CERAMIC COATINGS USING QUASI-STEADY MAGNETO-PLASMA-DYNAMIC ARCJET GENERATORS

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Abstract

A quasi-steady magneto-plasma-dynamic (MPD) arcjet with a cathode covered with a ceramic material was developed for spraycoating ceramic materials. High-velocity, high-temperature and great-number-density plasmas were generated with the MPD arcjet. This is effective for deposition of rigid films adhering strongly to substrate surfaces. The MPD plasma spraying showed that a dense uniform ceramic film with above 1200 Vickers hardness could be deposited. Furthermore, from the XPS spectra the peak area ratio of Si/Al of the coating film almost equaled that of the raw ceramic material, and the valence numbers of Al and Si did not change.

I. INTRODUCTION

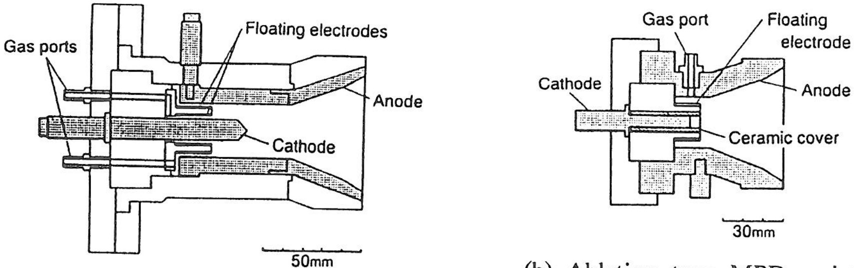
A quasi-steady magneto-plasma-dynamic (MPD) arcjet generator is a promising plasma accelerator, which has a coaxial electrode structure similar to that of conventional thermal arcjets. However, their acceleration mechanisms are different. The MPD arcjet utilizes principally electromagnetic acceleration of the interaction between the discharge current and the azimuthal magnetic field induced by it. The working gas is accelerated aerodynamically through a convergent-divergent nozzle in the thermal arcjet [1][2]. The MPD discharge feature, acceleration process and the exhaust plume can be controlled by applications of external magnetic fields [3][4][5].

MPD arcjets can produce higher-velocity, higher-temperature, higher-energy-density and larger-area plasmas than those of conventional plasma sources, because the MPD plasmas are accelerated by electromagnetic body forces in MW-class input power operations during the discharge [6][7][8]. The discharge plasmas are expected to be utilized for various material manufacturing processes [9]. In the present study, an MPD arcjet with a typical electrode structure for a high-speed plasma source, which is called the benchmark MPD arcjet, is demonstrated, and its operational characteristics and plasma features are examined. Secondly, an ablation-type MPD arcjet is developed for ceramic coatings. Discharge voltages and ablation rates of ceramic materials are examined. The cross sections of coated films are observed with a scanning electron microscope (SEM); their surfaces are analyzed by X-ray photoelectron spectroscopy (XPS), and their Vickers hardnesses are measured.

II. EXPERIMENTAL APPARATUS

Figure 1 shows the cross sections of the coaxial MPD arcjets used in the present study. The benchmark MPD arcjet, as shown in Fig. 1(a), has a conventional MPD discharge chamber for high-speed plasma sources. For ceramic spraying, this is modified as an experimental ablation-type MPD arcjet, as shown in Fig. 1(b). Both MPD arcjets are provided with straight-divergent anodes made of copper although the benchmark MPD arcjet has a longer straight part of the anode. The anode nozzles are 58 mm in exit diameter with 20° half-angle. The benchmark MPD arcjet has a cylindrical cathode 17.5 mm in length × 9.5 mm in diameter. On the other hand, the MPD arcjet for ceramic spraying is equipped with a cathode 6 mm in diameter, the side surface of which is covered with a cylindrical ceramic material. Both cathodes are made of thoriated tungsten. The composition of the ceramic cover is Al_2O_3 56 wt%, SiO_2 41 wt% and other components including CaO 3 wt%. The end of the ceramic material is set up at the same axial position as that of the upstream end of the discharge chamber, and the cathode end is placed 5 mm recessed from the ceramic cover end. Hence, ceramic vapor is supplied to the discharge and the acceleration zone by its ablation process due to a high current arc. Working gases are injected with a cathode slit / anode slit ratio of 50/50 into the discharge chamber through a fast acting valve (FAV) from a high pressure reservoir. The rise time and width of the gas pulse, measured with a fast ionization gauge, are 0.5 and 6 ms, respectively.

