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RF Induction Plasma Spraying: State-of-the-Art Review

M.I. Boulos

Radio frequency (RF) induction plasma technology has gained wide acceptance for the preparation of plasma spray coatings and structural free-standing parts of metals, ceramics, and metal-matrix composites. Its principal advantages are the relatively large volume and low velocity of the discharge, which coupled with the ease of axial injection of the powder into the plasma allows for the melting of relatively large particles at high throughput. The absence of electrodes offers the added advantage of ease of operation under a wide range of conditions at atmospheric and low pressure, with an inert, reducing, or oxidizing atmosphere. Highlights of recent advances in induction plasma melting and deposition of materials are presented in this article. The first section deals with advances in induction plasma spraying technology including system and torch design. This is followed by a brief overview of mathematical modeling and diagnostic studies of the induction plasma deposition process. Examples of applications of induction plasma spraying for the preparation of protective coatings and fiber-reinforced metal matrix composites are presented in the final section.

1. Introduction

MATERIALS have long been recognized as the key to technological advances in the aerospace, electronic, and automotive industries. With the increasing demand for higher performance materials, attention has been given to novel processing techniques such as plasma spraying of protective coatings and free-standing bodies of metals, ceramics, and composites. Direct current (dc) and arc plasma spraying are currently standard technologies for such applications as the deposition of thermal barrier coatings, abradables, wear- and corrosion-resistant coatings. In 1985, Jurewicz, Kaczmarek, and Boulos[1,2] reported one of the first applications of radio frequency (RF) induction plasma technology in the area of plasma spraying of metals and alloys. The approach evoked mixed reactions because of inherent limitations of the technique with respect to the velocity the molten droplets can achieve prior to their impact on the substrate and the uncertainty that it could economically compete with alternative approaches. Induction plasmas were, however, by no means a novelty at that time, because the development of the induction plasma torch as it is known today can be traced back to the early 1960s when Reed[3] reported in 1961 that an inductively coupled plasma discharge can be sustained in an open tube in the presence of a streaming gas.

Over the past 5 years, considerable progress has been achieved in induction plasma technology, generally with a wider acceptance of induction plasma spraying. Intensive studies have been reported on the subject by Akashi, Yoshida, and their collaborators at the University of Tokyo,[4-8] Amouroux *et al.* at Ecole Nationale Supérieure de Chimie de Paris, France,[9,10] Siemers *et al.* at the GE CRD Laboratories,[11-15] Thorpe and Kratochvil at TAFA,[16] Magome *et al.* at Osaka Sangiyo University and Sansha Electric, Japan,[17] Meyer *et al.* at Alcoa R & D Laboratories,[18] and Gigerenzer and Kumnick at Textron Specialty Materials Division.[19] Highlights of some of these advances are presented in this article. The first section deals with advances in the induction plasma spraying system and torch design. This is followed by a brief overview of mathematical modeling and diagnostic studies of the induction plasma deposition process. The final section presents some examples of applications of induction plasma spraying for the preparation of protective coatings and fiber-reinforced metal matrix composites.

Key Words: composite coatings, diagnostic studies, induction plasma spraying, RF plasma, review, system layout

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2. RF Induction Plasma Spraying Technology

A schematic showing the basic differences between dc and RF induction plasma spraying technologies is given in Fig. 1. In contrast to dc plasmas where powders are introduced from the

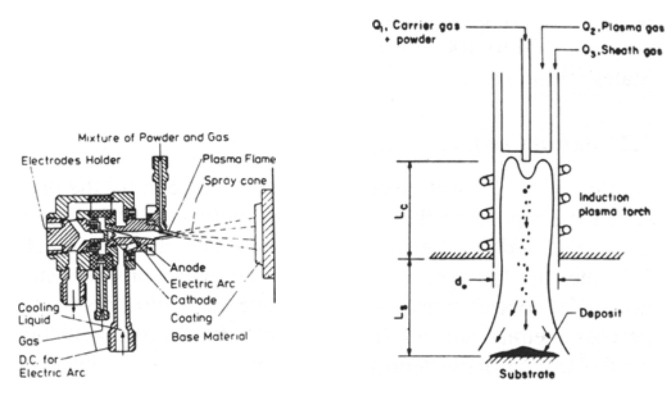

Figure 1 Schematic diagrams of a dc plasma torch (left) and an RF inductively coupled plasma torch (right).

