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Abstract

The total ion current generated by a vacuum arc plasma source was measured. The discharge system investigated allowed ion collection from the arc plasma streaming through a hemispherical mesh anode with geometric transparency of 72%. A range of different cathode materials was investigated, and the arc current was varied over the range 50-500 A. We find that the normalized ion current ($I_{\text{ion}}/I_{\text{arc}}$) depends on the cathode material, with values in the range from 5% to 19% and generally greater for elements of low cohesive energy. The application of a strong axial magnetic field in the cathode and arc region leads to increased normalized ion current, but only by virtue of enhanced ion charge states formed in a strong magnetic field.

I. INTRODUCTION

Vacuum arc ion sources are an established and versatile tool for forming high current metal ion beams [1]. In this kind of source a vacuum arc is used for generating the plasma from which the ion beam is formed. In the usual mode of operation the beam contains virtually only metal ions, with minimal gaseous ion impurity content. Application of a strong axial magnetic field in the cathode and arc region increases the metal ion charge states in the plasma and the extracted ion beam current [2].

Although vacuum arc ion sources have been developed intensely in recent decades [1], vacuum arc plasma phenomena have been investigated for over 200 years [3]. It has been shown by many researchers that the basic processes of plasma formation from the cathode material occur at non-stationary cathode spots [4-8]. Cathode spots are characterized by parameters roughly as follows: ignition and explosive time 1-10 ns, lifetime 10-100 ns, dimension $\sim 1 \mu\text{m}$, peak current density $\sim 10^{12} \text{ A/m}^2$, and plasma density before expansion $> 10^{26} \text{ m}^{-3}$. The extreme values of these parameters lead to difficulties in researching the spots.

Investigation of ion erosion rates has been reported by Plyutto and co-workers [9], Kimblin [10,11], Udris [12], Daalder [13, 14], Mesyats and Barengol'ts [15], and Brown and Shiraishi [16]. In these investigations it was found that the ratio of ion current to arc current is typically $\alpha_i = 0.1$. Furthermore it is known that the ratio of extracted ion current to arc current in vacuum arc ion sources is typically an order of magnitude less than α_i . For example, for an arc current in the Mevva V ion source of 100 A, the extracted ion beam current is usually less than 1 A. This relatively low extracted ion beam current is the result of ion loss within the anode cavity and to the extractor grids. Even state-of-the-art vacuum arc ion sources utilize only about 10% of all the ions "born" at the cathode spots. Increasing the ion source efficiency calls for increased utilization of the plasma ions, and good knowledge of the parameter $\alpha_i = I_{ion}/I_{arc}$.

II. EXPERIMENTAL DETAILS AND RESULTS

For the work described here we modified the geometry of the ion source plasma discharge and ion extraction systems in order to have it optimized for the measurements. The ion current was measured utilizing the full plasma flow. The discharge system used a cathode unit from a vacuum arc ion source, and a custom mesh anode of hemispherical shape providing high plasma transmission independent of the ion flow direction. In the measurements, much attention was paid to geometric effects so as to determine the necessary correction factors as accurately as possible, thereby accounting for ions collected by the anode and not recorded by the designated, biased ion collector.

A schematic of the experimental setup is shown in Fig. 1. The cathode surface 2 was positioned exactly in the center of a hemispherical stainless-steel mesh anode 1 of radius 109 mm. The mesh grid size was 2 mm x 2 mm, and the geometric transmittance was 72%. With this geometry, ions can “see” the same mesh regardless of their flow direction. The mesh anode was surrounded by a stainless-steel collector 4 that was negatively biased up to -100 V with respect to the mesh anode. Ion saturation was clearly reached when the bias approached -75 V. During an arc pulse, the bias of -100 V dropped less than 5 V at maximum ion current. A seven-stage pulse forming network provided arc pulses of 500 μ s duration, adjustable amplitude up to 500 A, with a repetition rate of several pulses per second. A strong pulsed axial magnetic field in the region of the cathode surface could be formed, when desired, by the magnetic field coil 5. The vacuum base pressure of the experimental system was about 10^{-4} Pa. Measurements included monitoring the arc current and the ion current to the collector electrode using a digital storage oscilloscope (Tektronix TDS 224). Typical experimental data are shown in Fig. 2.

The results of our measurements are shown in Fig. 3, where the dependence of the

(geometry-corrected) ion current is plotted as a function of vacuum arc discharge current. The relationship is linear as expected. These results indicate that the normalized extracted ion current I_{ion}/I_{arc} , does not depend on the vacuum arc current over the current range investigated.

