DEVELOPMENT OF AN ELECTROMAGNETIC ACCELERATION PLASMA GENERATOR FOR ZIRCONIA AND TITANIUM NITRIDE COATINGS

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Abstract

Electromagnetic acceleration plasma generators, which are called Magneto-Plasma-Dynamic (MPD) arcjet generators, can produce higher-velocity, higher-temperature and higher-density plasmas than those of conventional thermal plasma torches, because MPD arcjet plasma is efficiently accelerated by electromagnetic body forces in MW-class input power operation. These properties are effective for deposition of rigid coatings adhering strongly to substrate surfaces.

In the present study, we newly developed two types of MPD arcjet generators for ceramics spray coatings. The one is for calcia stabilized zirconia (CSZ) ceramics which is usually used for thermal barrier coatings. The other is for a reactive spray process of titanium nitride film deposition. These ceramics coatings were deposited onto steel substrates by means of the MPD arcjet generators. The phase structure and the composition of the coatings were analyzed by means of scanning electron microscopy (SEM) and X-ray diffraction (XRD), and their Vickers hardness were measured. These analyses showed that the MPD spray process could successfully form dense and uniform ceramics coatings. In titanium nitride coatings by means of MPD arcjet generators, the properties of the coating were highly sensitive to the titanium cathode diameter and discharge current.

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Introduction

Plasma spraying process is widely used as a various material coating technique for many fields of modern manufacturing industries. And now, the plasma spraying becomes a key technology for enhancing the surface functionality of mechanical equipment. However, because of the improvement of industrial machines, the performance of the coatings is required much higher, such as strong adhesion, more corrosion resistance, higher hardness and so on. In recent held international conference and workshop, many research and development efforts devoted to the improvement of the coating quality.

An electromagnetic acceleration plasma generator, which is called Magneto-Plasma-Dynamic (MPD) arcjet generator, has a coaxial electrode structure similar to those of conventional thermal arcjet generators. However, their acceleration mechanisms are different; that is, in MPD arcjet generators, plasmas are accelerated by the electromagnetic interaction between the discharge current and the magnetic field induced by it in MW-class input power operations during the discharge, as in Fig. 1, although in thermal arcjet generators the working gas is

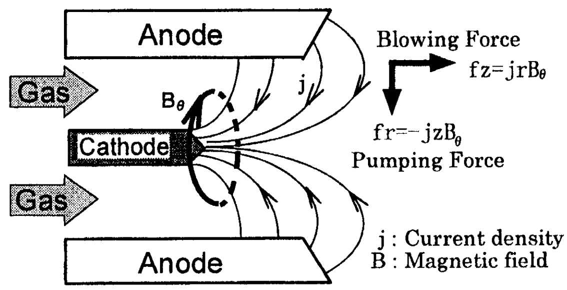


Fig. 1 Patterns of current, magnetic field and Lorentz force in MPD arcjet generator.

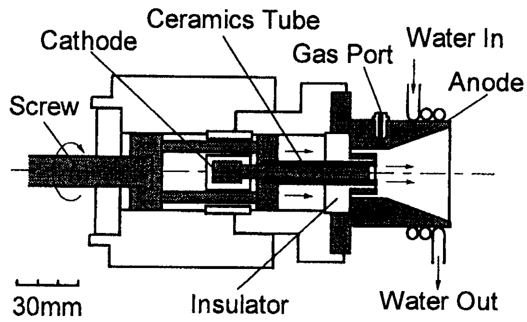
accelerated aerodynamically through a straight or convergent-divergent nozzle. As a result, the MPD arcjet generator can produce higher-velocity, higher-temperature, higher-energy-density, and larger-area plasmas than those of other conventional plasma torches can.[1-3] They are effective for deposition of rigid films adhering strongly to substrate surfaces.[4-7]

In order to apply MPD arcjet generators to ceramic spray coatings, we newly developed two types of MPD arcjet generators. The one is for calcia stabilized zirconia (CSZ) ceramics spray coating, and the other is for titanium nitride reactive spray coating. The CSZ ceramics are usually used as thermal barrier coatings, in high-temperature turbine blade applications for example. Titanium nitride has good wear resistance, corrosion resistance and heat resistance, therefore titanium nitride has many industrial applications such as wear resistant coating of cutting tools, heat resistant coating and corrosion resistant coating. However, ordinary titanium nitride forming methods are low deposition rate, and the coating is poor thickness.