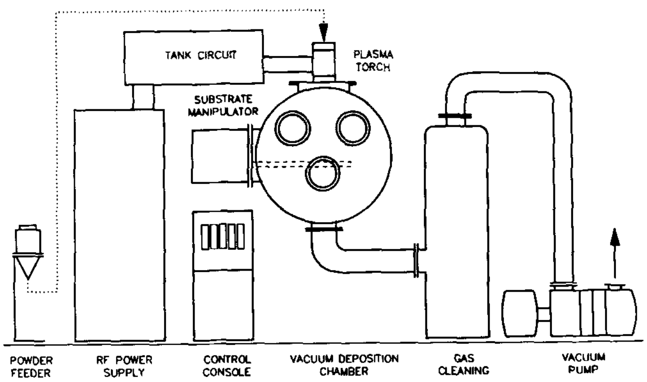

Figure 2 Induction plasma vacuum spraying installation.

side into a high-velocity dc plasma jet, materials are introduced axially into the center of the discharge in induction plasma spraying. Induction plasmas are characterized by their large volume, low velocity and energy density, and their ability to offer the particle a relatively long in-flight heating time, on the order of 10 to 25 ms, compared to 0.5 to 1.0 ms in dc plasma spraying. Due to the absence of electrodes, induction plasmas can be operated with an inert, reducing, or oxidizing atmosphere (Ar, Ar/H_2, Ar/O_2, air, etc.) over a wide range of conditions, with chamber pressures ranging between 50 torr and atmospheric pressure and power levels up to 100 to 150 kW. A typical RF induction plasma vacuum spraying installation is composed, as shown in Fig. 2, of the following principal components.

2.1 *RF Power Supply*

A typical RF induction plasma vacuum spraying installation consists of a RF power supply with an oscillator frequency in the range of 2 to 4 MHz for the low and intermediate power units (power < 100 kW). Frequencies in the range of 200 to 400 kHz are commonly used in larger installations (power > 100 kW). The minimum required power level is strongly dependent on the nature of the plasma gas, the operating pressure, the oscillator frequency, and the size of the discharge. An analysis of the interaction between these four critical parameters is given by Boulos.[20] Although most laboratory and pilot scale industrial induction plasma spraying installations have been limited to the 50- to 150-kW power range, larger power installations in the range of 200 to 400 kW have been developed in the United States[21] and Japan.[22]

2.2 *Control Console*

The control console serves to monitor and control the pressure in the deposition chamber, gas and cooling water flow rates, and power setting. It also contains necessary safety interlocks that interrupt the operation of the system under unsafe conditions. The control console can also have the controllers for the powder feeding and any on-line monitoring instrumentation needed to control the deposition process.

2.3 *Plasma Torch*

The plasma torch is composed, as shown in Fig. 3, of a water-cooled plasma confinement tube, typically of 35 to 70 mm internal diameter and 150 to 200 mm long, for plasma torches with a nominal power rating in the range of 30 to 150 kW, respectively. It is surrounded by a three to five turn induction coil connected to the RF power supply through the tank circuit. Because of the high-frequency current (a few hundred amps) that passes through these leads, they must be water cooled, with a rigid configuration to maintain a constant impedance matching the power supply and to ensure optimum energy transfer between the power supply and the plasma.

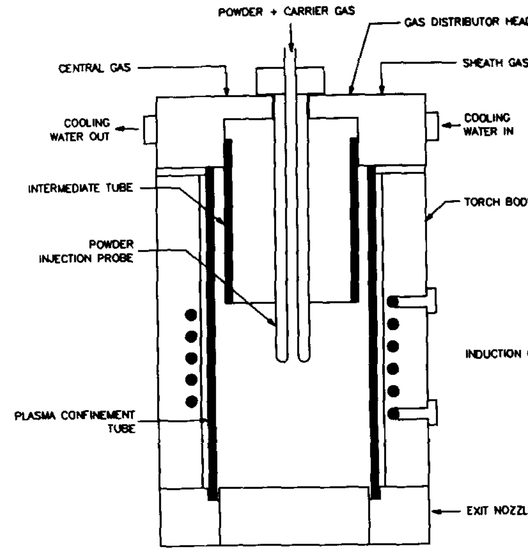

Figure 3 Induction plasma torch.

