometry) plasma plumes can be produced in the middle of a GA plasma channel by a plasmatron operated in molecular gas flow. Based on the correlation of the plasma plume (named in [8] as ‘arc lump’) production with the formation of micro-vortices, which were established in [8], one can suppose that a source of micro-vortices by plasmatron operation in this case are the inner edges of the respective thin anode tube (diameter of 7 mm) (see figure 1). The GA channel in a reverse vortex plasmatron without a plasma plume is a filamentary discharge with a diameter of about 200 $\mu$m to 300 $\mu$m and a gas temperature of $T_g = 2000 \text{ K}$ to 2500 K. At these plasma conditions the probability of thermal dissociation of polyatomic molecules, like CO$_2$, H$_2$O and CH$_4$, can be estimated based on the rate constants in [11–13] to about 0.5 s$^{-1}$, 10 s$^{-1}$ and 100 s$^{-1}$, respectively. By the formation of plasma plumes the gas temperature increases in this part of the plasma channel up to $T_g = 5500 \text{ K}$ to 6000 K [10] and the probability of respective thermal dissociations drastically increases up to about $7 \times 10^6 \text{ s}^{-1}$, $3 \times 10^6 \text{ s}^{-1}$ and $10^7 \text{ s}^{-1}$. If the plasmatron geometry, gas flow and electric current are optimized a plasma plume will not have any contact to the surface of the plasma reactor besides the GA channel, which plasma conditions are only slightly changed by the formation of the plasma plume. At that, the electrodes of the plasma reactor are not damaged and overheated.

In the presented paper, the formation and properties of the plasma spot on the anode of a plasmatron operated with a nitrogen gas flow are shown. An anode spot is a highly ionized plasma formed at the contact area of a plasma channel to a positively biased electrode. The formation of the anode spot was studied under different pressure and voltage–current conditions (see e.g. [14, 15]).

Despite the multiplicity of studies devoted to the formation and properties of anode spots, the mechanism of initiation for these plasma objects is still subject of discussion. By analyzing the behavior of the anode surface and the nearby plasma, the most probable explanation for the formation of anode spots can be given as a combination theory, which considers magnetic constriction in the plasma together with the material fluxes from the anode as well as the thermal, electrical, and geometric effects of the anode [16, 17]. At least three modes, namely diffuse mode, foot-point mode and real anode spot mode itself can be established by the anode spot formation. The diffuse mode is a low-current mode, where the anode is inert. The foot-point mode is at intermediate current. The anode starts to be an active part in the discharge. The so called foot-points are luminous spots, which are associated with anode melting. The third mode is the real anode spot mode, which is at high current and is associated with a very high temperature (near the boiling point of the anode material) and thereby with the vaporization of the anode material [18].

The properties of anode spots, which are formed inside a GAP, are used to test the idea of an helical current produced by the interaction between micro-vortices and a GA plasma channel. Therefore, to exclude a diamagnetism of the plasma and the formation of a plasma plume, a GAP was designed (see figure 2), to provide conditions for the interaction of micro-vortices with the GA plasma channel directly near the anode. The gas flow is controlled by a mass flow controller (El-Flow Select, Bronkhorst) and enters tangentially through six gas inlets into the outer cylindrical vessel of the GAP, where a preliminary swirl is produced (see figure 2). By choosing the inner diameter of the tangential gas inlets to 1 mm, the creation of micro-vortices directly at the exit of these thin inlet tubes is achieved. A secondary swirl with a much higher velocity is produced inside the hollow cathode, which is further
accelerated in the outlet tube that is used as anode. As shown in figure 2, the minimum gap between the anode and the cathode, between preliminary swirl vessel and hollow cathode, amounts to 3 mm. Stainless steel electrodes are used in the present experiment. The inner anode diameter amounts to 7 mm. The GAP is operated with nitrogen flow of \( Q = 10 \) slm with a purity of 99.999\% (Alphagaz 1) and a total electric current of \( I = 100 \) mA DC. The applied DC power supply (XR10000, Magna Power Electronic) delivers a maximum negative voltage of \( U_{\text{max}} = 10 \) kV and a maximum current of \( I_{\text{max}} = 600 \) mA. The anode is grounded. The profile and composition of the treated electrode surface is characterized using a scanning electron microscope (SEM) (JSM6510, Jeol). Further a digital optical microscope (DigiMicro Profi, Toolcraft) with a maximal amplification of \( \times 150 \) and a resolution of 2592 \( \times \) 1944 pixel is used.

By the operation of the plasmatron a GA channel is formed. Since the electric field has its maximum at the 3 mm gap between the anode and the cathode, the filamentary discharge probably ignites in this gap and is then shifted by the gas flow in direction to the plasma source axis. During this movement a plasma channel can interact with micro-vortices, which are produced at the exit of the tangential gas inlets (see figure 2). Due to missing windows in the hollow cathode area, it is not possible to take images of the plasma channel in this region. Hence, traces on the anode, which were left by the plasma spot, are observed. We assume that the anode spot behavior is similar to the behavior of the cathode spot discussed in [9].

Under these experimental conditions (\( Q = 10 \) slm nitrogen flow and \( I = 100 \) mA DC) a cathode spot is at glow mode and practically no eroded or melted traces are observed on the treated cathode using digital optical microscope images. The top layer of the cathode is slightly changed in several places near the plasmatron axis, possibly because of ion bombardment in the cathode spot area. At the same time, eroded traces were left on the anode, which are produced due to the formation of anode spots. The grainy microstructure of melted and solidified metal differs strongly from the metal surface after machining with a lathe during the plasmatron manufacturing and can be easily distinguished in SEM images (see figure 3).

