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The Characteristics of a Low-Power-Consumption Plasma Jet and Ceramic Coatings

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The effects of the composition of plasma gases (Ar-N_2, Ar-H_2), arc current, and voltage on the temperature and velocity of a low-power (5 kW) plasma torch in the arc field free region has been investigated using an enthalpy probe. Coatings of Al_2O_3-13TiO_2 were deposited under different conditions. The results show that in the Ar-N_2 plasma, the enthalpy, temperature, and velocity change little with arc current and voltage when regulating the nitrogen proportion in the plasma gas. The hardness of the resulting coatings is 800 to 900 kg/mm^2 HV.300. For Ar-H_2 plasma, however, increases in the H_2 content in the mixture of the gases remarkably enhanced the velocity and heat transfer ability of the plasma jet, with the result that the coatings showed high hardness up to 1200 HV.

Keywords ceramic coating, enthalpy probe, low-power plasma, plasma jet, plasma spraying

1. Introduction

In thermal plasma spraying, the temperature and velocity of the plasma jet affect the heating and acceleration of the spray powder directly, which is important to the quality of coatings. It is a fundamental subject for research in thermal plasma to simulate and measure the distributions of plasma temperature, velocity, and enthalpy in the arc field free region (Ref 1). By means of a laser-doppler-velocimeter and spectral analysis, plasma velocity and temperature can be determined in some situations, but these measuring techniques require both expensive optical instrumentation and suitable measuring conditions. Besides, in some regions of the plasma jet, the temperature is less than 4000 K. Thus, the radiant intensity of atoms or ions is too small to be measured. The enthalpy probe becomes a reliable tool to measure high-temperature gas in the range from 2000 to 14,000 K (Ref 2). Recently, this has been widely applied to the study of plasma characteristics such as temperature and velocity. Swank et al. (Ref 2–4) have introduced in detail the technique of using the enthalpy probe to measure plasma temperature and velocity. In addition controlling and predicting the microstructure of the coatings is significant for improving the quality of the coatings.

Recently, an innovative plasma spray torch with low power consumption and high deposit efficiency was developed (Ref 5). It was operated at an arc current of 50 to 150 A and with voltage from 50 to 80 V. The powders were injected into the plasma jet from the nozzle inside by the carrier gas and then were transferred through the plasma flame. Coatings of Al_2O_3 can be obtained when the plasma power supply is less than 5 kW, and the deposit efficiencies of the powder can reach up to 70% with a powder feed rate of 30 to 50 g/min (Ref 6). In this article, the effects of plasma gas composition, arc current, and voltage on the enthalpy, temperature, velocity, and heat transfer ability of the low-power plasma jet were investigated using an enthalpy probe. The microstructure of the coatings in the different spray conditions also were observed under the microscope.

2. Experiment

2.1 Conditions of the Experiment and Measurement

The enthalpy probe system is shown schematically in Fig. 1. The enthalpy probe is made from three concentric copper tubes with different diameters. The inner tube and outer tube are welded together, while the middle tube is inserted between them. The inner tube has an inside diameter of 0.8 mm, providing the passage for the plasma gases to flow into and out of the probe. The outside diameter of the outer tube is 6 mm, and the outside diameter of the middle tube is 4 mm. The tip of the probe is in a hemispherical shape to decrease the disturbance to the plasma jet. The cooling water flows into the probe from the passage formed by the outer tube and the middle tube, turning back at the tip of the probe, and then out of the probe through the passage formed by the middle tube and the inner tube. Two type-K thermocouples are respectively routed into the inlet and the outlet for the cooling water to measure the temperature of the cooling water flowing in and out the probe. The cooling water has a mass flow rate of 0.032 kg/s, which is provided by a high-pressure pump. Between the pump and the probe there is a tank holding ice water to make the temperature of the inlet water constant.