The upstream part of the torch is the gas distributor head, which is responsible for the introduction of the different gas streams into the discharge chamber. In induction plasma torch design, it is particularly important to keep close control of the gas flow pattern in the discharge region. Three different gas streams are introduced into the torch. The sheath gas serves to protect the wall of the plasma confinement tube from the high temperature of the discharge. The central gas, which has a swirl velocity component, serves to stabilize the plasma. The powder gas serves as carrier for the axial injection of the powder into the center of the discharge. These three gas streams need not have the same chemical composition. A water-cooled stainless steel probe, which penetrates through the torch head, is used to introduce the powder axially into the center of the discharge. Due to the complexity of the flow pattern in the discharge region, the position of the tip of the powder injection probe is of critical importance. If located above the first turn of the induction coil, it could result in the excessive deposition of the powder on the walls of the plasma confinement tube, which may lead to its eventual failure. A low position of the powder-injection probe at the downstream end of the induction coil will result, on the other hand, in excessive cooling of the plasma and a reduction of the particle residence time in the discharge. This will give rise to a reduction of the ability of the plasma to completely melt the particles in flight. The downstream end of the torch is a water-cooled exit nozzle, which acts essentially as an interface between the plasma torch and the deposition chamber, thus ensuring vacuum tightness through proper seals.

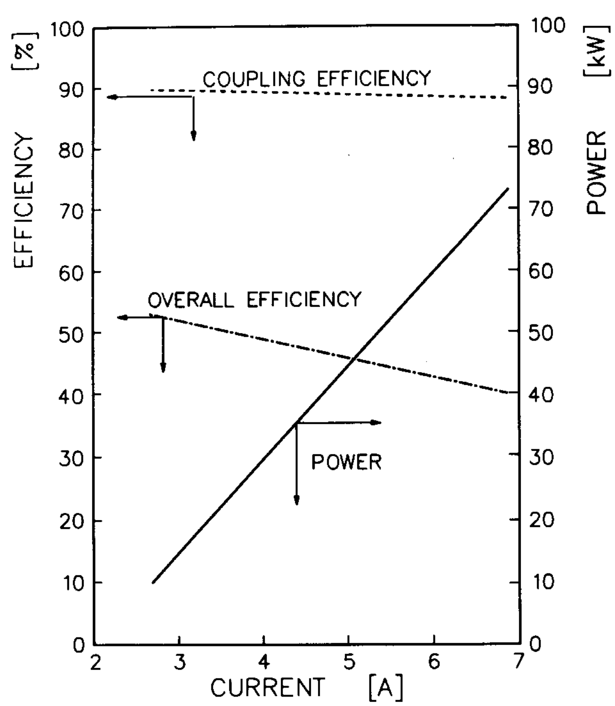

Figure 4 Torch power and energy coupling efficiency as a function of the oscillator plate current for operation with Ar/H_2 mixture (chamber pressure = 450 torr).

Substantial effort has been devoted to the development of improved designs for the induction plasma torch. These have ranged between the use of metallic wall[23-25] or porous wall torches,[26] radiatively cooled ceramic wall[27-28] and hybrid combinations of dc-RF[29] or RF-RF[30,31] plasma torches. Each of these developments has its respective advantages and limitations. A new design developed by Boulos and Jurewicz[32] is based on the use of a water-cooled ceramic plasma confinement tube. It is characterized by its high energy density in the discharge region and the long lifetime of the tube, which exceeds 10 months of laboratory service at peak power of 60 to 70 kW for a 50-mm internal diameter torch. Typical torch performance data are given in Fig. 4 in terms of the torch power and its energy coupling efficiency as a function of the oscillator plate current for operation at a chamber pressure of 450 torr using an Ar/H_2 mixture as the sheath gas at 104 l/min STP (7.9% by volume, H_2). The plasma gas, in this case, is pure argon at a flow rate of 73 l/min (STP).