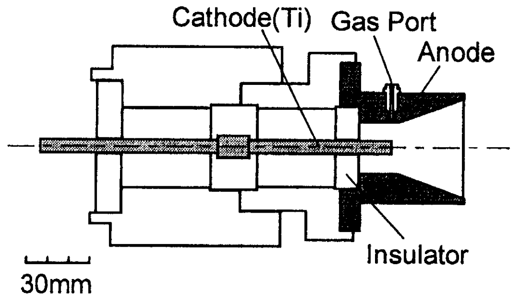
In this study, CSZ ceramics coatings and titanium nitride coatings are formed onto the substrates by means of the newly developed MPD arcjet generators, and the property of the coatings are studied. The coating properties are examined by several diagnostic techniques. The cross sections of the coatings are observed with a scanning electron microscope (SEM), and their surface structures are analyzed by means of X-ray diffraction (XRD). The Vickers hardness of the coatings are also measured.

Experimental Apparatus

Figure 2 shows the cross sectional diagrams of the MPD arcjet generators for CSZ coating and titanium nitride coating used in the present study. Both the MPD arcjet generators are equipped with a rod cathode and a cylindrical copper anode. The anode nozzle is 48 mm in exit diameter with a 20 degree half-angle and has 4 gas ports in its sidewall. Figure 2(a) shows an ablation type MPD arcjet generator for CSZ spray coating. The cathode made of ThO_2-W is covered with a tube-shape CSZ ceramic material, and working gas is Ar. 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 upstream of the ceramic material end. The ceramic material is supplied by turning the screw at the end of the MPD generator body. Figure 3 shows the schematic diagram of an ablation type MPD arcjet generator for CSZ spray coating. A high current arc



(a)



(b)

Fig.2 Cross sections of ablation-type MPD arcjet generators.
(a) For CSZ coating
(b) For titanium nitride coating

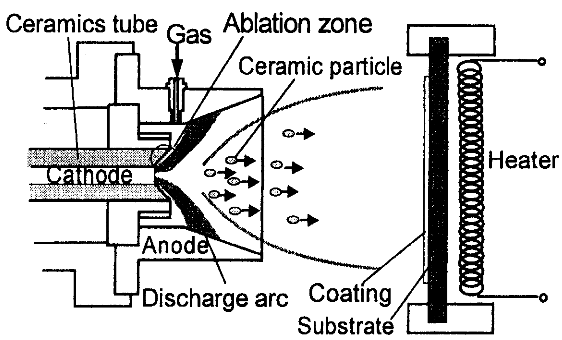


Fig.3 Illustration of ceramics spraying using ablation-type MPD arcjet generator.

between the electrodes melts the tube-shape ceramics. Hence, ablated CSZ particles are supplied to the discharge and acceleration zone by its ablation process due to a high current arc. Finally, the ablated ceramics particles are deposited onto the substrate. The tube-shape CSZ ceramics consist of ZrO_2 94 wt%, CaO 4 wt% and other components including Al_2O_3 2 wt%.

Figure 2(b) shows an ablation type MPD arcjet generator for titanium nitride reactive spray coating. The cathode is made of titanium. The working gas is nitrogen. Titanium particles are supplied to the discharge and acceleration zone by its ablation process due to a high current arc, and at the same time, the titanium particles react on nitrogen plasma. The cathode diameter can be changed from 6 to 10 mm in order to control the amount of ablated titanium particles. The weights of the titanium cathode are measured before and after 50-shot spray coating operations, and the change in the weights, i.e., ablation rates are estimated.

