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Current-voltage characteristics of a non-transferred plasma spray torch

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Abstract. *I-V* characteristics of a non-transferred DC plasma spray torch operating on argon and argon + nitrogen mixtures are reported. Arc voltage is decreased with increase in arc current and increased with increase in electrode gap. Arc power is higher at higher percentage of nitrogen in argon. Nottingham co-efficients were calculated using numerical method.

PACS. 52.75.Hn Plasma torches – 52.75 Rx Plasma applications in manufacturing and materials processing (etching, surface cleaning, spraying, arc welding, ion implantation, film deposition, etc.) – 52.80.Mg Arcs; sparks; lightning

1 Introduction

A plasma torch is probably the simplest tool for generating high temperature plasma. The arc is initiated between the tip of the cathode (copper with thoriated tungsten) and water-cooled anode (copper). The working gas is introduced either axially or with an additional swirl component. The later improves arc stability in the vicinity of the cathode and rotates the anode root. The gas heated by the arc emanates as a plasma jet from the torch orifice [1]. Plasma torches can be used for the preparation of protective coatings, metal cutting and drilling, melting and synthesis of fine powders to mention a few [2,3]. It is clear that plasma torches form the most critical element of the plasma processing equipment.

One of the major operational characteristics of an arc plasma torch is its current-voltage characteristics. The characteristics depend upon the nature of the design and input source. The current-voltage characteristics of an arc plasma device is basically a reflection of the energy to and from the plasma column.

To give the generalized characteristics of DC arcs, Ayrton [4] first experimentally introduced a hyperbolic characteristics relation connecting the arc voltage, arc current and length of the arc. However, Ayrton characteristics are valid for an arc between carbon electrodes in air with arc length of only a few millimeters. Nottingham [5,6] proposed a characteristics relation which is much more broader in applications. Gage [7] patented the effect of nozzle diameter on the electric field gradient in a channel for a constant current and gas flow rate. Goldman [8] reported the electrical characteristics of the argon arc at different electrode gaps. He obtained the sum of cathode and anode drops by cross plotting and extrapolating the data. He concluded that the characteristics depend on the materials of the electrodes, arc atmosphere, geometrical arrangement of the electrodes and efficiency of their cooling. Eberhart *et al.* [9] studied the characteristics of a free-burning high intensity argon arc with water cooled anode and developed an empirical relation connecting the arc voltage, current and electrode gap. Krolikowski [10] developed a new relation connecting the arc voltage, current and gas flow rate.

Das *et al.* [11] tested the applicability of the Nottingham relation to stabilized arcs in a non-transferred plasma torch by correlating the measured electrode heat losses, input power and arc current under different flow rates and gas mixture ratios. A gas mixture of nitrogen and argon has been used. The authors reported that when the nitrogen flow rate was more than 20% of argon flow rate saturation was reached in the electrode drop of potential. Wood *et al.* [12] measured the *I-V* characteristics of a low power steady-state magnetoplasmadynamic device (MPD device). Painkanger *et al.* [13] reported a detailed study of characteristics of a non-transferred arc plasma spray torch, transferred melter torch and internal diameter (ID) coating plasma torch for different gas flow rates and different mixture ratios of argon and nitrogen gas using dimensionless analysis. Brilhac *et al.* studied the dynamic and static behavior of DC vortex plasma torches with well-type cathode [14] and button type cathode [15]. Planche *et al.* [16] reported the *I-V* characteristics of the DC plasma spray torch in relation to gas flow rate, and nozzle diameter.

Only a few reports are available [11,13,16,19] on the *I-V* characteristics of the plasma spray torch. This paper is a report of the study on the current-voltage characteristics of a non-transferred plasma torch. The characteristics

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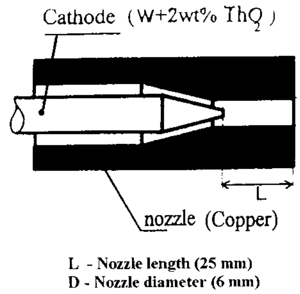

Fig. 1. Schematic of the plasma spray torch.

of the arc formed between the cathode and nozzle were measured for different flow rates and gas mixtures and electrode gaps. The plasma forming gases were argon and argon + nitrogen mixtures. Nottingham type equation was used to describe *I-V* characteristics of the torch. Nottingham co-efficients were found through the linear regression method. Simple sketch of the plasma spray torch is shown in Figure 1.

2 I-V characteristics

2.1 Experimental method

The plasma torch used in the experiment was a non-transferred arc plasma torch operating in argon and argon + nitrogen gas mixture of maximum power level of 20 kW. Cooling is provided separately to the electrodes and electrical cable connections.