The nozzle of the plasma torch for the experiment has an inside diameter of 5 mm. Plasma temperature and velocity are measured along the axis of the nozzle exit at distances of 5, 10, 20, and 35 mm from the nozzle exit. The experimental condi-

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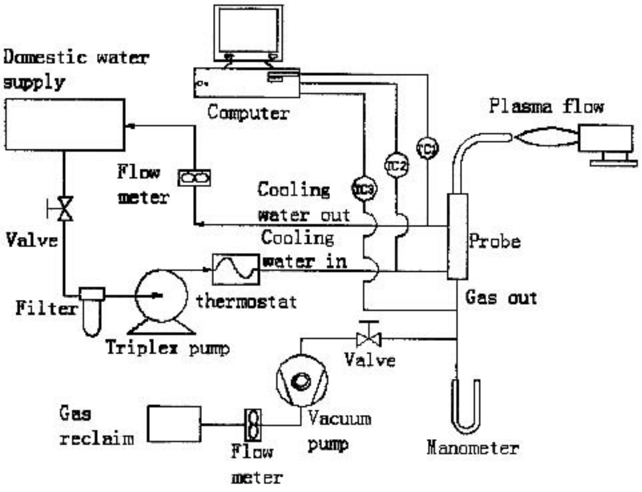

Fig. 1 Schematic diagram of the enthalpy probe system showing instrumentation

Table 1 The conditions for the measurement of the plasma characteristic by the enthalpy probe

Plasma	Current, A	Voltage, V	Ar, L/min	Nitrogen, L/min	Hydrogen, L/min
$Ar-N_2$	70	70	21.5	24	…
	100	50	24	12	…
$Ar-H_2$	70	70	24	…	12
	100	50	24	…	8.5

tions are shown in Table 1, and the plasma gases are $Ar-N_2$ or $Ar-H_2$ mixtures. Equal power (5 kW) is input with different arc voltages and currents. The measurement steps are stated as below: start up the plasma system and ignite the arc; adjust the arc current, voltage, and flow rate of the plasma gases to make the arc stable; close the gas exit of the probe to make sure that no gases are flowing through the inner tube of the probe; record the inlet and outlet temperatures of the cooling water using a U-tube manometer to measure the stagnation pressure of the plasma jet; then, open the gas exit to allow the gas flow through the inner tube; start up the vacuum pump to evacuate the plasma gases; and record the inlet and outlet temperatures of the cooling water once again. The gases are collected at the exit of the vacuum pump for calculation of the gas flow rate and analysis of the gas composition.

2.2 The Equations for Calculating the Temperature and Velocity

The assumption of local thermodynamic equilibrium is required when using the enthalpy probe to measure the enthalpy and velocity of plasma gas. According to the theory of energy conservation, the relation between the temperature rise of cooling water and the enthalpy decline of plasma gases flowing through the probe is:

$$m_g(h_{1g} - h_{2g}) = m_{cw}C_p(\Delta T_{\text{gas flow}} - \Delta T_{\text{no gas flow}}) \tag{Eq 1}$$

where m_g is the gas sample mass flow rate, m_{cw} is the cooling water mass flow rate, h_{1g} is the unknown gas enthalpy at the probe entrance, h_{2g} is the gas enthalpy at the probe exit, C_p is the cooling water specific heat, and ΔT is the cooling water temperature rise.

The temperature of the plasma jet can be derived from the enthalpy h_{1g} once the gas species and contents are known. The gas enthalpy h_{1g} at the probe tip can be calculated from Eq 1, provided the gas sample flow rate and the gas enthalpy at the probe exit are known. The gas enthalpy h_{2g} can be determined directly by measuring its temperature and gas composition at the probe exit. To calculate the temperature of the plasma jet, the specific heat of gases at different temperatures will be known beforehand. This was calculated based on the data of Ref 7.

The right side of Eq 1 represents the heat change of the cooling water in and out of the probe. Under the conditions of this experiment, with temperature rising, the specific heat and density of the cooling water are almost constant. According to Eq 1, decreasing the flow rate of the cooling water will enhance the measuring precision for the temperature rise of the cooling water as it becomes more notable. However, decreasing the flow rate also makes the probe prone to damage while it is measuring plasmas with higher temperatures. In addition, increasing the gas displacement of the vacuum pump will reduce the error. However, the plasma flow structure around the probe will be destroyed if the displacement of the vacuum pump is more than the plasma mass flow rate over the probe tip. A suitable mass flow rate of cooling water and evacuation rate of the vacuum can minimize the error of measurement.

