Experimental observations of arc-anode attachment in steam-argon-air environment

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Abstract. DC arc plasma torches performance depends strongly on processes near anode. Arc-anode interaction not only defines lifetime of the electrode but also influences power distribution in the plasma and flow structure of the jet. This paper presents an experimental investigation of effects of gas properties and flow conditions on an arc-anode attachment. Several optical and electric diagnostic means were used to provide complex image of behaviour of the attachment and resulting state of anode surface. It is shown that even in one particular regime of the arc-anode attachment, which is called a restrike mode, dynamic behaviour and resulting erosion of anode can be significantly different. For example with argon in arc-anode gap the anode surface melts more intensively than with air environment. Despite increased melting weaker radiation of copper vapour was found in plasma. It was also shown that control of arc-anode attachment position in air environment had substantial effect on anode erosion pattern and plasma flow behaviour.

1. Introduction
An arc-anode attachment is one of the least known and predictable phenomena in non-transferred dc arc plasma torches. In such torches an anode surface is parallel to an arc column and dynamics of the attachment is controlled by a balance of a drag by boundary gas flow and magnetic force acting on the anode attachment with heating and electrochemical processes influencing conductivity in arc-anode gap [1-3]. The anode attachment strongly influences flow of generated plasma and its position controls the arc power. In this way it affects all main parameters of generated plasma and influences a process of plasma treatment, which was observed in experimental studies [4, 5] and in simulations [6].

In classic non-transferred torches anode surface is hidden inside the torch and is not accessible easily. Authors of work [7] simulated conditions in the torch by special geometrical and flow configurations. They observed three typical regimes of arc-anode attachment behavior: steady, takeover and restrike modes. Different types of anode erosion for different modes were reported. The restrike mode is the most frequent in commercial torches as this mode is typical for the highest power and enthalpy of plasma. Restrike mode features repeated process of movement of the attachment stream wise due to drag by boundary gas flow and magnetic force and followed appearance (restrike) of new current path in upstream position leading to decay of the old attachment.

In this work a special plasma torch was used. It features an external anode and allows access of diagnostics and observations in anode region. Here the authors examine restrike modes at different flow conditions and with different gasses in anode region. Distinct behaviors as well as different types of anode erosion were observed for the same mode in dependence on environment conditions.
2. Experimental set-up and diagnostics

2.1. Plasma torch

The plasma jet generated by dc arc plasma torch WSP®H-2000 with a combination of gas and liquid arc stabilization [8] was used for the investigation. Water is utilized as the primary plasma forming medium and it mainly defines heat transfer processes in the torch. Argon is secondary medium for plasma generation. An anode of the torch is created by the rotating water-cooled copper disc, which touches the arc from the bottom. The anode surface moves perpendicular to the flow with the velocity 47 m/s, which is several times lower than the arc-anode attachment velocity and two orders lower than plasma velocity.

The arc consists of three parts: an argon stabilized cathode region, water stabilized arc column in the main arc chamber, and free arc in the anode region. The length of the stabilized parts is approximately 50 mm while the anode part of the arc can vary in the range of 16 mm, restricted by the width of the anode. The arc-anode attachment usually does not move in the whole possible range and the arc power fluctuations reach values of approximately 20 % for the total arc power of 110 kW. Plasma jet and anode attachment is shown in figure 2. The length of the jet is approximately 60 mm. Two types of arc-anode connection can be seen in the picture.

Figure 1. Sketch of dc arc plasma torch WSP®H-2000.

Figure 2. Plasma jet in two operation regimes dependent on anode position.
2.2. Conditions of the experiments
In this investigation arc current and argon flow rate, which are the main operation parameters, were kept at values 400 A and 20 slm respectively. Thus, parameters of the plasma jet at the exit of the arc chamber were constant. Anode attachment behavior was defined by a distance of the anode from the jet edge and by control of ambient gas flow in anode region. Four tests with the most prominent results were chosen to show three types of influences: an effect of the anode position, an effect of properties of gas in the arc-anode gap and an effect of air flow pattern in the arc-anode gap.

Anode position was changed by 1 mm from standard position to further one. It was expected that increase of distance would reduce temperature in the arc-anode gap and heat transfer to anode surface while amount of air dragged by anode surface to arc-anode gap will increase. The only exception in conditions is in figure 2 where gap was increased by 1.5 mm for better distinction.

Injection of argon to anode region was done as it is shown in figure 3a. Weak flow of argon of 8 slm through blower tube with outlet cross section 1x16 mm impinged upon anode surface in vicinity of plasma flow core. Anode surface dragged argon instead of air into the arc-anode gap. By comparison of experiments with and without argon blowing effect of properties of gas in the arc-anode gap was analyzed.

Injecting of air was done against anode surface movement (Figure 3b). The aim of this configuration was to compensate air drag by the anode surface and prevent anode attachment from movement across the plasma jet. Optimal flow was found to be 15 slm and it was checked that flow in such position of blower distributes in anode vicinity rather and does not influence plasma jet.

Thus four experiments are presented: 1) standard configuration; 2) wider arc-anode gap by 1 mm; 3) blowing of air into arc-anode gap; 4) blowing of argon into arc-anode gap. And three effects (three cases) will be discussed: effect of anode distance, effect of gas in arc electrode gap, effect of flow pattern in the arc-anode gap.