Appropriate gas flow meters were used to monitor the plasma forming gas flow rates.

The arc voltage (V) was measured in between the cathode and anode using a digital multimeter and the current was measured using an ammeter.

The current and voltage were measured for different gas flow rates of argon and different gas mixture ratios of argon and nitrogen at different electrode gaps.

Experimental parameters are given as follows:

argon gas flow rate: 20–35 l/min,
nitrogen gas flow rate: 1–3 l/min,
arc voltage: 20–35 V,
arc current: 200–375 A,
cooling water flow rate: 10–20 l/min,
nozzle length: 25 mm,
nozzle diameter: 6 mm.

2.2 Calculation of Nottingham coefficient

The relationship connecting the arc voltage V, current I and arc length l is given by the Nottingham equation [20]

$$V = a + bl + (c + dl)/I^n \quad (1)$$

where a, b, c and d are constants depending on the kind and pressure of the gas and the dimensions of the electrodes. For arcs of constant length, equation (1) can be

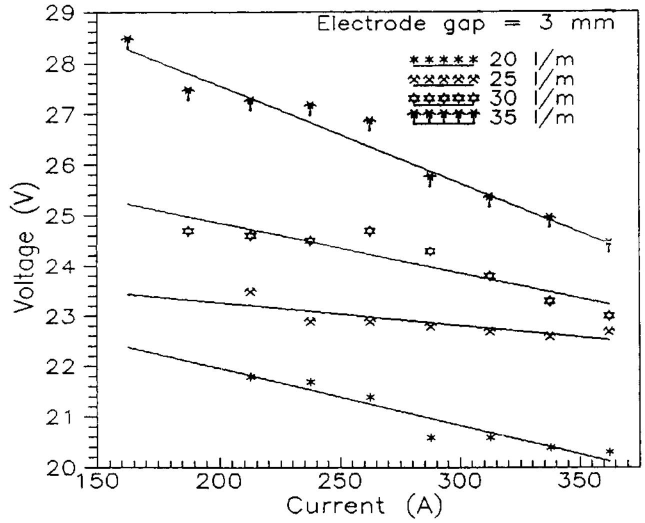

Fig. 2. Variation of arc voltage as a function of arc current for different flow rates of argon gas.

represented as [11]

$$V = a_1 + a_2/I^n \quad (2)$$

where, n depending on the anode material is 1.38 for tungsten.

For an anode made of copper $n = 0.65$–0.67 [20] and depends to some degree on the intensity of anode cooling (greater values occurred at more intensive cooling). For the torch under consideration, anode is made up of copper. The values of a_1 and a_2 can be determined by using the method of least squares.

The sum of squares of residuals (E-error) of the observed values of V is useful to find out how close the curve $V = f(I)$ fits the given data. When error $E = 0$, the curve is a perfect fit [21]. The residual sum of squares E is calculated from the following equation:

$$E = \sum_{i=1}^{N} V_i^2 - a_2 \sum_{i=1}^{N} V I_i^{0.67} - a_1 \sum_{i=1}^{N} V_i. \quad (3)$$

3 Results and discussion

3.1 Argon plasma

3.1.1 Effect of gas flow rate

Figure 2 shows the variation of arc voltage as a function of arc current for argon gas at four different flow rates. The gap between the electrodes (rod type cathode and nozzle type anode) was kept at 3 mm.

The arc voltage decreases with increase in arc current exhibiting a linear relationship. The falling trend is due to the fact that the arc conductance increases with increase in current as a result of an increase of electrical conductivity (temperature) or decrease in arc diameter or both

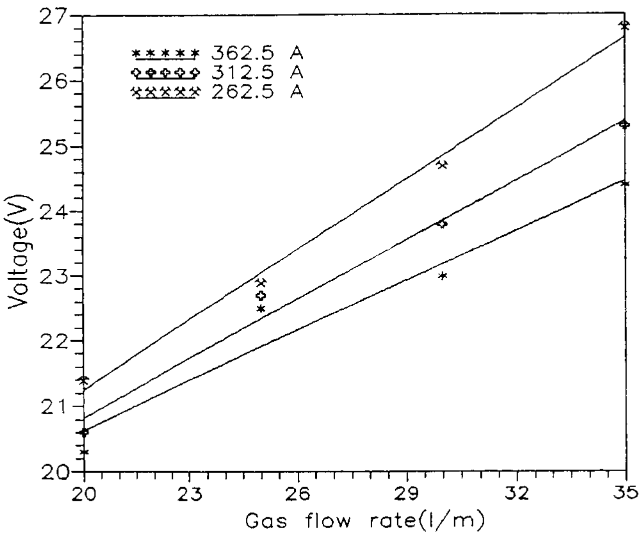

Fig. 3. Arc voltage as a function of gas flow rate of argon gas different arc currents.