According to the Bernoulli equation, the velocity of the plasma jet can be calculated by measuring the gas stagnation pressure at the probe tip:

$$V = [2(P_{\text{stag}} - P_{\text{atm}})/\rho]^{1/2} \tag{Eq 2}$$

where P_{stag} is the stagnation pressure at the probe tip, P_{atm} is the atmospheric pressure, and ρ is the density of the plasma mixture at the probe tip.

2.3 The Coatings of Al_2O_3-$13TiO_2$

Angular Al_2O_3-$13TiO_2$ powder particles with sizes of 10 to 20 μm were used for depositing the coatings. The powder feed rate was 30 g/min, and the spray distance was 40 mm. Other spray conditions were the same as those listed in Table 1. The Vickers microhardness profiles of the coatings were measured with a microhardness tester at a 300 g load. The reason for selecting Al_2O_3-$13TiO_2$ as the spray powder is that the Al_2O_3 phase and the TiO_2 phase take on different colors under the microscope, so the sandwich in the coatings is easily distinguished.

3. Results and Discussion

3.1 Enthalpy, Temperature, Velocity, and Thermal Conductivity

The probe will disturb the flow of the plasma jet when the gas flow is over the probe tip, and the temperature field around the probe also will be altered. However, the disturbance of the probe will not change the characteristics of the gas sample. Moreover, the gas displacement of the vacuum pump is much less than the flow rate of the plasma gas. Whether the vacuum pump exhausts or not, the flow fields and the temperature distributions around the probe are almost the same; that is, the heat transferring to the outer walls of the probe is equal. Thus, the difference in the rising cooling water temperatures ($\Delta T_{\text{gas flow}} - \Delta T_{\text{no gas flow}}$) results just from the heat released by the gas sample to the inner wall of the probe. This is consistent with Eq 1. So, the disturbance of the probe will bring little error to measurement.

Figure 2(a) to (d) shows the distributions of enthalpy, temperature, velocity, and heat transfer to the probe in Ar-N_2 plasmas with an input power of 5 kW, and with different voltages and currents (i.e., 71 V and 70 A, and 50 V, 100 A). Augmenting the N_2 content in the plasma gas will increase the arc voltage and heat transfer ability of the plasma jet. The Ar-N_2 plasma of 71 V and 70 A has a higher enthalpy and heat transfer value than does the plasma of 100 A and 50 V, but the difference is small. Besides, the temperatures and velocities of the two plasma jets are almost equal.

Figure 3(a) to (d) shows the results of measurements of the Ar-H_2 plasmas under the same conditions as the Ar-N_2 plasmas. Just like the Ar-N_2 plasma, augmenting the H_2 content in plasma gas will increase the arc voltage and heat transfer ability of the plasma jet. The temperature near the nozzle exit of the Ar-H_2 plasma is less than half that of the Ar-N_2 plasma, but its temperature decline along the axis is slower, which becomes more obvious with the increase of arc voltage. In the position of 20 mm, the enthalpy and temperatures of the Ar-H_2 plasma are all higher than those of the Ar-N_2 plasma. The reason for the low temperature of the Ar-H_2 plasma at the nozzle exit is the high specific heat of hydrogen. With the rise of the gas temperature, the dissociation of hydrogen molecules becomes much stronger, which leads to the sharp increase in the specific heat of hydrogen. At a temperature of 3000 K, the specific heat of hydrogen is 51.2 kJ/(kg · K), which is much higher than that of nitrogen [1.35 kJ/(kg · K)] (Ref 7). So, the temperature of Ar-H_2 plasma is less than that of Ar-N_2 plasma using the same power supply, because the rising temperature requires more energy. However, the heat transfer ability of Ar-H_2 plasmas is superior to that of Ar-N_2 plasmas, with the latter having even higher temperatures. The reason for this is that hydrogen has a high thermal conductivity [7 W/(m · K) at 3000 K] (Ref 7), which is much greater than that of nitrogen [2.96 W/(m · K) at 6000 K]. Increasing the H_2 content in the plasma gas will raise the heat transfer ability of the plasma remarkably.