2.4 *Vacuum Deposition Chamber*

The vacuum deposition chamber interfaces directly with the plasma torch. It is made of double-wall, water-cooled stainless steel. The volume of the chamber depends on the application considered and can vary between 0.5 and 3 m^3. Because the induction plasma torch cannot be easily articulated to spread the material sprayed over a large surface, the substrate holder must be manipulated in this case through appropriate robotic control. It should be emphasized, however, that in induction plasma spraying, the material is normally sprayed over a considerably larger surface area (80 to 100 mm in diameter) compared to dc plasma spraying (15 to 20 mm in diameter) and substrate manipulation has to be designed accordingly.

2.5 *System Accessories*

System accessories are essentially similar to any standard dc vacuum plasma spraying installation. They include an adequate gas cleaning system with a cyclone, filter and/or scrubber, a vacuum pump, such as a roots or a liquid-ring pump, and a standard powder feeder, which may either be of the screw-feeding type, vibrating double cone, or any other type.

3. Mathematical Modeling and Diagnostics

Studies of the basic phenomena involved in induction plasma melting and deposition can be grouped in two broad categories dealing, respectively, with the mathematical modeling and diagnostic measurements of the plasma and particles in flight.

3.1 *Mathematical Modeling*

Most research efforts in this area have been devoted to the computation of the flow, temperature and gas composition fields in the plasma, particle trajectories, and their temperature history and plasma-particle interactions. The models developed are generally for two-dimensional, axisymmetric, steady-state, laminar flows, with an optically thin plasma in local thermodynamic equilibrium (LTE). They involve the solution of the continuity, momentum, energy, and mass conservation equations simultaneously with a simplified form of Maxwell's equations. Considerable attention has been given to the formulation of electric and magnetic field equations, which have substantially improved from the one-dimensional representation used in earlier works[33-39] to the more realistic two-dimensional vector potential formulation.[40-46]

Specific attention has also been given to the development of turbulent flow models,[36] equilibrium and reaction kinetic models,[37,38] and a non-LTE two-temperature model for the induction plasma under low-pressure operating conditions.[35,41] Mathematical models were also developed for both dc-RF[29,47] and RF-RF[30] hybrid plasma torches.

Computations of in-flight particle trajectories and their temperature history are based on a force balance on single particles taking into account the particle inertia, gravity, and drag force. The temperature history of the particles is computed through solving the transient heat transfer equations. Although most studies assumed the particles to be at a uniform temperature,[48-52] studies by Yoshida *et al.*[53] and Bourdin *et al.*[54] examined the effect of internal conduction in particles. It was shown[54] for ceramic particles (Al_2O_3) under high heat flux conditions that internal conduction was responsible for the development of large temperature differences, on the order of 1000 K, between the surface temperature of the particle and its center.

Plasma-particle interactions under dense loading conditions are taken into account using the PSI-cell model,[49,52] which represents the energy exchange between the plasma and the parti-

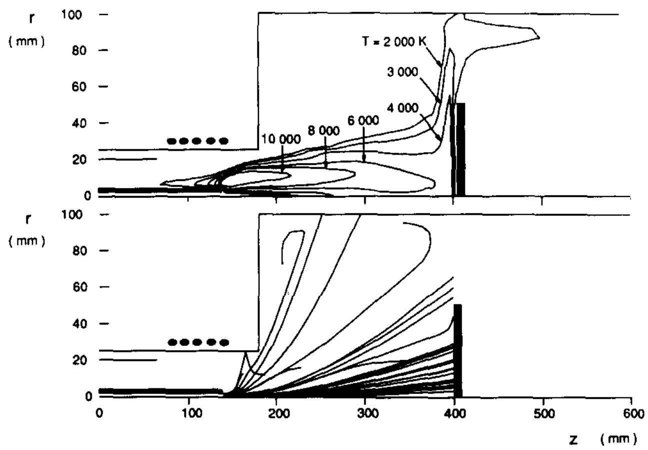

Figure 5 Plasma temperature field (top) and particle trajectories (bottom) in an induction plasma deposition of nickel at a chamber pressure of 450 torr, carrier gas flow rate of 4.0 l/min, and average particle diameter of 60 μm. After Robitaille.[55]