[1,11,17–19]. The result is in qualitative agreement with earlier results [14–19].

From the graph it is seen that the difference of arc voltage corresponding to a difference in arc current is higher at higher values of gas flow rates. For example for the change of current from 212.5 to 362.5 A at 20 l/min, in the change in arc voltage is 1.5 V and at 35 l/min for the same current range voltage is 2.8 V.

The net power transferred to the plasma with an increase of the gas flow rate is well-known. In their works, Capetti and Pfender [18] observed an increase of about 30% of the net power transferred to the plasma using a current intensity around 400 A when the gas flow rate increased from 23.6 to 47.2 l/min and Singh *et al.* [19] reported that the increase is about 4 and 9% respectively for 50 and 180 A and for a change on the gas flow rate 20 to 30 l/min. In our study this increase is about 12.83 and 15.53% respectively for 212.5 and 312.5 A and for a change on the gas flow of 20 to 30 l/min.

Figure 3 represents the variation of arc voltage with gas flow rate for three different currents. It is seen that the arc voltage is increased with increase in gas flow rate. At higher currents the voltages are lower; for example at 362.5 A, and at a gas flow rate of 35 l/min the voltage is 24.4 V and at a current of 262.5 A at the same gas flow rate, the voltage is 26.8 V. For a given current an increase in flow rate decreases conductivity and hence the arc voltage increases. The increasing tendency observed for all the cases is attributed to the lengthening and thermal pinch of the arc column, which are both enhanced by the increase in gas flow rate [16].

3.1.2 Effect of electrode gap

Figure 4 illustrates the variation of arc voltage with variation in electrode gap at different arc currents. As electrode gap is increased the voltage is also increased. The effect is more significant than that of flow rates. For flow rate the rate of change of voltage is 0.13 V/mm and for the electrode gap the rate of change is 0.44 V/mm, for the same current of 312.5 A.

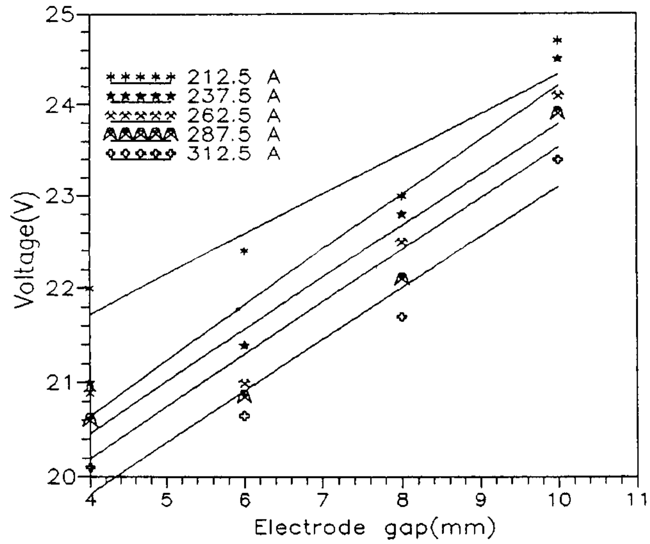

Fig. 4. Variation of arc voltage as a function of electrode gap.

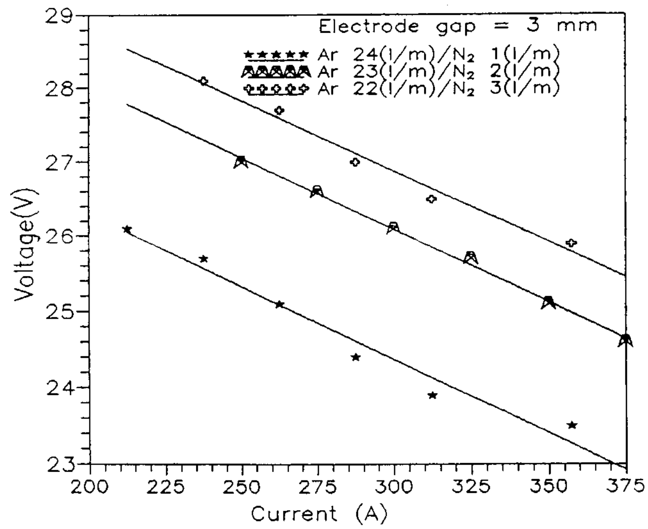

Fig. 5. *I-V* characteristics for argon + nitrogen mixture (total flow rate 25 l/min).

An increase in electrode gap increases the arc plasma contact area surrounding the same and hence the plasma temperature will decrease which in turn will reduce the conductivity of plasma resulting in increase in arc voltage.

