PLASMA FLOW CHARACTERISTICS OF
ELECTROMAGNETIC ACCELERATION PLASMA JET GENERATORS
FOR TITANIUM-NITRIIDE REACTIVE SPRAY COATINGS

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Abstract
In magneto-plasma-dynamic (MPD) arcjet generators, plasma is accelerated by electromagnetic body forces. A cathode-ablation-type MPD arcjet generator was developed for titanium nitride reactive spray coating. The coating characteristics were evaluated, plasma diagnostic measurement and flowfield analysis were also conducted to understand plasma features and plasma acceleration processes and to clarify relationships between the coating characteristics and the plasma flow characteristics. A large amount of N and N⁺ was expected to be exhausted with a high velocity from the MPD generator. Both the electron temperature and the electron number density were kept high at a substrate position compared with those for conventional low-pressure thermal sprayings. A chemically active plasma with excited particles of N⁺, Ti, Ti⁺ and Ti²⁺ were expected to contribute to better titanium nitride coatings.

1. Introduction
The quasi-steady magneto-plasma-dynamic (MPD) arcjet generator is a promising plasma accelerator, which has a coaxial electrode structure similar to those of conventional plasma torches[1]. However, their acceleration mechanisms are different, that is, the MPD arcjet generator principally utilizes electromagnetic acceleration of the interaction between the discharge current of kiloamperes and the azimuthal magnetic field induced by the discharge current, although the working gas is aerodynamically accelerated through a nozzle in a thermal arcjet generator[2]-[4]. MPD arcjet generators can produce higher-velocity, higher-temperature, higher-density and larger-area plasmas than those of conventional plasma sources. The discharge plasmas are expected to be utilized for various material manufacturing processes[5]-[10].

In the present study, a cathode-ablation-type MPD arcjet generator is developed for titanium nitride reactive spray coating. The operational characteristics is examined, spray coating is conducted, and the coating characteristics are evaluated. Furthermore, plasma diagnostic measurement and flowfield analysis are conducted to understand plasma features and plasma acceleration processes and to clarify relationships between the coating characteristics and the plasma flow characteristics.

2. Experimental Apparatus
Figure 1 shows the cross section of the cathode-ablation-type MPD arcjet generator for titanium nitride reactive spray coating. The anode nozzle made of copper is 58 mm in exit diameter with 20 deg half-angle. The cathode is made of titanium, and its diameter can be changed from 6 to 10 mm. Nitrogen is used as the working gas. As shown in Fig 2, a high current arc is expected to melt the Ti cathode surface, and then the ablated Ti particles react on nitrogen plasma.

Working gas is injected into the discharge chamber of the MPD generator 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 mass flow rate is controlled by adjusting the reservoir pressure and the orifice diameter of the FAV.

The main power-supplying pulse forming network (PFN) is capable of storing 62 kJ at 8 kV and 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 discharges is about 20 s, i.e., at a repetitive frequency of 0.05 Hz. The MPD arcjet generator is installed on a stand in a vacuum tank 1 m in diameter × 1.2 m in length. The tank pressure is kept 2.5 × 10⁻¹ Pa during periodical operations. Unprepared substrate plates 4.5 mm thick, made of steel or silicon, are placed 100 mm downstream from the MPD generator exit. The substrate temperature is kept 400 °C by an electrical heater placed behind the substrate. Discharge currents are measured with a Rogowski coil calibrated with a known shunt resistance. Voltage measurement is performed with a current probe (Iwatsu CP-502), which detects the small current through a known resistor (10 kΩ) between the electrodes.

Three probe measurements are made to evaluate electron temperatures and electron number densities in the downstream region, and emission spectroscopic measurements are also conducted to identify excited ion and atom species in the plasma.

3. Flowfield Calculation

Axisymmetric MPD generator flowfield is numerically calculated in order to understand nitrogen plasma acceleration processes [11]. In this analysis, we assume that (1) velocities of electron, ion, neutral are equal, i.e., one-fluid model, (2) electron temperature equals heavy species temperature, i.e., one temperature model; (3) nonequilibrium ionization process and first ionization are considered; (4) molecular vibration and rotation are not considered; (5) the Hall effect and viscosity are neglected; (6) heat conduction is considered, and (7) vapor and melted particles of titanium are neglected, i.e., only nitrogen fluid is analyzed. Conservation equations of mass, momentum and energy in addition to the magnetic field equation are a group of modified Euler equations.

The Total Variation Diminishing (TVD)-MacCormack scheme with Roe-Yee-Davis's dissipation term is used. In addition, a point-implicit method is also included in order to stabilize numerical oscillation due to chemical reaction terms, which are sensitive to temperature. The induction equation of magnetic field is solved by the successive over relaxation method, and time-dependent term is removed because we want to get only a steady-state solution. A steady-state solution is obtained by solving both the Euler equations and the magnetic field equation alternatively with coupling them together.
4. Results and Discussion

4.1 Titanium Nitride Sprayings

The MPD arcjet generator for titanium nitride reactive spraying was operated with 50 shots for N₂ and 2.5 g/s at 10 kA. The Vickers hardness of the coatings increased with increasing cathode diameter from 6 to 10 mm although the thickness decreased from 40 to 3 μm. TiN, Ti₃N and Ti mixed layers were observed. The contents of Ti and Ti₃N decreased with increasing cathode diameter, that is, TiN came to be dominant. This is explained as follows. Since the current density on the cathode decreases with increasing cathode diameter, an amount of titanium ablated by current concentration on the cathode decreases. In other words, when the cathode with the largest diameter of 10 mm was used, the TiN-richest coating was constructed by suppressing supply of excess of titanium from the cathode. Accordingly, the coating characteristics are sensitive to cathode diameter, that is, MPD flowfield characteristics dependent on cathode diameter.

