JTTEE5 12:536-541

Peer Reviewed

Design of a Circular Cascaded Arc Torch Array for Plasma Spray

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(Submitted 12 June 2002; in revised form 12 October 2002)

A new concept has been verified for a plasma spray electrode system that improves plasma plume uniformity over that of a single arc torch. A six-electrode, circular, arc-cascade discharge was formed by mounting seven tungsten-rod electrodes radially around a stream of argon gas. To maintain the plasma plume, the cascade-arc discharge was repetitively triggered using a cascaded high-voltage spark initiated by a secondary spark gap. The typical cascade arc voltage and current were 130 V and 20 A. Results show that the cascaded arc array system can create a ring-shaped plasma plume having near-uniform electrical energy in the circular direction. This feature suggests that the configuration may have future use in plasma torch systems requiring uniform circular symmetry. In such a system, spray particles can be injected into the center of the plasma ring. At the same time, such an arrangement also could provide a lower-cost alternative to systems that use multiple two-electrode plasma torches arranged in a circular configuration. In the latter system, each two-electrode plasma torch is fed by a separate power supply.

Keywords array, cascade, circular, plasma, plume, torch

1. Introduction

Direct-current plasma-torch systems are widely used in industry as sources of heat energy for applications such as welding, ceramic spraying, metal coating, and material synthesis. Conventional dc arc torches use coaxial electrodes comprised of an inner cathode and an outer anode, with gas flow in the axial direction. In this configuration, self electromagnetic forces do not significantly affect the stability of the plasma plume. Previous investigators have predicted or measured the distributions of current density,[1,2] gas velocity,[3-5] and temperature[6] inside the plasma plume of a coaxial plasma torch. The hottest region, typically exceeding 10 000 °C,[2] is along the center axis of the cylindrical column of the plasma plume. This temperature falls sharply in the radial direction.[3]

One of the more common applications of the dc plasma torch is its use in plasma spray systems in which metal or ceramic particles are fed into the plasma plume to be melted and deposited onto a desired target.[7-14] The anode in such systems is positioned on the central axis; hence granules of the material to be melted and sprayed must be fed in from one side of the plasma plume. The asymmetry inherent to such an arrangement sometimes can cause serious problems in particle deposition because it is difficult to control the trajectories of sprayed particles that have been injected off axis into the plume. A two-electrode, coaxial plasma torch has a steep radial temperature gradient, thus the thermal energies given to the particles vary widely depending on their trajectories. Particles passing through outer regions of the plasma plume encounter much less heat energy than do particles traveling through the central region, leading to a nonuniform surface coating on the work piece. One manufacturer of plasma torch systems, the MetTech Corp., (Richmond, BC, Canada)[15] overcomes this problem by using a proprietary method for injecting particles axially, rather than radially. Sulzer-Metco (Westbury, NY), another commercial vendor, attempts to overcome this problem in their Triaxial system by arranging multiple plasma torch guns in a circular configuration.[16] The difficulty encountered with this latter approach is that each torch requires a separate power supply and three guns. The requirement dramatically increases maintenance overhead and the cost of the system.

This paper presents a plasma-spray torch configuration, which attempts to widen the region of near-uniform temperature. The plume is composed of multiple arcs connected in a circular, series-cascade arrangement, such that each arc carries the same current. The resulting plasma plume has the shape of a ring, which will allow spray particles to be fed directly into its center. Because the voltage of a gaseous arc is determined by its current,[17] the electrical energy of each of the arcs in the cascade will be the same if the electrode configuration has circular symmetry, and if all the arcs carry the same current. It differs from the MetTech system in that the plasma arc current is azimuthal, providing a large, plasma-free aperture into which particles can be injected axially. Unlike the Sulzer-Metco system, which also permits axial particle injection. The system described here requires only one power supply; hence the arc energy is evenly distributed around the plasma without external control.