The eroded traces of plasma spots with very different dimensions from several micrometers up to several hundred micrometers (see figure 3) with a mean diameter value of about 200 \( \mu \)m are observed on the plasmatron anode using an electron microscope (SEM). The averaged electric current density of about \( J = 300 \) A cm\(^{-2}\) is estimated based on the averaged area of the eroded traces and the applied DC current of
The temperature (K) of the stainless steel wire with a diameter of 200 μm measured by applying an optical pyrometer under variation of DC current at a distance of about 1 mm from the stainless steel surface. The solid line presents the fitted linear least-square regression.

$I = 0.1$ A. This method is often applied by the rough estimation of the dissipated power density in cathode spots of an arc discharge [19]. Because the eroded area is smaller than the total cross section of the plasma channel on the electrode surface, this method gives only an overestimated current density. However, this current density is comparable to the diffuse mode value of a plasma spot of about $J = 100$ A cm$^{-2}$ determined in other experiments [17]. Most of the anode spot traces observed in our experiment are produced in foot-point mode, with an molten area (see figure 3). Based on the literature data this mode is formed by current contraction up to $J = 10^4 - 10^5$ A cm$^{-2}$. To validate this assertion, the current density which is needed to melt the anode material is estimated. To do so, the temperature of a stainless steel wire with a diameter equal to the average diameter of the eroded traces of 200 μm at different DC electric current values (Hewlett-Packard, 20 V × 20 A) are measured (see figure 4). The steady state temperature of the metal wire depends not only on heating by the electric current but also on cooling by thermal conductivity. The cooling of the treated area in our experiment is simulated by fastening the wire between two stainless steel ducts with a total mass equal to the mass of the plasmatron anode. The temperature of the wire is measured with a pyrometer (Pyroskope 202/270, Kleiber) at a distance of about 1 mm from the surface of the stainless steel plate. At that, the steady state temperature of the wire is higher than the temperature of the anode surface. The measured values can be fitted with linear regression (see figure 4) and then be extrapolated to get the current density at which the melting point of stainless steel ($T_m = 1800$ K) is reached. By doing so, the current density is underestimated because of the temperature difference between the wire and the anode surface. However, this current density amounts to about $J = 1.6 \times 10^4$ A cm$^{-2}$ and fits in the expected interval for the production of anode spots in foot-point mode. In addition, this estimated current density is about two orders of magnitude higher than the maximum current density, which the used power supply can provide in the averaged anode spot. Based on these results, it can be concluded that an axial current of the plasma spot ($I = 100$ mA) cannot cause the erosion traces observed in our experiment. Hence, a high helical current inside the plasma plume as was supposed in [10] is the most feasible interpretation of these experimental results. This assumption is surprisingly confirmed by the structure of erosion traces of anode spots observed in SEM images of the anode surface with high magnification (see figures 4–6). In the most eroded areas, a formation of mounds of melted metal with small plates of non-melted metal on the top is established. These plates, whose diameter amounts to about 10–17 μm, can be easily distinguished in SEM images by lathe traces on their surface. The direction of these traces on the surface of the non-melted area differs slightly (to several degrees) to the direction of traces of the surrounding non-treated material. All observed eroded traces of anode spots testify that the melted metal under the non-melted area is not rotated. Only one exception from this rule is found, which is shown in figure 5, where the non-melted area is turned to about 50 degrees in respect to the lathe traces in the untreated area. The thickness of the non-melted plates of 4 μm can be estimated using the SEM image presented in figure 7, where a turned plate is shown and its edge is observed. Figure 6 shows the eroded trace of an anode spot at the stage of transformation from foot-point mode to anode spot mode. This can be seen from the partially vaporized metal. At that, an area of the anode spot with a maximum temperature equal to the boiling point of stainless steel at a distance of about 20–30 μm from the axis can be easily determined.

The structure of the eroded traces left by plasma spots on the GAP anode operated with nitrogen flow differs strongly...
from the structure of conventional plasma spots discussed in the literature [14–18]. The most important difference is the non-melted plate (and therefore low current) in the middle of the eroded areas, where, based on conventional models, a maximum current density is expected. The most probable interpretation of this effect is a toroidal heating of the treated surface by an helical current, which was expected based on the just discussed measured current density. These experimental results conform the conclusion of [10] about an helical current around a core of the plasma plume, formed in the anode tube of a GAP by optimized geometry and gas flow.

Together with the observed effects in [8], an axial magnetic field is the most feasible interpretation of these experimental results. Because no reliable theoretical model exists which can directly explain the formation of an axial magnetic field by the interaction of the plasma channel with a micro-vortex, a hypothesis presented in [20] and discussed in [21] can be used by qualitatively interpret this effect. The interaction between two electrons participating in spherically symmetric oscillations was considered in [20]. This study predicts an effective attraction between electrons in a dense plasma similar to that of the Cooper pairing of electrons in superconductors [22]. The formation of an extreme high magnetic field in instabilities of this dense plasma was expected in [21]. Despite the fact that no theoretical model can be used by sufficiently interpretation of the considered event and additional theoretical and experimental studies are needed, this effect, as was shown before, can already be used for e.g. the effective optimization of gas flow conversion.

Acknowledgments

The authors gratefully acknowledge the financial support of the German Research Foundation (DFG) within the transregional collaborative research center TR87 (SFB-TR 87) and collaborative research center CRC1316 ‘Transient atmospheric plasmas: from plasmas to liquids to solids’ (Project B5), as well as the BMBF funded project ‘Methane pyrolysis’.

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