Figure 4 shows an illustration of the experimental system with an ablation-type MPD arcjet generator. Working gases are injected through a fast acting valve (FAV) from a high pressure reservoir. The mass flow rates of the working gases can be controlled by adjusting reservoir pressure and the orifice diameter of FAV. In this study, the mass flow rates are 4.6 g/s Ar for CSZ coating and 2.5 g/s N_2 for titanium nitride coating. The main power-supplying pulse forming network (PFN), which is capable of storing 62 kJ at 8kV, 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 and the substrate are installed in a vacuum tank. The tank pressure is kept 2-5×10^{-2} Pa during periodical operations. An unprepared substrate plate is placed 100 mm downstream from the MPD arcjet exit. In the present study, we use two type substrates. The one is 4.5 mm thick steel S45C, and the other is 0.5 mm thick silicon for the Vickers hardness measurement of titanium nitride coatings. The substrate temperature is kept constant by an electrical heater placed behind the substrate. In the present study, all the substrates temperature is kept 673 K. The surface of the substrate is polished by #100 sandpapers before spraying. 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.

Results and Discussion

Figure 5 shows the typical waveforms of discharge current and discharge voltage of the MPD arcjet generator. The discharge voltage gradually increases with the discharge current in an ablation-type MPD arcjet generator, and high input powers above 1

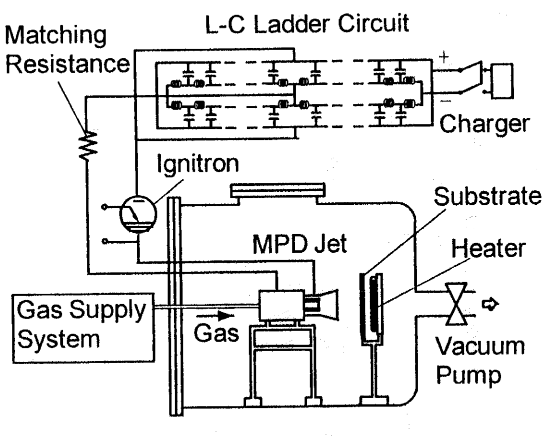


Fig. 4 Experimental system with MPD arcjet generator.

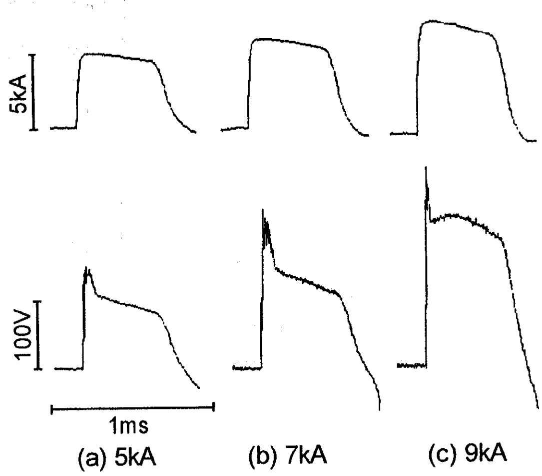


Fig. 5 Typical waveforms of discharge current and discharge voltage of MPD arcjet generator.