The cascaded arc system embodied in our work also has some resemblance to the Twin Anode α-Torch system developed by the Japanese company Onoda Cement (Onada, Japan). This device was developed to produce high-speed, high-temperature plasma in air, rather than in argon, with the latter used for protection of the cathode only. The design concept of the twin-anode torch differs from that reported here in that particles are injected asymmetrically, and azimuthal uniformity of the plasma plume is not considered.

In the work reported here, the concept of a circular-cascaded

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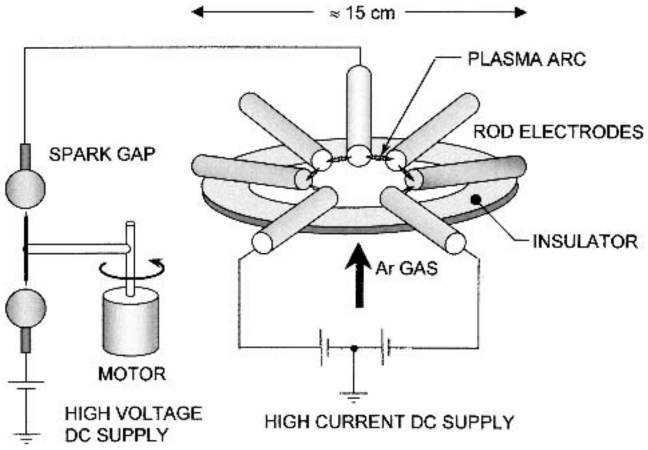

Fig. 1 Concept for a circular cascaded-arc torch

arc is demonstrated in an experiment-using rod electrodes mounted radially, like the spokes of a wheel, around a stream of argon gas. The high-current arcs are triggered using a short duration, high-voltage cascaded spark initiated by applying a high-voltage impulse to the circular cascade. The characteristics of the cascade arc have been investigated experimentally on a laboratory scale.

2. System Overview

The basic concept for the circular cascade plasma-torch array is illustrated in Fig. 1. Cylindrical rod electrodes, supported by a high-temperature, electrically insulating material, extend radially inward toward the center such that their inner ends form a circle. The gaps between all adjacent electrode edges are set to the same distance in the range of 1 mm to 2 mm with an accuracy of approximately 10%. Two adjacent electrodes, called the terminal electrodes, are chosen to define the beginning and end of the circular cascade and are connected to a high-current dc voltage source. The voltage of this latter source is low enough such that it is incapable of breaking down the electrode gaps, but it can supply substantial current if the gaps are bridged by a momentary, high-voltage trigger spark.

If an odd number of electrodes are chosen for the array, then one electrode will be equidistant from the two terminal electrodes. This centrally located "trigger" electrode is connected to a high-voltage spark-gap impulse generator. When energized, this impulse voltage produces two parallel sparks that propagate simultaneously around both sides of the circle on the tips of the rod electrodes and terminate on the two terminal electrodes. All other electrodes in the array remain electrically floating. These parallel triggers sparks initiate a circular, cascaded plasma arc fed by the high-current dc supply. A stream of argon gas is fed into the center of the electrode arrangement and is ionized by the cascade arc, resulting in a ring-shaped, cylindrical plasma plume that has the geometrical form of the flame from a kitchen stovetop burner. One key feature of our cascaded-arc system is the serial connection of its multiple arcs, which are powered from a single dc source, thereby ensuring that the current through each arc is identical. Given that each arc sustains nearly the same voltage drop, each individual arc ultimately receives the same electrical energy.

The concept of cascading multiple arcs from a single supply has been investigated in the past. One paper[18] cites the use of an ac arc torch array for studying the effect of the plasma torches on the propagation of microwaves in rectangular waveguides. Multiple electrode pairs were connected in parallel via ac coupling capacitors with the electrical energy supplied from a single ac voltage source. This method is effective in applications requiring a low-energy ac arc torch. For a high-energy dc arc torch, such as one might use in a commercial plasma-spray system, it is difficult to provide the same electrical energy to multiple arcs connected in parallel from a single dc power supply. Doing so requires that each arc have precisely the same voltage-current characteristic. Because the equivalent resistance of a dc arc decreases with increasing arc current,[17] the current supplied to parallel-connected electrodes in a dc system will tend to concentrate in the arc that has the smallest arc resistance, further tending to reduce the resistance of that same arc. To provide the same electrical energy to parallel arcs in a multiple-arc system, separate, adjustable voltage sources are usually required for each torch.