Also, the variation of arc voltage with electrode gap is in agreement with the earlier results of Goldman [8].

3.2 Argon + nitrogen mixture

3.2.1 I-V characteristics

I-V characteristics for argon + nitrogen mixtures are also presented (Fig. 5). *I-V* characteristics for Ar (24 l/min) + N_2 (1 l/min), Ar (23 l/min) + N_2 (2 l/min)

Table 1. Nottingham co-efficients a_1, a_2 and error E.

Set No.	G_{N_2} (l/min)	G_{Ar} (l/min)	G_{tot} (l/min)	a_1 (V)	a_2 (V)	E
1	0	20	20	16.25	206.33	0.19
2	0	25	25	20.84	88.22	0.11
3	0	30	30	20.49	151.87	0.87
4	0	35	35	19.52	275.09	1.18
5	1	24	25	16.86	338.79	0.11
6	2	23	25	17.10	406.34	0.09
7	3	22	25	18.61	373.24	0.03
8	1	34	35	24.46	259.78	0.22
9	2	33	35	22.26	402.60	0.08
10	3	32	35	24.18	352.88	0.007

(G_{N_2} – nitrogen gas flow rate, G_{Ar} – argon gas flow rate and G_{tot} – total flow rate).

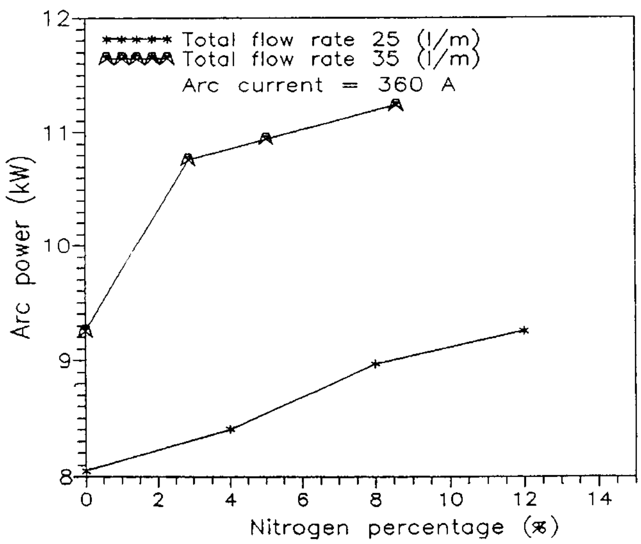

Fig. 6. Variation of arc input power with nitrogen percentage in argon + nitrogen mixture.

and Ar (22 l/min) + N_2 (3 l/min) are illustrated for constant total flow rate of 25 l/min in Figure 5. All the measurements were made at electrode gap of 3 mm.

The nitrogen percentage up to 12 has been studied. The purity of the nitrogen gas is 99.95%.

I-V characteristics for the argon + nitrogen mixture is illustrated Figure 5 at the electrode gap of 3 mm. The total gas flow rate is 25 l/min. The trend is the same as for argon gas. The voltage is higher for argon + nitrogen mixtures when compared to the results for argon gas only (Fig. 2). For example at 212.5 A current at 25 l/min for argon, the arc voltage is 21.8 V, and for argon + nitrogen mixtures in the ratio 24/1, 23/2 and 22/3 the voltages are 26.1, 27 and 28.1 V respectively. The results are in agreement with the results of Das *et al.* [11] and Paingankar *et al.* [13].

3.2.2 Effect of nitrogen percentage on arc power

In Figure 6 the variation of arc power with the nitrogen percentage is presented. Arc power (VI) is increased with increase in nitrogen percentage. The reason for increase in power is due to the fact that since nitrogen is a diatomic gas, it needs extra energy to dissociate. Nitrogen molecules get ionized after dissociation into atoms. The arc power up to 12% (by volume) of nitrogen is reported in the present study. Compared to argon whose thermal conductivity is low (mean integrated thermal conductivity of nitrogen is about three to ten times that of argon [22]) the arc voltage was higher when nitrogen was used as plasma gas [15]. At 12% nitrogen the increase in power is 15.01% over that of pure argon. The nature of variation is in agreement with the earlier results [11,13,15,16,23].

3.3 Nottingham co-efficients

Nottingham co-efficients a_1 and a_2 were calculated from equation (2) using the method of least squares. Coefficients are tabulated in Table 1 with error E.

4 Conclusion

The *I-V* characteristics for argon and argon + nitrogen mixtures for a plasma spray torch were studied. Nitrogen mixtures up to 12% by volume were studied. Addition of N_2 increased the plasma arc power.

The above aspect of electrical characteristics of arc as a function of gas flow rate, electrode gap and composition of plasma gas are important in the designing of plasma spray torch and design of power supplies for the same.

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