Because the density of H_2 (0.089 kg/m^3) is much less than argon (1.783 K g/m^3), changing the H_2 content in Ar-H_2 plasma has a great influence on the arc voltage, temperature, and velocity of the plasma. However, for Ar-N_2 plasma, the density difference between argon and N_2 (1.251 kg/m^3) is relatively small. So, a small change in the N_2 content in Ar-N_2 plasma has little effect on plasma temperature and velocity.

3.2 Microstructure of the Al_2O_3-13TiO_2 Coatings

Figure 4 shows the microstructures of the coatings deposited in the Ar-N_2 plasmas. In two different sprayed conditions, the sandwich spaces between the phases of Al_2O_3 and TiO_2 are almost the same. The hardness values, i.e., Vickers hardness (HV)

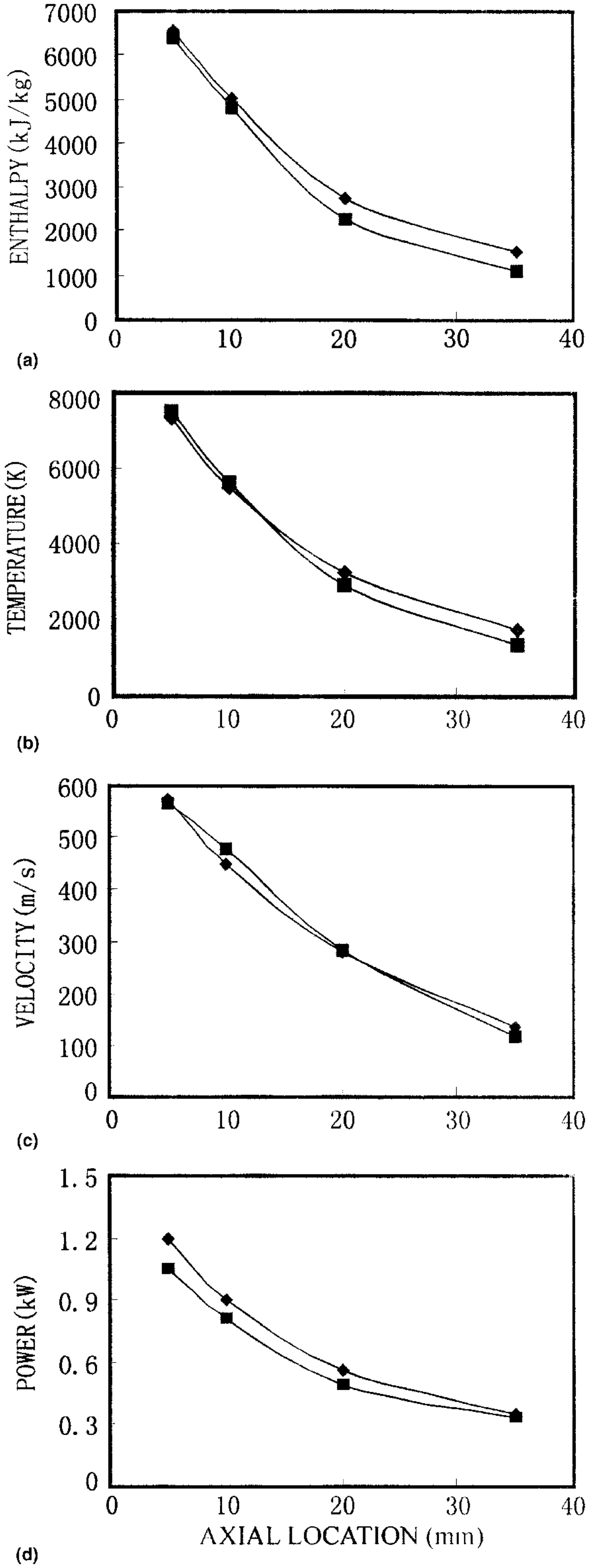