III. DISCUSSION

The approximate independence of $\alpha_i = I_{ion}/I_{arc}$ from arc current (Fig. 3) is consistent with the findings that increasing the arc current leads to an increase in the *number of emission centers* (spot fragments) rather than changing the character of these centers. In Fig. 4 we plot the normalized ion current α_i and also the cohesive energy for a range of different cathode materials. (The cohesive energy is defined as the energy needed to remove an atom from the solid to infinity). From these data it can be seen that although the normalized ion current α_i is independent of arc current, it is far from independent of cathode material, as often assumed. The values of α_i range from 5% (W) to 19% (C). One might use an average α_i -value of 8%, keeping in mind that the actual value may be different by more than 50%.

The ion erosion rates estimated by our measurements are lower than Mesyats' [7] and Daalder's [14]. Possible reasons for these differences may lie in the details and methodology of data interpretation. Although much attention was paid to use accurate correction factors, a small systematic error in our measurement could be due to overestimating the actual transmittance of the anode mesh. However it is more likely that the contributions of macroparticles were not accurately accounted for in experiments that utilized mass determination methods [7, 14].

From Figure 4 it is clear also that the ion current and cohesive energy are roughly in opposing phase, as one would expect from the "cohesive energy rule" for vacuum arc discharges [17]. Fig. 4 demonstrates that, in general, a cathode material of greater cohesive energy will produce fewer ions for a given discharge current. The physical interpretation is clear: materials

of greater cohesive energy require more energy for the phase transformation from solid cathode material to metal plasma, and thus an equal amount of energy produces more (or less) plasma for materials of lower (or higher, respectively) cohesive energy.

It has been shown [2] that the application of a strong axial magnetic field in the vicinity of the cathode leads to an increase in the metal ion charge states in the plasma, but a mechanism for this phenomenon was not proposed. The influence of magnetic field on the normalized ion current is shown on Fig. 5. Thus the magnetic field leads to increased ion current for all cathode materials. Bearing in mind our hemispherical experimental setup, focusing (or magnetic collimation) of plasma flow by the magnetic field cannot be completely responsible for the observed ion current growth, but can only redistribute the current density on the collector. A comparison of the normalized ion current increase with magnetic field (Fig. 5) and the ion charge state increase with magnetic field shows quite similar magnetic field dependences. For example, the increase factors of normalized ion current for carbon, aluminum, copper and platinum are 2.05, 1.4, 1.65, and 1.65, and the increase factors of the mean ion charge state number for these cathode materials are 1.9, 1.4, 1.5, and 1.7, respectively. The difference in these factors for a given cathode material is less than 15%. This suggests that the effect of the magnetic field is not to just change the plasma flux distribution but rather to increase the measured (electrical) ion current via increasing the ion charge states.

IV. SUMMARY

The maximum ion current formed by a vacuum arc plasma discharge has been measured for sixteen different cathode elements. It was found that the normalized ion current (ratio of ion current to arc current, α_i) is not the universal constant of 0.1 as often claimed and used, but depends somewhat on the cathode material, ranging from 5% to 19%. Cathode materials with high cohesive energy tend to have lower α_i . This is in accordance with the empirical *cohesive*

energy rule, which originally was formulated for ion charge state distributions and arc voltage. From the present experiments it is clear that vacuum arc ion sources utilize only about 10% of all plasma ions and further ion source development should be directed to increasing the ion current extracted from the plasma.

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FIGURE CAPTIONS

- Fig. 1. Schematic of the experimental discharge system with hemispherical anode.
1 – anode mesh; 2 – cathode rod; 3 – trigger; 4 – ion collector; 5 – magnetic field coil.
- Fig. 2. Typical oscillograms of the arc current and the collected ion current for carbon and copper cathodes.
- Fig.3. Ion current, corrected for limited transmission by the mesh anode, as a function of arc current for different cathode materials.
- Fig.4. Normalized ion current, α_i , and cohesive energy of different cathode materials. The lines are to guide the eye.
- Fig.5. Normalized ion current as a function of magnetic field strength for different cathode materials.