2.3. Diagnostic methods
Several diagnostics were used for arc characterization. Anode region was observed with a fast shutter camera from the top and the side (Figure 4a). Top view was applied as the attachment in some regimes traveled to the side of the jet as it is seen in the photograph. Statistical processing was used for visualization of fluctuating regions. Brightness distribution in every point was analyzed and effective width of the distribution was derived via Shannon entropy parameter [9, 10]. Resulting map (Figure 4b) is in relative units, shown in a color scale so that red relates to the most intensive brightness fluctuation and blue show most stable brightness areas.

Figure 3. Position of argon blower (a) and air blower (b), anode surface moves clockwise.
The arc-anode attachment was in the restrike mode during the measurement and voltage on the open part of arc had typical saw tooth pattern (Figure 5). A special processing was applied to characterize saw tooth fluctuations. Sudden voltage drops were identified by signal derivative using an adaptive threshold. A distribution of voltage drops during the restrike and periods between the drops were analyzed. As the distribution had close to Gaussian shapes only mean values are discussed.

Emission spectroscopy was done. Optical fibre bunch head was positioned so that plasma jet section on position just after the anode was projected on a slit of the head. Spectra across the plasma jet were recorded in the band from 499 to 525 nm. This range includes argon, nitrogen and copper lines and allows considerations about elements distribution in plasma jet and its vicinity.

3. Results and discussion
In the next figures (7-10) a comparison of results of different diagnostics are shown for the studied experimental conditions as it was numbered in section 2.2. They are grouped by diagnostic used. The experiment 2 is referential as in all cases only one parameters was changed with respect to the case 2: 2-1 – arc-anode distance, 2-3 arc-anode gap gas (air to argon), 2-4 arc-anode gap flow pattern (air blowing compensated boundary layer drag by anode surface). In the following text the results will be discussed according to the cases rather than grouped by diagnostics as in the figures.

3.1. Effect of arc-anode gap width (conditions 2 and 1)
Maps of fluctuations (Figure 7) of the top view show intensive local fluctuations on the side of the jet for the wider arc-electrode gap. It means travelling of the anode attachment to the side of the jet following the anode surface motion. The side view shows more intensive and localised fluctuations for the wider gap. Together it leads to a conclusion that wider gap lead to travelling of the attachment across the jet with anode surface while for close arc position travel direction is along the jet forced by
plasma boundary flows. Voltage parameters (Figure 8) changed substantially also. Wider gap led to increased period (a lifetime of the attachment) and increased amplitude of the saw tooth fluctuations while mean voltage did not change critically. In addition, figure 2 shows that wider gap change the shape of anode attachment from constricted to a wide current channel. As a result surface erosion pattern (Figure 9) changes from 0.2 mm droplets to 0.8 mm stains including small scale structures. Anode surface is also covered with a crack network which testifies lower melting intensity. However spectra of emission (Figure 10) show intensive copper lines in both cases. The difference is in propagation of copper vapour. For wider gap copper radiates also above the jet carried by anodic jet on the side of the main plasma flow.

3.2. Effect of air flow pattern in arc-anode gap width (conditions 2 and 3)
Maps of fluctuations (Figure 7) of the top view show that blowing with air in against anode surface movement forced attachment to stay under the plasma jet. Fluctuations in the view from the top became more symmetrical and in the view from the side very well distributed along the jet and anode surface. Analysis of voltage fluctuations (Figure 8) shows increased amplitude of saw tooth pattern claiming an increased range of attachment movement too. The anode surface (Figure 9) shows exceptionally low erosion. Inclined paths are visible on the surface and only at the beginning there some small structured droplets indicating the melting. Spectra of plasma radiation (Figure 10) prove drastically reduced evaporation copper as copper lines fully disappeared.

3.3. Effect of argon in arc-anode gap (conditions 2 and 4)
Maps of fluctuations (Figure 7) of the top view show that substitution of air with argon led to restoration of longitudinal travelling of the attachment. It is not dragged to the side of the jet anymore and side view also indicates very uniform distribution of fluctuation in anode vicinity. Amplitude of voltage fluctuations decreased drastically with argon but the period remained the same. Anode surface pattern also changed radically. Surface roughness increased claiming intensive melting. Nevertheless copper lines in spectra almost disappeared.

Figure 7. Fluctuation intensity maps for the studied experimental conditions. Views from the top and the side of the jet. Grid step is 10 mm.
Figure 8. Mean voltage on the open arc (circles) mean amplitude of saw tooth fluctuation (ranges) and mean period of saw tooth fluctuation of voltage (diamonds) for the studied experimental conditions.

Figure 9. Anode surface pattern for the studied experimental conditions.
4. Conclusion

This work demonstrates behavior of the arc-anode attachment in restrike mode and resulting erosion of the anode surface. The restrike mode was studied at different gas and flow conditions in the arc-anode gap. Gap width between the arc and anode was first factor which influences its behavior. For the narrow gap plasma jet boundary layer forced fast stream-wise travel of the attachment and provoked concentration of the current path at the anode to a small dot. For wider gap broader radiation channel reveal better distribution of current density and boundary flows created by anode movement controlled attachment behavior. If these boundary flows were compensated by air blowing the flows of plasma boundary took advantage again. Attachment moves stream wise but preserve its wider channel shape. It reduced melting and evaporation of anode material drastically.

Blowing of argon into arc-electrode gap reduced the effect of anode surface movement on behavior of anode attachment. It was noted that despite intensified melting of anode surface vapor is radiation significantly weakened.

The work showed that in the frame of restrike mode the attachment can behave in substantially different way, structure and resulting erosion intensity and type differs drastically. It shows importance and potential of control of flow pattern and boundary layer properties on processes in the anode region of arc and on the lifetime of anode.

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