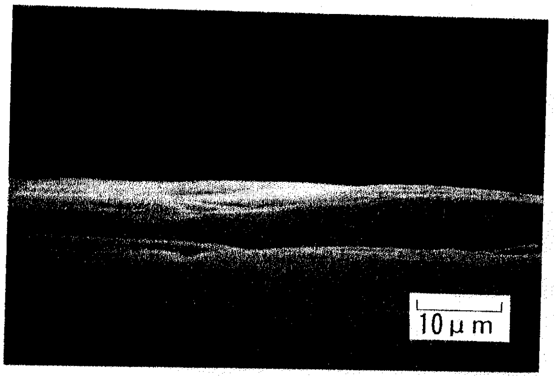
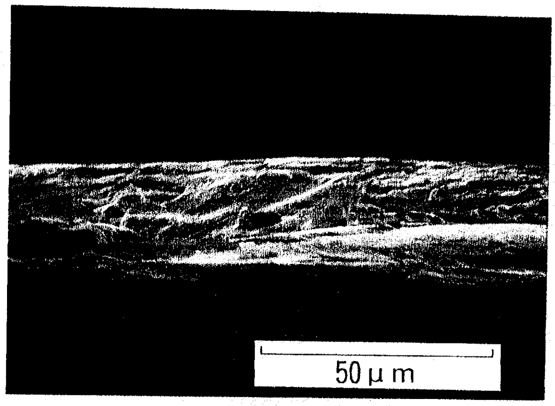
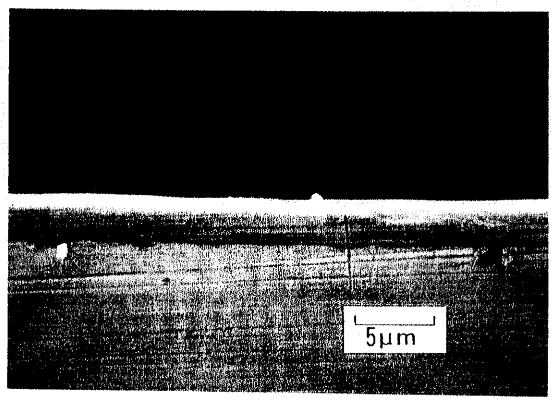


Fig. 6 Photograph of cross section of CSZ coating.

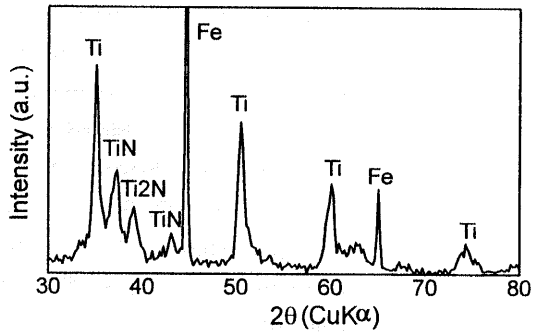


(a)

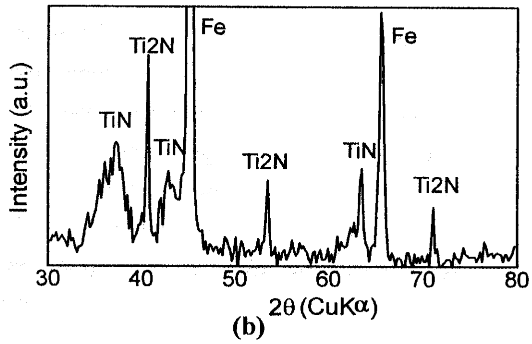


(b)

Fig. 7 Photographs of cross section of titanium nitride coatings.
(a) ϕ6 mm cathode
(b) ϕ10 mm cathode



(a)



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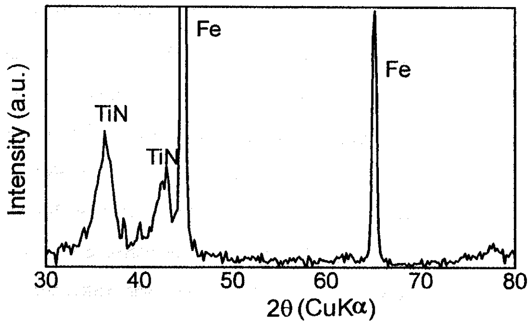

(c)

Fig. 8 X-ray diffraction patterns of titanium nitride coatings at 10 kA.
(a) 6-mm-diam. cathode
(b) 8-mm-diam. cathode
(c) 10-mm-diam. Cathode

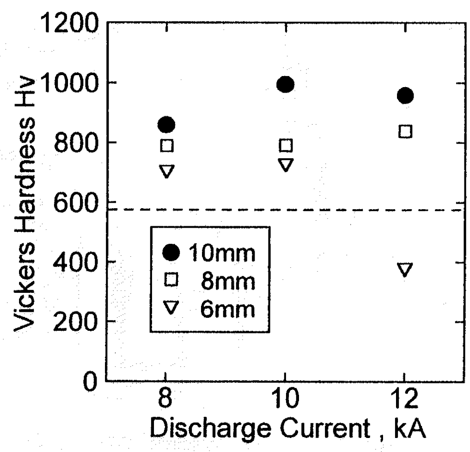

Fig. 9 Vickers hardness vs discharge current characteristics. (Substrate: Hv=580)

MW are achieved.