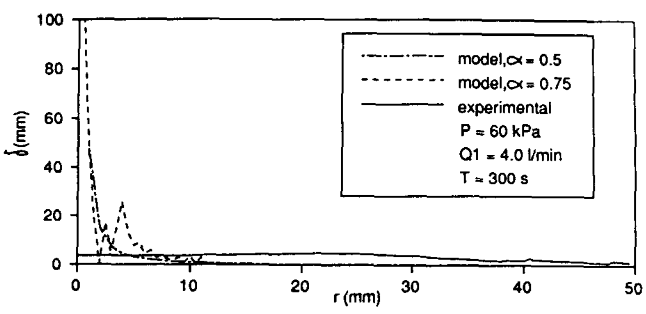

Figure 6 Comparison of the experimental and computed profile of the deposit obtained in induction plasma spraying of nickel at a chamber pressure of 450 torr, carrier gas flow rate of 4.0 l/min, and deposition time of 300 s. After Robitaille.[55]

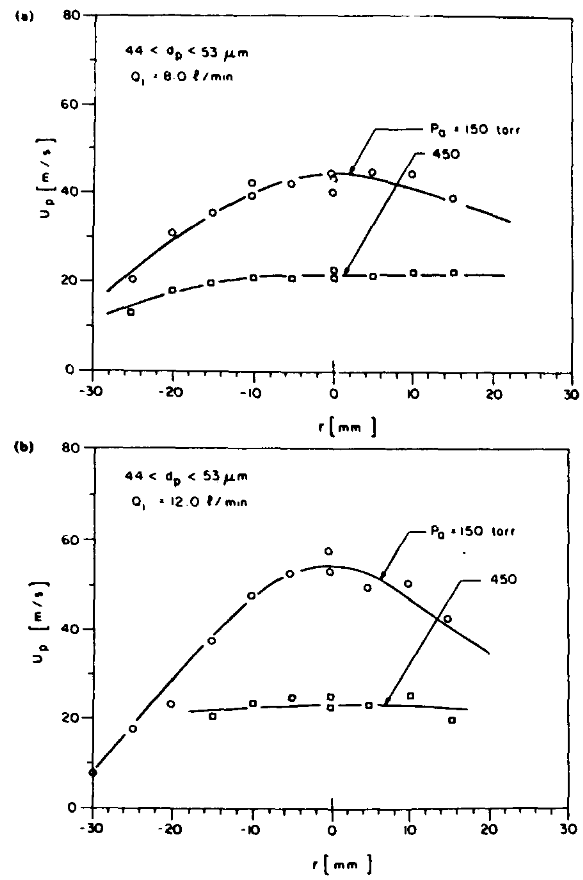

Figure 7 Laser doppler anemometry particle velocity profile in induction plasma deposition of nickel and nickel-base alloys. Power = 16 kW, powder mass flow rate = 48.0 g/min, spraying distance = 380 mm. d_p refers to the particle size range and Q_1 the carrier gas flow rate. After Bronet and Boulos.[64]

cles through the use of local source/sink terms in the energy equation. Momentum exchange between the plasma and the particles is generally neglected in such a formulation.

Typical results obtained by Robitaille[55] for the induction plasma deposition of nickel particles are given in Fig. 5. These show, in the upper part of the figure, the temperature isotherms in the plasma torch and discharge chamber in the vicinity of a 100-mm diameter fixed substrate. The corresponding particle trajectories are given in the lower part of the figure showing the spread of the particles over the substrate due to a combination of inertia and centrifugal force caused by the swirl velocity component of the flow field. Comparisons of the computed profiles of the deposit obtained with typical experimental data (Fig. 6) show considerable differences in the central region, which can be attributed to the fact that turbulent diffusion of the particles in the flow is not incorporated in this model. The data given in Fig. 6 show, on the other hand, only a minor sensitivity of the computed deposit profiles on the initial particle slip parameter, α, in the powder injection probe. The parameter, α, is defined as the ratio of the initial particle velocity to the average carrier gas velocity in the powder injection probe.