The main power-supplying pulse forming network (PFN), which is capable of storing 62 kJ at 8 kV, delivers a single nonreversing maximum quasi-steady current of 27 kA with a pulse width of 0.58 ms. A high PFN charging voltage is applied between the electrodes exactly at 3.4 ms after the gas pulse is triggered; arc discharge then begins. The interval between



(a) Benchmark MPD arcjet.
(b) Ablation-type MPD arcjet for ceramic coating.

Fig. 1 Cross sections of quasi-steady MPD arcjets.

discharges is about 20 s, i.e., at a repetitive frequency of 0.05 Hz. The MPD arcjet is installed on a stand in a vacuum tank 1 m in diameter × 1.2 m in length. The tank pressure is kept $2\text{-}5 \times 10^{-1}$ Pa during periodical operations. Unprepared substrate plates 4.5 mm thick, made of stainless steel S45C, are placed 50-200 mm downstream from the arcjet exit. The substrate temperature is kept a constant of 100-400 ℃ by an electrical heater placed behind the substrate.

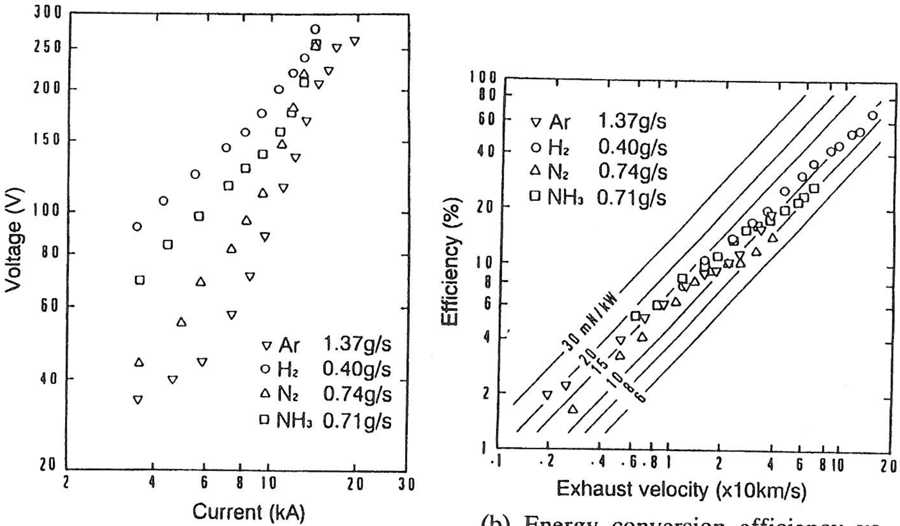
Average exhaust plasma velocities are measured by a pendulum method; energy conversion efficiencies, which are defined as ratios of the axial kinetic energy to the input power, are also evaluated [3]-[6]. The MPD arcjet and FAV are mounted on a stand suspended with a brass bar, and the position of the stand is detected by a linear differential transformer. The reaction forces are calibrated before and after a series of experiments by applying impulses of known magnitude using small steel balls in an atmospheric-pressure environment. Axial and radial profiles of electron temperature and ion number density are measured at downstream positions using an electrostatic double probe in order to understand the structure of the exhaust plume.