Fig. 2 The distributions of enthalpy, temperature, velocity, and heat transfer to the probe with distance to the nozzle exit for the Ar-N_2 plasma jet: (◆) 70 V, 70 A, and gas flow rates of Ar and N_2 = 21.5 and 24 L/min, respectively; (■) 50 V, 100 A, and gas flow rates of Ar and N_2 = 24 and 12 L/min, respectively. (a) Enthalpy. (b) Temperature. (c) Velocity. (d) Heat transferred to the probe

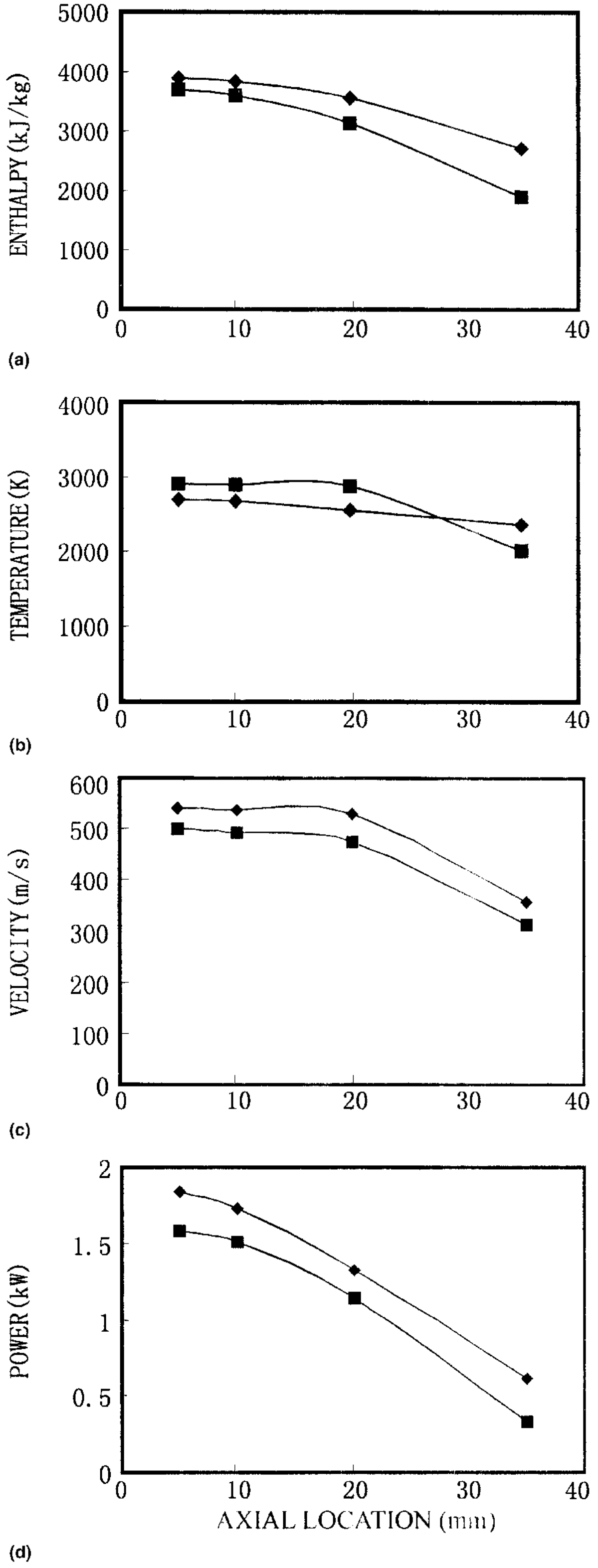

Fig. 3 The distributions of enthalpy, temperature, velocity, and heat transfer to the probe with distance to the nozzle exit for the Ar-H_2 plasma jet: (◆) 70 V, 70 A, and gas flow rates of Ar and H_2 = 24 and 12 L/min, respectively; (■) 50 V, 100 A, and gas flow rates of Ar and H_2 = 24 and 8.5 L/min, respectively. (a) Enthalpy. (b) Temperature. (c) Velocity. (d) Heat transferred to the probe

of coatings sprayed under conditions of 70 A and 70 V, and 100 A and 50 V were HV.300 = 890 and HV.300 = 855, respectively. The former value is a little higher than the latter.