In our system, the dc supply feeds the cascaded arcs in series. If one of the arcs is extinguished by electromagnetic self-instability or other factors, the rest of the series-connected arcs in the cascade will have their current disrupted and will extinguish as well. This problem is overcome by periodically applying the high-voltage triggering impulse voltage to the electrode array. The 30-Hz refresh frequency is rapid enough that the arc plume does not fully extinguish, allowing it to attain a thermal steady state.

3. Experimental Setup

3.1 Electrode Configuration

To test the feasibility of the circular arc concept, the system outlined in Fig. 2 was constructed from seven 3.2-mm diameter tungsten rod electrodes, as shown in Fig. 2. This prototype is not intended to represent the final form of a commercial plasma torch, but only to verify that a uniform circular arc can be produced by the cascade effect. The high-voltage trigger impulse is applied to electrode 4, which lies equidistant from the terminal electrodes 1 and 7. This impulse triggers sparks that cascade around the inner edges of the radially oriented rod electrodes, terminating on electrodes 1 and 7. These sparks allow the low-voltage dc supply to initiate a circular plasma arc between electrodes 1 and 7.

As illustrated in Fig. 2, the seven 3.2-mm diameter tungsten rod electrodes were radially mounted on a 6-mm thick, machinable ceramic plate, into which an 8-mm central hole was drilled for the purpose of passing argon gas. The electrode rods were inserted into cylindrical brass holders such that their positions could be adjusted in the radial direction. The electrode positions were adjusted such that their inner ends formed a 9.1-mm diameter circle around the argon gas orifice. Copper tubing of 1.7-mm inner diameter was wound around and soldered to each brass holder to allow for the cooling of the tungsten electrodes by de-ionized water. The details of the cooling coils are illustrated in Fig. 2 (see, for example, electrode #2.) Electrode cool-

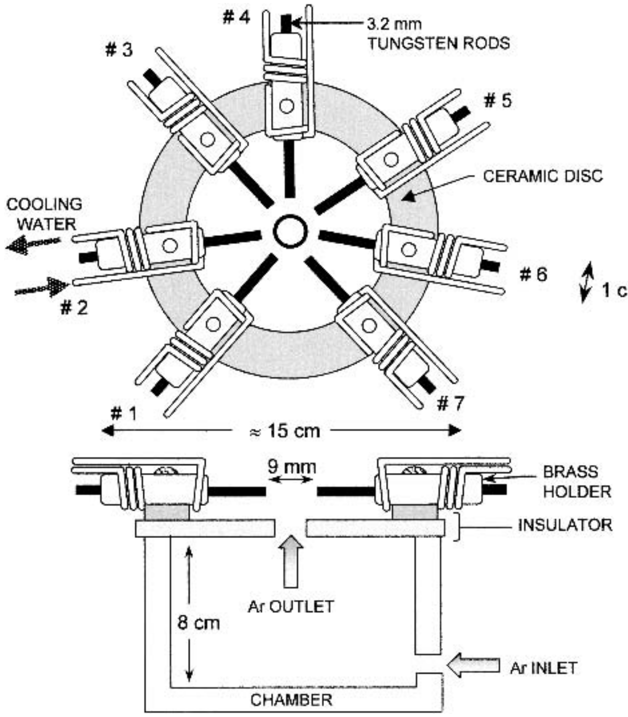

Fig. 2 Details of electrode mounting and cooling

ing coils were connected in parallel via 2-mm inner-diameter rubber tubing to input and output water manifolds of 2.5 cm diameter. The latter were located on either side of the electrode mounting area. The cooling coils from the seven brass holders were connected in parallel to a cooling water manifold via insulated rubber tubing. The flow of cooling water was adjusted to a rate of approximately 1 lpm, which kept the various electrode temperatures well below the melting points of its various components. This flow rate was sufficient for the laboratory-scale experiment but would need to be higher in a commercial-scale plasma torch system operating at high power.