The cross sections of coatings were observed with a scanning electron microscope (SEM). Figure 6 and 7 show cross sectional micrographs of the ceramics coatings. Figure 6 shows the cross section of the CSZ coating in 110-shots operation at 10 kA. A dense uniform coating 10 μm in thickness is deposited onto the substrate. However, we could not obtain the CSZ ceramics coating under 10 kA discharge current. When the discharge current was lower than 10 kA, the tube-shape CSZ ceramics was little ablated. Therefore, ceramic particles could not supply to the discharge and acceleration zone, and the coating could not form on the substrate. Figure 7 shows the cross sectional micrographs of the titanium nitride coatings in 50-shots operation at 10 kA. Dense and uniform titanium nitride coatings were found to be deposited onto the steel substrate. The coating thickness was greatly changed by the titanium cathode diameter. In 10 kA discharge current, the coating thickness reached about 3 and 30 μm at cathode diameters of the 10-mm-diam. and the 6-mm-diam., respectively.

Accordingly, figure 8 shows X-ray diffraction patterns for the titanium nitride coating at a discharge current of 10 kA. Using the 6-mm-diam. cathode, a TiN, Ti_2N and Ti mixed layer was observed. However increasing cathode diameter, a TiN ratio of coatings increased. In addition, using the 10-mm-diam. cathode, a TiN mono layer could be constructed. Coating properties strongly depended on cathode diameter.

The Vickers hardness of the titanium nitride coatings was measured at the substrate center. Figure 9 shows the Vickers hardness characteristics of the titanium nitride coatings at 10 kA. The Vickers hardness reached about 1000 at the substrate center. This figure shows that the hardness of the coatings was highly sensitive to the cathode diameter and discharge current. The hardness of the coatings increased with increasing cathode diameter at a constant discharge current although the thickness decreased. The X-ray diffraction patterns indicate that TiN contents increases with increasing cathode diameter. Hence, the hardness of the coating increased. These experimental results are explained as follows. Increasing the cathode diameter, the current density on the cathode decreased, and an amount of ablated titanium particles decreased. The ablation rate was greatly changed from 0.342 mg/shot by the 10-mm-diam. cathode use to 15.1 mg/shot by the 6-mm-diam. cathode use at 10 kA. Therefore, the titanium particles are nitrided sufficiently and TiN contents increases. In other words, with the large diameter cathode, a TiN-richest coating is constructed by suppressing supply of excess of titanium from the cathode.

Conclusions

For applications of MPD arcjet generators to ceramic spray coatings, we newly developed two types of MPD arcjet generators. The one is for CSZ ceramics spray coating and the other is for titanium nitride reactive spray coating. For CSZ ceramics coating, the MPD arcjet generator is equipped with a cathode made of ThO_2-W, of which the side surface is covered with a tube-shape CSZ ceramics. On the other hand, the MPD arcjet generator for titanium nitride coating has a rod titanium cathode, and working gas is nitrogen.

The coating properties were examined by several diagnostic techniques. From cross sectional SEM photograph, a dense uniform CSZ coating was successfully deposited onto steel substrate, and its thickness reached 10 μm in 110-shots operation at 10 kA. Moreover, the MPD arcjet reactive spray coatings showed that a dense uniform titanium nitride coating with above 1000 Vickers hardness was deposited. From the X-ray diffraction patterns, coating properties strongly depended on cathode diameter of MPD generators. Using the 6-mm-diam. cathode, a TiN, Ti_2N and Ti mixed layer was observed. However increasing cathode diameter, a TiN ratio of coatings increased. In addition, using the 10-mm-diam. cathode, a TiN mono layer could be constructed. The Vickers hardness of the coating reached about 1000 at the substrate center. The Vickers hardness characteristics showed that the hardness of the coating was highly sensitive to the cathode diameter and discharge current.

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