Figure 5 shows the microstructures of the coatings deposited in the Ar-H_2 plasmas. The sandwich space between the Al_2O_3 phase and the TiO_2 phase decreases with the augmentation of the H_2 contents in Ar-H_2 plasma. The coating created under conditions of 70 A and 70 V had a hardness of HV.3 = 1243, which is almost equal to the hardness of HV.3 = 1236 of the coating created under conditions of 100 A, 50 V.

The coatings deposited in the Ar-H_2 plasma were distinctly different from the coatings created in the Ar-N_2 plasma. Compared with the latter, the microstructure was more uniform, the porosity was smaller, and the hardness was higher. In plasma spraying, the quality of the coating is related to the velocity and the degree of melting of the spray powders. According to the results of measurements for the Ar-H_2 and Ar-N_2 plasma jets using the probe, their velocities were comparable, but the former had a higher heat transfer value than the latter. This indicated that the Ar-H_2 plasma jet could better heat and melt the spray powders, which results in the superior quality and greater hardness of the coatings. For plasma spraying with different gas compositions, the properties of the coatings, such as hardness and porosity, are not only determined by the plasma temperature, but depend more on the heat-transfer ability of the plasma gas.

4. Conclusions

The effects of gas composition, arc current, and voltage on the behavior of plasma jets were investigated. The microstructures of coatings created under different spray conditions also were observed. The main results are:

- Increasing the N_2 content in Ar-N_2 plasma gas will enhance the arc voltage of plasmas. However, the enthalpy, temperature, velocity, and heat transfer ability of the plasmas are almost equal with different N_2 contents. The hardness of the coating sprayed under the 70 A and 70 V condition was a little higher than that of the coating sprayed under the 100 A and 50 V condition.
- In Ar-H_2 plasma, the temperature and velocity decrease slowly along the axis of the plasma jet, which becomes more obvious when the arc voltage rises. Increasing the hydrogen content in the Ar-H_2 plasma can raise the enthalpy and heat conductivity of the plasma gas. Compared with Ar-N_2 plasma, the Ar-H_2 plasma had a higher heat transfer to the probe even when its temperature was lower.
- For plasma spraying with different gas compositions, the properties of coatings such as hardness and porosity are determined not only by the plasma temperature, but rely more on the heat transfer ability of the plasma gas. The coatings deposited by the Ar-H_2 plasma have more uniform microstructure and much higher hardness compared to those deposited by Ar-N_2 plasma.