3.2 *Plasma and Particle Diagnostics*

Diagnostic studies have been conducted to measure the flow and temperature fields in the plasma, particle velocity, and in-flight particle surface temperature. Extensive emission spectroscopic data are available in the literature[56,57] for the standard inductively coupled plasma (ICP) used in spectrochemical analysis. These operate typically at high frequency (13.7 to 40 MHz) and low power (1 to 5 kW) under atmospheric pressure. In contrast, relatively few studies have been reported for the plasma spray induction plasma torch. The works of Beaulieu,[58] Gravelle *et al.*[59] Kruger,[60] and Sabsabi[61] are of special interest, because they examine the effect of central gas injection and low pressure operation (150 to 500 torr) on deviations from local thermodynamic equilibrium conditions in the discharge.

In-flight particle diagnostics has been the subject of intensive study over the past 10 years.[62-70] The works by Lesinski and Boulos[62,63] and Bronet and Boulos[64,65] dealt with laser doppler anemometry (LDA) measurements of the plasma and particles under induction plasma spraying conditions. Typical results reported by Bronet and Boulos[64] for the induction plasma deposition of nickel and nickel-base alloys (Fig. 7), show a sub-

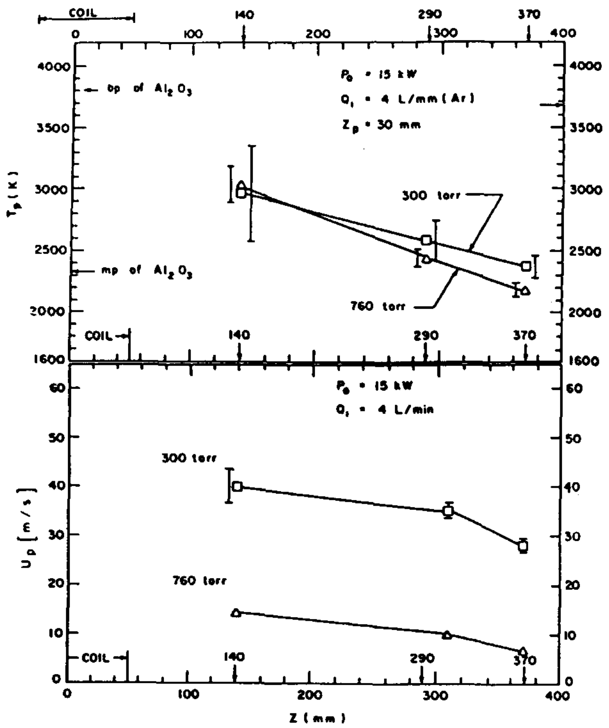

Figure 8 Alumina particle surface temperature (top) and velocity (bottom) along the centerline of an induction plasma. Chamber pressure = 300 and 760 torr; power, P_o = 15 kW; powder carrier gas, Q_1 = 4 l/min. After Takikawa, Sakuta, and Boulos.[67]

stantial increase in the average particle velocity along the centerline of the discharge from about 20 m/s to about 45 or 55 m/s with the reduction of the deposition chamber pressure from 450 to 150 torr. Although the reported velocities are almost one order of magnitude lower than those normally encountered under dc plasma spraying conditions, the deposits obtained in this case were of near theoretical density. Similar results have also been reported by Fan *et al.*[71] with alumina, as discussed in the next section. These two studies together with data by Savkar and Siemers[13] show that the high particle velocity, which is typically associated with dc plasma spraying, is not necessary for achieving high-density deposits, provided the particles are completely molten prior to their impact on the substrate.

Simultaneous measurements of the in-flight particle velocity and particle surface temperature in the induction plasma deposition of alumina have been reported by Sakuta, Takikawa and Boulos.[66-70] These were obtained through time-of-flight measurements and two-color pyrometry. Typical results, given in Fig. 8, show the substantial influence of the deposition chamber pressure on the particle velocity and surface temperature prior to impact on the substrate. The results also show the relatively fast radiation cooling of the alumina particles as they emerge from the plasma. The effect is particularly important at atmospheric pressure when the particle velocity is lowest. The results underline the influence of the plasma-substrate distance on the particle velocity and its surface temperature, which has long been recognized as a critical parameter in induction plasma spraying.