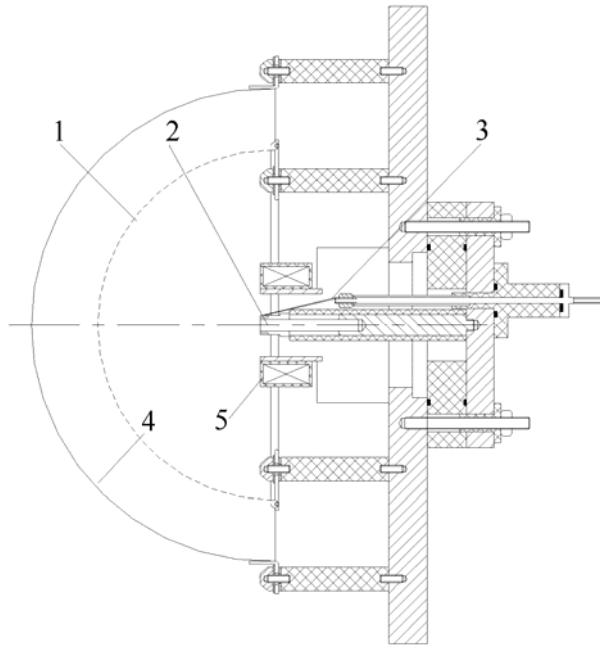


Fig. 1

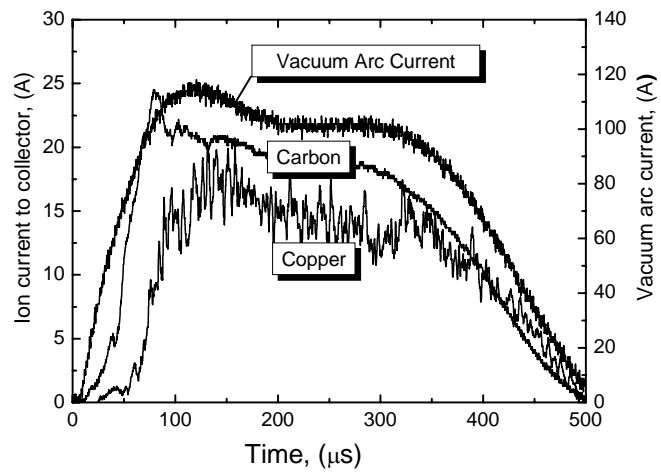


Fig. 2

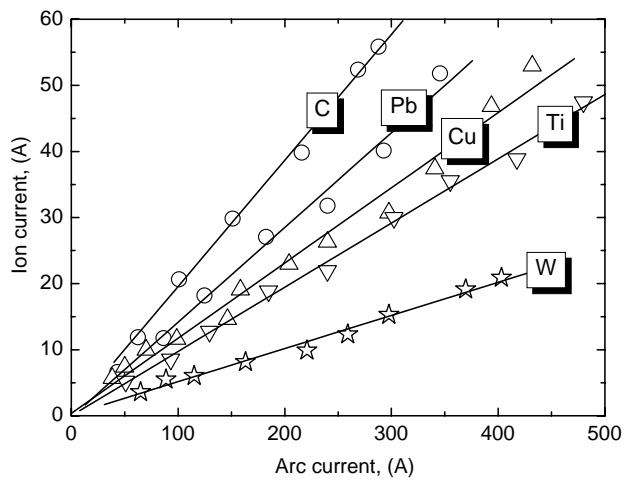


Fig. 3

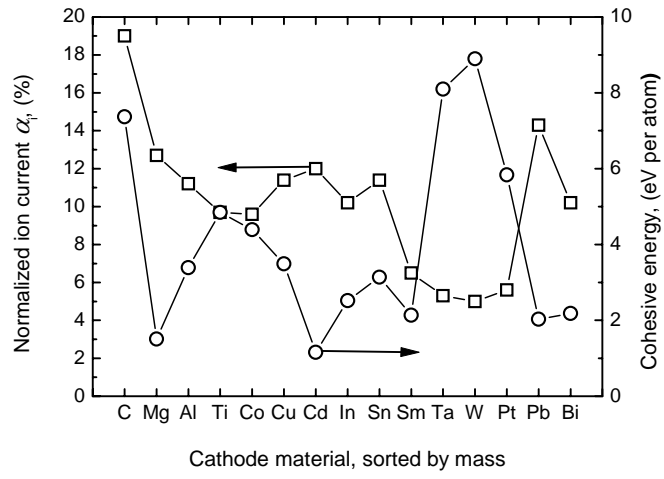


Fig. 4

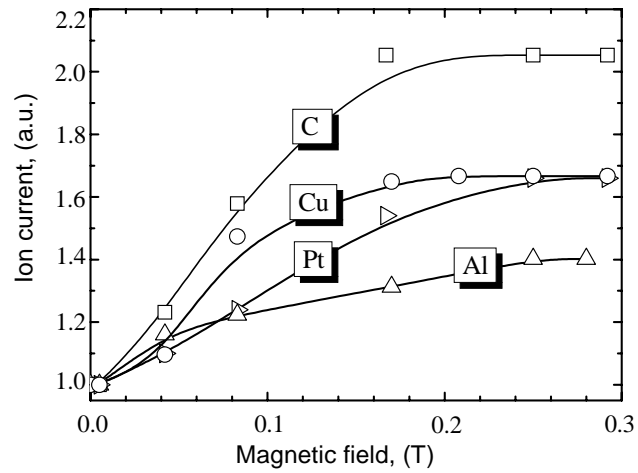


Fig. 5