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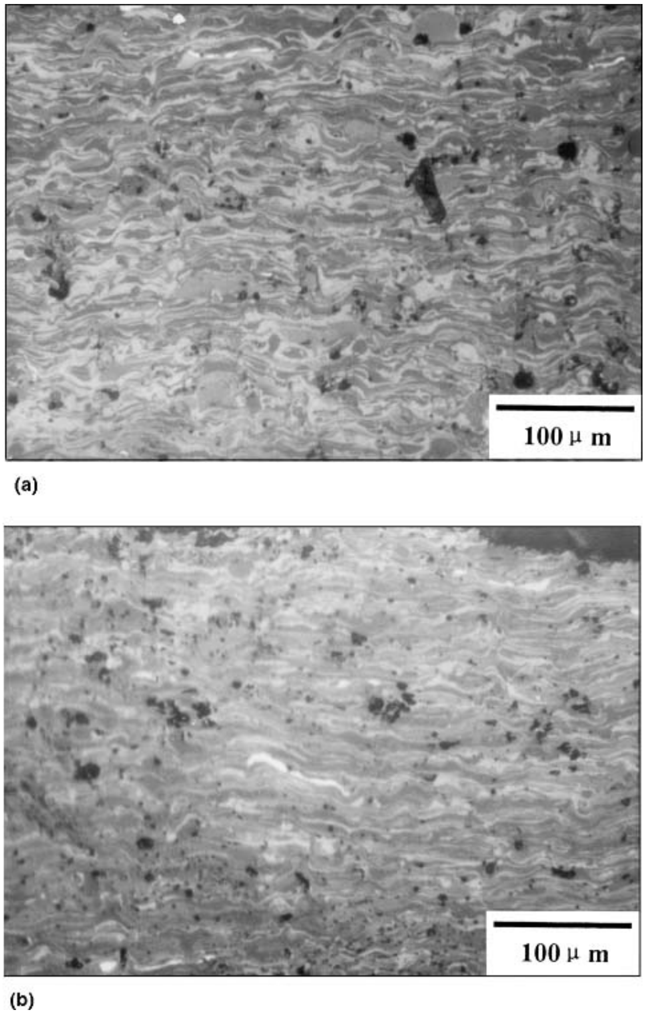

Fig. 4 The coatings sprayed in the Ar-N_2 plasma. (a) 70 V, 70 A, and gas flow rates of Ar and N_2 = 21.5 and 24 L/min. (b) 50 V, 100 A, and gas flow rates of Ar and N_2 = 24 and 12 L/min, respectively

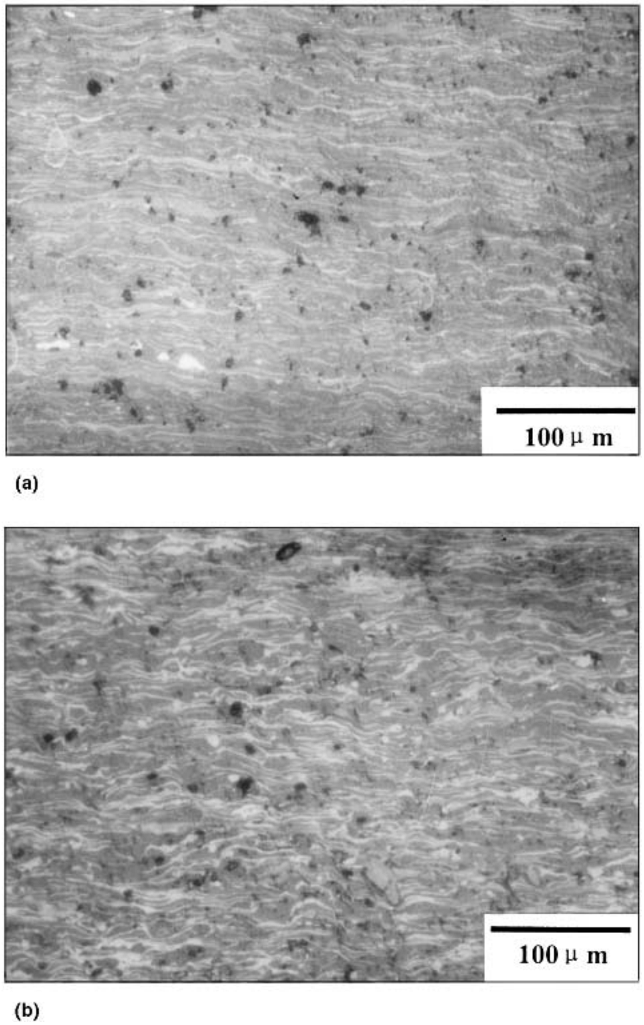

Fig. 5 The coatings sprayed in the Ar-H_2 plasma. (a) 70 V, 70 A, and gas flow rate of Ar and H_2 = 24 and 12 L/min. (b) 50 V, 100 A, and gas flow rates of Ar and H_2 = 24 and 8.5 L/min, respectively

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