III. RESULTS AND DISCUSSION

FUNDAMENTAL OPERATIONAL CHARACTERISTICS AND PLASMA FEATURES OF BENCHMARK MPD ARCJET

Typical discharge voltage vs discharge current characteristics for the benchmark MPD arcjet are shown in Fig. 2(a). The discharge voltage gradually increases with the current at low current levels because the input power is mainly consumed in chemical reaction processes such as dissociation and ionization with increase of temperature. However, an increase in the discharge current drastically raises the voltage with high current levels. This is because the fraction of the kinetic energy due to electromagnetic acceleration increases with high discharge current levels. As shown in Fig. 2(b), the energy conversion efficiency increases with the average exhaust velocity. The exhaust velocity ranges from 5 to 100 km/s with various working gases, and the conversion efficiencies above 30 % are achieved with H_2.

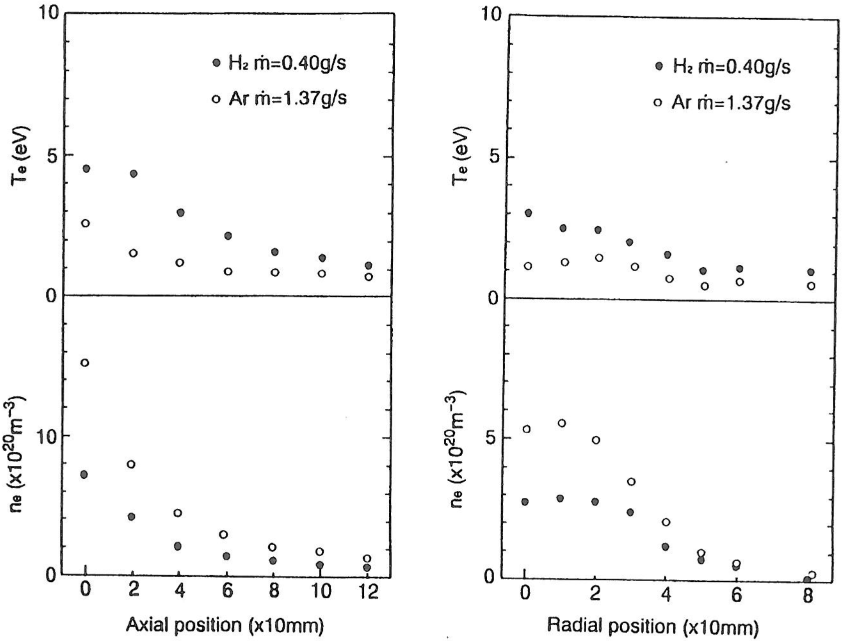
Figure 3 shows the axial and radial profiles of the electron temperature and the ion number density at downstream locations from the arcjet exit. The electron temperature gradually decreases from 4-6 eV to about 1 eV downstream on the center axis of the arcjet. The ion number density decreases to about 1×10^{20} m^{-3} as well as the electron temperature. On the other hand, the radial profile of the electron for Ar is almost flat with about 1 eV although that for H_2 has a negative slope. The ion number densities for both gases have almost constant values of $3\text{-}5 \times 10^{20}$ m^{-3} up to a radial location of about 30 mm. Also, it is noted that the heavy species temperature was expected to range from 0.5 to 2 eV in the discharge chamber [10].



(a) Voltage vs current

(b) Energy conversion efficiency vs plasma velocity

Fig. 2 Operational characteristics of benchmark MPD arcjet.



(a) Axial profiles on arcjet axis.

(b) Radial profiles at 50 mm downstream from nozzle exit.

Fig. 3 Spatial profiles of plasma parameters of benchmark arcjet at 10 kA.

Accordingly, MPD arcjets are found to efficiently produce high-velocity, high-temperature, high-density, large-area plasmas.

DISCHARGE VOLTAGE, ABLATION RATE AND DISCHARGE CHAMBER CONDITION AFTER CERAMIC SPRAYING

Ceramic coatings are performed using the ablation-type MPD arcjet with Ar at 1.37 g/s. The weights of the ceramic covers are measured before and after 100-shot operations, and the change in the weights, i.e., ablation rates, are estimated. After spraying ablated ceramic covers and electrodes are observed, and the features of the ablation arc are inferred.

