Measuring of mean electrical conductivity of a plasma volume in hot anode area of DC arc plasma torches

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1. Introduction

Direct current (DC) arc plasma torches are used in many industrial applications like waste treatment [1] or plasma spraying [2]. A DC electric arc burns between the torches' cathode and anode. In hybrid liquid-gas plasma torches [3] or water plasma torches [4], the anode is outside and the anode area can be therefore easily observed. The bright and electric connection between the main plasma flow and the anode is called anode arc attachment and it moves typically with the restrike. During the restrike process, the attachment moves downstream along the anode surface and suddenly restrikes nearer to the cathode because of a dielectric breakdown. The process repeats and the corresponding cathode-anode voltage waveform is sawtooth-shaped. The anode area of DC arc plasma torches with an external anode has temperature above 10,000 K [5] and plasma density up to 6 g/m^3. Therefore, the plasma electrical conductivity in these areas cannot be directly measured, for example by using probes. It can be only calculated from simulations [6], or obtained indirectly from plasma temperatures measured spectroscopically [7] by using transport properties of plasmas in thermodynamic equilibrium [8]. In addition, only little has been written about measurements in the anode area of the plasma torches at ambient pressures lower than the atmospheric pressure [9]. This paper presents measurements of a mean electrical conductivity of a plasma volume in the hot anode area of DC arc plasma torch under different ambient pressures, arc currents, and argon flow rates.

2. Experiments

Our measurements were performed on hybrid water-argon plasma torch [3] with a DC electric arc stabilized by argon flow and water vortex at the atmospheric pressure as well as at the lower ambient pressures in the range of 25-95 kPa . The anode of that plasma torch is outside and the anode area was directly filmed by using a monochromatic high-speed camera with the frame rate of 300,000 fps, exposure time of 0.29 μs and pixel resolution of 256x80. The arc voltage was measured with a sampling rate of 80 MHz by using a high-voltage probe.

3. Methods

We calculated a mean plasma electrical conductivity of a plasma volume above the anode, during the restrike, when a former current path ceases to exist further from the exit nozzle and a new current path starts to exist closer to the exit nozzle. The corresponding sawtooth-shaped voltage waveform is shown in Fig. 1b. Our investigated plasma volume $\bar{V}$ is an average volume of the volumes *V*, shown in Fig. 1a. The horizontal distance *L* between the former and the new attachment equals to the horizontal length of those cylindrical volumes *V* and changes a little in each restrike period together with the corresponding voltage drop *U*. For the calculation of the mean plasma electrical conductivity, we used the following definition equation:

$$\sigma_{\bar{V}} = \frac{J}{E} = \left(\frac{0.99 \cdot I}{S}\right) \cdot \left(\frac{\bar{L}}{\bar{U}}\right), \tag{1}$$

where *J* is the average magnitude of the current density and *E* is the average magnitude of the electric field in the investigated volume $\bar{V}$.

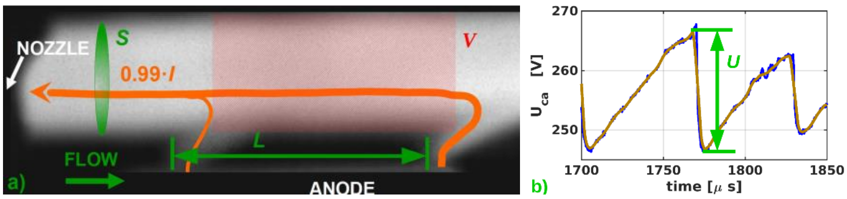

Figure 1. a) Detail of the anode area in the hybrid water-argon plasma torch obtained by the camera. **b)** Voltage waveform after removing frequencies higher than 1MHz (the background curve) and smoothed. Atmospheric pressure, electric current of 400 A, argon flow rate of 22.5 slm.

For every volume *V*, *J* was calculated as the ratio of the electric current that flows from the arc column to the anode through the attachment, to the cross section *S* of the conducting arc column. Chumak et al. [10] have measured that about 99 % of the whole arc current flows to the anode through the anode arc attachment. The values of the cross section *S* depend on the arc electric current *I* and were obtained from the model calculations published in [6] as average cross sections for the current 0.99·*I* between the distance of 3 mm and 5 mm from the exit nozzle. All used diameters of the cross section *S* were larger than the diameter of 5 mm of the bright main plasma flow, seen on the camera images through the gray optical filter 1000x, but not larger than the diameter of the exit nozzle gap (6 mm). Further, for every volume *V*, *E* was calculated as the ratio of the distance *L* to the corresponding voltage drop *U*. According to the model results published in [11], this electric field *E* is almost constant inside the plasma torch closed to the anode area. We did not take into account the fact that the potential drops on the former and new attachments during the restrike are not exactly the same.