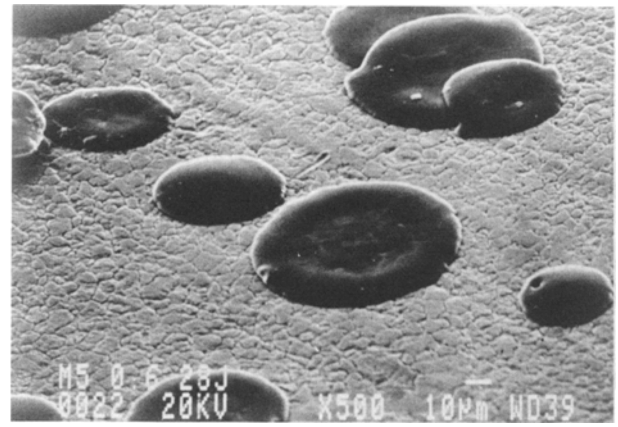

Figure 9 Typical alumina droplet splats on polished steel substrate during induction plasma spraying process. Particle diameter = 21 ± 5 μm, chamber pressure = 200 torr, and powder = 25 kW. After Fan *et al.*[71]

4. RF Induction Plasma Spraying

Systematic investigations of the RF induction plasma spraying process have been carried out to elucidate the influence of the principal operating parameters on the properties of the deposits obtained. Studies have been conducted with metals,[1,2,5,9,10] ceramics,[4-8,71] mechanically alloyed powders,[72] and metal matrix composites.[11-15,18,19]

The results reported by Fan *et al.*[71] show the influence of the in-flight particle velocity and surface temperature on their deposition properties on the substrate. Figure 9 shows well-developed droplets of molten alumina on a polished steel substrate. This is a clear indication of the thoroughness of the melting of the alumina particles and their low impact velocity, which is characteristic of induction plasma deposition processes in general.

The possibility of melting much larger particles with induction plasmas than typically possible under dc spraying conditions played a major role in the study by Jackson *et al.*[12] of the plasma spraying of refractory metals, which are sensitive to oxygen contamination. The results summarized in Table 1 show that the amount of residual oxygen and nitrogen in niobium deposits obtained by induction plasma spraying is closely dependent on the level of gas adsorbed on the surface of the powder used, which in turn is a function of the particle size range of the powder. For example, the oxygen contamination of a niobium deposit increases for 675 ppm when using a powder with a particle diameter, dp, range of $74 < d_p < 105$ μm to 835 ppm for $44 < d_p < 74$ μm and 1960 ppm for $d_p < 44$ μm. Such a substantial increase in the oxygen contamination of the deposits reflects a corresponding increase in the oxygen content of the powder used.

A comparison between the mechanical properties of as-cast, dc and RF induction plasma sprayed deposits of structural parts made of René 80 is given in Fig. 10. These show higher temperature performance of the induction plasma deposited materials, which may be attributed to a lower gas contamination of the deposits.

Savkar and Siemers,[13] Meyer *et al.*[18] and Gigerenzer and Kumnick[19] also reported the preparation of metal matrix com-

Table 1 Effect of Particle Size on Oxygen and Nitrogen Contamination of Niobium Powders and the Plasma Deposits Obtained

Powder	Gases in powder, ppm		Gases in deposit, ppm	
	Oxygen	Nitrogen	Oxygen	Nitrogen
–140 + 200 mesh, Nb	410	50	675	230
–200 + 325 mesh, Nb	600	55	835	360
–325 mesh, Nb	2010	130	1960	365

After Ref 12.

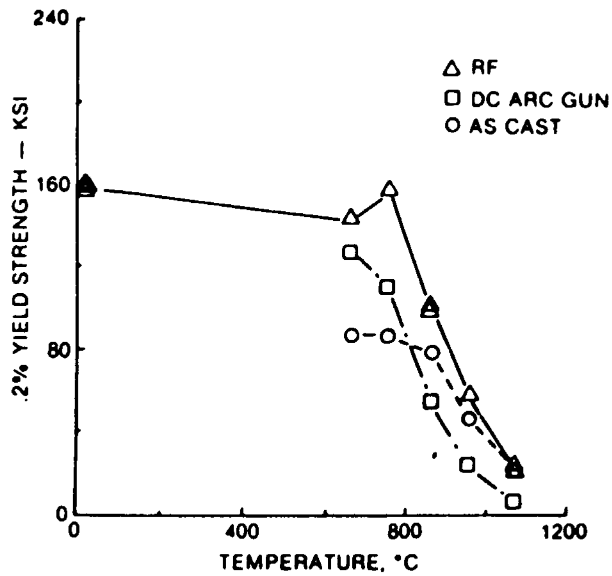

Figure 10 Yield strength of as-cast, dc and RF rapidly solidified plasma deposits. All samples were heat treated at 1225 °C for 1 hr prior to test. After Savkar and Siemers.[13]