In 100-shot operations, the discharge voltages for Ar with the ceramic cover were about 200 and 350 V at discharge current levels of 5 and 10 kA, respectively although they were 40-60 V with no ceramic cover. After 100 shots, the inner diameter of the ceramic cover increased to about 8 mm. The ablation rates of the ceramic cover were 1.1 and 7.5 mg/shot at 5 and 10 kA, respectively. On the inner surface of the ceramic cover many grooves existed axially; that is, current spokes were expected to be generated along the inner surface. Accordingly, since the entire discharge current flew in the narrow ceramic cover, it was inferred that the ablation of the ceramic material occurred extensively. As for the electrode condition after 100 shots, both electrodes were negligibly eroded.

COATING FILM ANALYSIS

The substrate is located 100 mm downstream of the arcjet exit. From the SEM photograph of the cross section of the substrate coated with Ar and 1.37 g/s at 5 kA, a dense uniform film 15 μm in thickness was found to be deposited. Furthermore, the Vickers hardness reaches about 1200 at a substrate temperature of 400 ℃, as shown in Fig. 4. A hard film with above 800 Vickers hardness was deposited within 3 cm in diameter from the substrate center.

Figure 5 shows the XPS spectra of the coating film and the raw ceramic material in the 100-shot operation at 5 kA. The peak area ratio of Si/Al for the coating film almost equals that for the raw ceramic cover. In addition, the valence numbers of Al and Si are found to be unchanged.

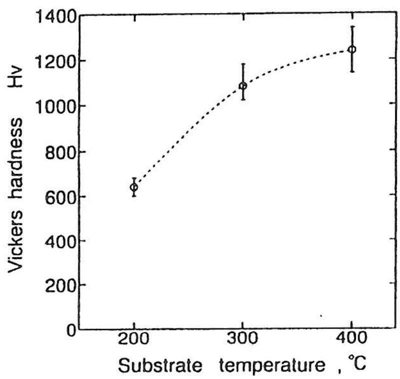
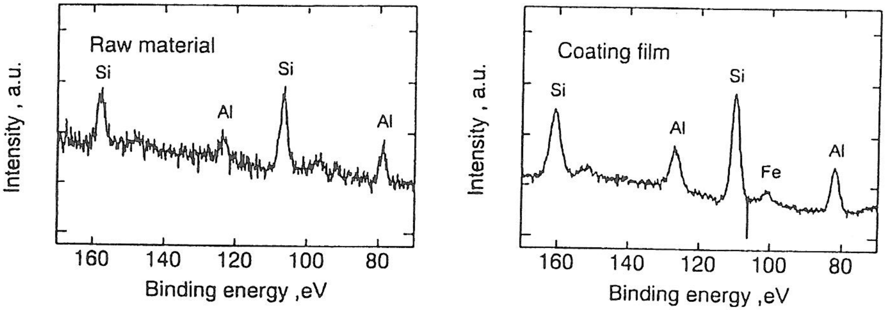


Fig. 4 Vickers hardness vs substrate temperature for Ar and 1.37 g/s at 5 kA.



(a) Raw ceramic cover. (b) Coating film.

Fig. 5 XPS spectra before and after 100 shots with Ar at 5 kA.

IV. CONCLUSIONS

A quasi-steady magneto-plasma-dynamic (MPD) arcjet generator was introduced as a high-speed plasma source, and it was found to efficiently produce high-velocity, high-temperature, high-density, large-area plasmas, making the present method effective for the deposition of rigid films adhering strongly to substrate surfaces. For applications of MPD arcjets to ceramic coatings, an ablation-type MPD arcjet with a cathode covered with ceramic materials was developed. In 100-shot operations, the discharge voltages with the ceramic covers drastically increased compared with those with no ceramic cover. The ablation rates of the ceramic covers ranged from 1.1 to 7.5 mg/shot with Ar working gas. The MPD plasma spraying showed that a dense uniform ceramic film with above 1200 Vickers hardness was deposited. From the XPS spectra, the peak area ratio of Si/Al for the coating film almost equaled that for the raw ceramic material, and the valence numbers of Al and Si did not change. Consequently, the MPD arcjet was found to have a high potential for material processing.

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