4.2 Inner Plasma Flowfield Features

Figure 3 shows the calculation results of the distributions of discharge current, axial velocity, temperature, pressure, and number densities of nitrogen atom and nitrogen atom ion in the MPD arcjet generator with a cathode diameter of 10 mm at 6 kA. The discharge current is concentrated at the cathode tip, melting and evaporation of the titanium cathode are expected to be enhanced by an intensive Joule heating at the cathode tip. As shown in Fig.3(b), plasma is drastically accelerated near the cathode tip by a strong Lorentz force, and it smoothly flows downstream from the cathode tip on the central axis, that is, it is named a cathode jet. The maximal velocity of 8150 m/s is achieved at the nozzle exit in the cathode jet. Both the temperature and the pressure reach the maximum of 2.29 x 10⁷ K and 1.25 x 10⁵ Pa, respectively, at the cathode tip. As shown in Fig.3(e), the number density of nitrogen atom is high in an interelectrode region upstream from the cathode tip and in a region from the side boundary of the cathode jet near the cathode to the anode surface, i.e., except in the cathode jet. In the regions, dissociation of nitrogen molecules is active because of Joule heating in the main current conduction region as shown in Fig.3(a). On the other hand, the number density of nitrogen ion, as shown in Fig.3(f), is very high near the cathode tip, i.e., in the cathode jet. As a result, a high-temperature, high-pressure and highly-ionized plasma is generated near the cathode tip. The number densities of N and N⁺ are 8.7 x 10¹⁷ and 8.0 x 10¹⁷ m⁻³, respectively, at the nozzle exit on the central axis. Large amounts of chemically active particles of N and N⁺ are expected to be exhausted with high velocities from the MPD generator.

4.3 Outer Plasma Flowfield Features

Figure 4 shows the axial variations of electron temperature and electron number density on the central axis in the downstream region outside the MPD arcjet generator, in which the axial position of zero represents the MPD generator exit. The electron temperatures gradually decrease downstream from 25000-35000 K at the generator exit to 10000 K at an axial position of 100 mm. The electron temperature slightly increases with the discharge current at a constant axial position. The electron number densities also decrease downstream from 1.5-2.0 x 10¹⁷ m⁻³ to 2-3.5 x 10¹⁷ m⁻³. An increase in discharge current slightly raises the electron number density at a constant axial position. The electron number density measured at the MPD generator exit is lower than the calculated one as presented above. This is expected because of too simple model of calculation such as one-fluid, one-temperature and no wall losses etc. However, the calculation values are roughly acceptable within one order. Hence, both the electron temperature and the electron number density are kept high even at an enough downstream position of 100 mm, i.e., at the substrate position, compared with those for conventional low-pressure thermal sprayings.

Figure 5 shows the spectra observed on the central axis at 100 mm downstream from the MPD generator exit with cathode diameters of 6, 8 and 10 mm at 10 kA. Since the intensive spectra of N⁺ are observed regardless of cathode diameter, a chemically active plasma with a large amount of excited nitrogen ions is expected to flow even at 100 mm as
Fig 3 Calculation results of distributions of physical properties in MPD arcjet generator with cathode diameter of 10 mm at 6 kA. (a) Discharge current (b) Axial velocity (c) Temperature (d) Pressure (e) Number density of N (f) Number density of N'.

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Fig. 4 Axial variations of electron temperature and electron number density on central axis in downstream region of cathode-ablation-type MPD arcjet generator for titanium nitride reactive spray coating. (a) Electron temperature. (b) Electron number density

Fig. 5 Spectra observed on central axis at 100 mm downstream from exit of cathode-ablation-type MPD arcjet generator for titanium nitride reactive spray coating with cathode diameters of 6, 8 and 10 mm at 10 kA. (a) 6 mm (b) 8 mm (c) 10 mm

predicted from the calculation results. Furthermore, since the spectra of Ti atom, Ti⁺ and Ti²⁺ ions are observed, the excited titanium particles in addition to the excited nitrogen ions are expected to contribute to the titanium nitride reactive spray coatings.

The spectral intensities of titanium relatively decrease with increasing cathode diameter compared with those of N⁺. This agrees with the coating characteristics as mentioned above, that is, an amount of excited titanium particles with the 6-mm-diam cathode are larger than that with the 10-mm-diam cathode because an amount of titanium supplied by melting and
evaporation with 6 mm is larger than that with 10 mm. Hence, taking account of these spectral characteristics, when the spectral intensities of N⁺ are relatively high and those of titanium are very low, that is, with a larger diameter cathode, high-quality titanium nitride films, i.e., TiN-rich films are expected to be created.

5. Conclusions
The cathode-ablation-type MPD arcjet generator was operated for titanium nitride reactive spray coating. The coating characteristics were evaluated, plasma diagnostic measurement and flowfield analysis were also conducted. Large amounts of chemically active particles of N and N⁺ were expected to be exhausted with high velocities from the MPD generator. Both the electron temperature and the electron number density were kept high even at an enough downstream position, i.e., at the substrate position, compared with those for conventional low-pressure thermal sprayings. A chemically active plasma with excited particles of N⁺, Ti, Ti⁺ and Ti²⁺ were expected to contribute to the titanium nitride reactive spray coatings. The emission spectral intensities of titanium relatively decreased with increasing cathode diameter compared with those of N⁺. This agreed with the coating characteristics. Hence, when the spectral intensities of N⁺ are relatively high and those of titanium are very low, that is, with a larger diameter cathode, high-quality titanium nitride films, i.e., TiN-rich films are expected to be created.

References

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