4. Results and Discussion

The measured values of the mean plasma electrical conductivity for different arc electric currents, ambient pressures, and argon flow rates are shown in Fig. 2. The corresponding mean model values were obtained from the computations published in [6] and are available only for argon flow rate of 22.5 slm and atmospheric pressure. In the model, the presence of the anode was neglected and the position of the cylindrical plasma volume $\bar{V}$ was fixed between the distance of 15 mm and 9 mm from the exit nozzle. The position 15 mm and 9 mm were chosen in the model as typical distances where in reality the former attachment ceases to exist and the new attachment starts to exist, during the restrike.

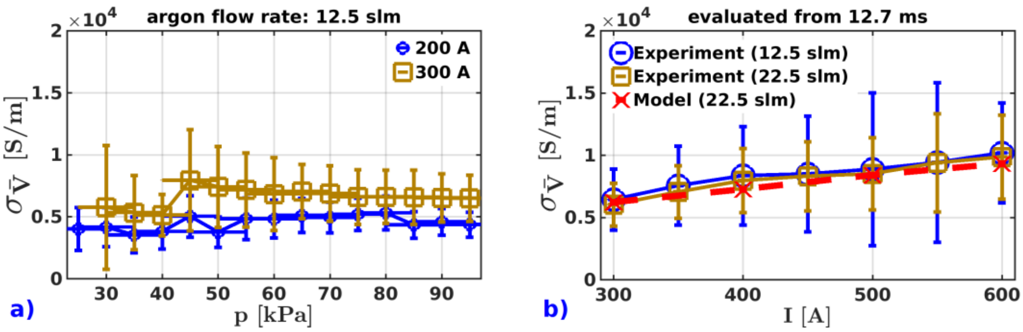

Figure 2. a) The results of the measurements at the ambient pressures of 25-95 kPa and **b)** at the atmospheric pressure compared with the model [6]. The error bars represent the level of confidence of approximately 95 %.

The mean plasma electrical conductivity above the anode did not change with the ambient pressure but it suddenly droped to a lower value when the ambient pressure changed from 45 kPa to 40 kPa (Fig. 2b). This transition was the transition from a subsonic to a supersonic plasma flow and we observed it directly by using the camera. The supersonic plasma flow has typical expansion zones with a low plasma temperature. This zones are bigger for the current of 300 A than for the current of 200 A. We think that this expansion zones decreased the mean plasma temperature as well as the mean plasma electrical conductivity above the anode. The bigger expansion zones caused the bigger drop in the mean plasma electrical conductivity values (Fig. 2b). At the atmospheric pressure (Fig. 2a), the mean plasma electrical conductivity was a little higher for the argon flow rate of 12.5 slm than for the argon flow rate of 22.5 slm and increased with the electric current, that is with the plasma temperature. The lower argon flow rate means a greater percentage of the water and a lower percentage of the argon in the plasma. It indicates that at a given temperature the steam plasma has a little higher electrical conductivity than the argon plasma.

The mean plasma temperatures corresponding to the measured mean conductivity values, according to the calculated transport properties of steam-argon plasma in thermodynamic equilibrium [8], are in Table 2. The values in bold were compared with spectroscopy measurements [5,7,12] and they agree with them.

Table 2. Mean plasma temperatures in the anode area corresponding to the measured mean conductivity

	300 A	400 A	500 A	600 A
12.5 slm	**14,000**	**15,500**	**16,500**	18,000
22.5 slm	**13,500**	**15,500**	16,000	17,500

5. Conclusion

A mean plasma electrical conductivity in the arc column above the anode was determined from measurements of arc voltage in the restrike mode and from images of the anode area recorded by a high-speed camera. The measurements were performed on hybrid water-argon DC arc plasma torch with an external anode, and the measured mean conductivity values are in agreement with the model of the same plasma torch. From our results, we were able also to detect the transition into the supersonic plasma flow, and estimate mean plasma temperatures in anode areas that are in agreement with the plasma temperatures measured spectroscopically. The similar measurements can be theoretically performed on each plasma torch where the movement of the anode arc attachment can be directly observed during the restrike mode.

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