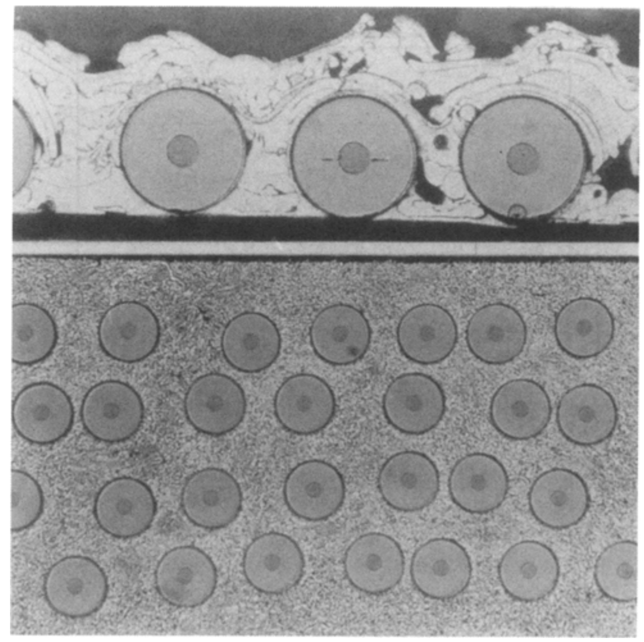

Figure 11 Induction plasma sprayed, fiber-reinforced, metal matrix composite (SCS-6/Ti6Al-2Sn-4Zr-2Mo) (top). As-sprayed monotape (bottom), hot isostatically pressedconsolidated four-ply composite fiber diameter = 140 μm. After Gigerenzer and Kumnick.

posites of titanium aluminides reinforced with silicon carbide fibers using induction plasma spraying technology. Figure 11 shows a typical microstructural section of an induction plasma sprayed SCS-6/Ti6Al-2Sn-4Zr-2Mo monotape. As noted by Gigerenzer and Kumnick,[19] the fiber spacing has remained uniform and matrix fill has occurred between fiber-to-fiber spacing as small as 76 μm. A lamellar layer structure is evident, achieved by a buildup of "splat boundaries," due to the impact of the superheated molten particles. Figure 11 shows that the molten droplets completely envelop the fiber on impact. The sprayed matrix not only fills the spaces between the fibers, but also penetrates behind the fiber wrap. This total coverage is desirable from the standpoint that metal-to-metal surface contacts, between stacked monotape plies, will enhance diffusion bonding during hot isostatic pressing consolidation.

5. Summary and Conclusions

From the above, it can be seen that the ability of achieving near theoretical density deposits of metals and ceramics using RF induction plasma deposition techniques indicates that the particle temperature rather than the particle velocity is of prime importance in plasma deposition processes. Dense deposits of nickel and alumina were reported with particle velocities as low as 20 m/s, provided the particles were fully molten prior to their impact on the substrate.

The review presented emphasizes the principal characteristics of RF induction plasma spraying torches, which are large-volume, long residence time devices. Coupled with the ease of axial injection of the powder into the plasma, they can be used for melting relatively large particles at high throughputs. The absence of electrodes offers the added advantage of ease of operation under a wide range of conditions at atmospheric and low pressure with an inert, reducing, or oxidizing atmosphere.

From a comparison of the induction plasma spraying process with standard atmospheric and vacuum dc plasma spraying technologies, it may be noted that both have complimentary features with important potential impact on material processing technologies. Induction plasmas are particularly suited for the spraying of relatively simple shapes with materials sensitive to contamination. The ability to melt large particles at high throughputs is particularly interesting for the preparation of monotapes for metal matrix composites. The ability of induction plasmas to operate over a wide range of chemical compositions of the plasma gas makes it particularly well suited for the thermal spraying of sensitive materials such as high T_c superconductors, and, in the long run, for reactive deposition processes that involve the in-flight chemical transformation of the deposited material.

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