The argon was supplied from beneath the ceramic support plate via a small plenum chamber that allowed the gas to flow through the axis of the electrode circle via an 8-mm diameter hole drilled into the ceramic plate. The flow rate of the argon gas was adjusted by an external flow valve and brought to the desired pressure inside the chamber.

The entire assembly was mounted horizontally in a 25-cm high-boxed enclosure with the argon gas flowing upward. One wall of the enclosure included a clear window with a light filter to permit observation of the arc discharge from the outside. The arc discharge was recorded on videotape using a digital video camera filtered by a No. 10 welding glass.

3.2 Circuit Configuration

The electrical connections in our system are illustrated in Fig. 3. As shown in the figure, electrodes 1 and 7 are connected to a 30-A, ±170-V dc source derived from a three-phase rectifier and three-phase, 208-V ac supply. The voltage is smoothed by two 3300-μF capacitors connected to ground, thereby supplying +170 V to electrode 1 and −170 V to electrode 7. The arc current can be adjusted by a variable 30-Ω resistor inserted in series within the electrode array. The gap between electrodes 1 and 7 is made slightly larger than the gap between the other electrodes so as to discourage the formation of an arc directly between these two electrodes. Similarly, the adjacent inner edges of these electrodes are ground flat to increase their relative spacing, thereby discouraging direct arc formation. The cascade arc current is measured by monitoring the voltage across the variable 30-Ω resistor using a digital storage oscilloscope.

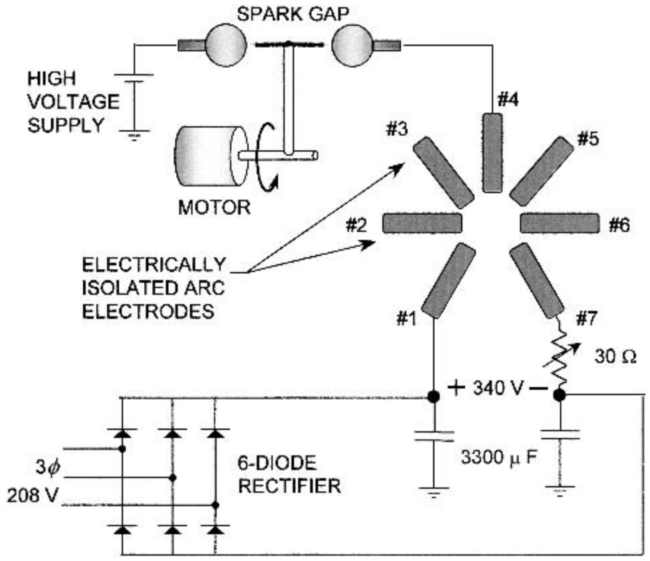

Fig. 3 Electrical connections used in the experiment

When a high-voltage impulse is applied to electrode 4, it initiates parallel sparks that travel around either side of the electrode cascade and terminate on electrodes 1 and 7, respectively. The resulting voltage “spikes” at electrodes 1 and 7 can damage the rectifier diodes during their reverse-biased phases if the capacitors are not present to absorb the electrical energy. Hence, in addition to voltage smoothing, the filter capacitors play the important role of protecting the diodes from high-voltage breakdown.

3.3 Spark Trigger

If a high current arc is to be initiated in the system of Fig. 3, a conducting path must first be established via a low-energy spark cascade between the electrodes. As previously discussed, the conducting path provided by this spark cascade must be replenished periodically if the plasma plume is to be sustained. In our proof-of-concept experiments, we used a rotating spark gap external to the electrode array as a low-cost method for producing the required spark. In a commercial plasma spray system, more conventional means of producing the spark, such as an electronic ignition system similar to that used in automobiles could be used.

The impulse voltage in our system is generated by a double-tipped needle electrode rotating between two electrodes of a secondary gap, as shown in Fig. 1 and 3. Alignment of the needle

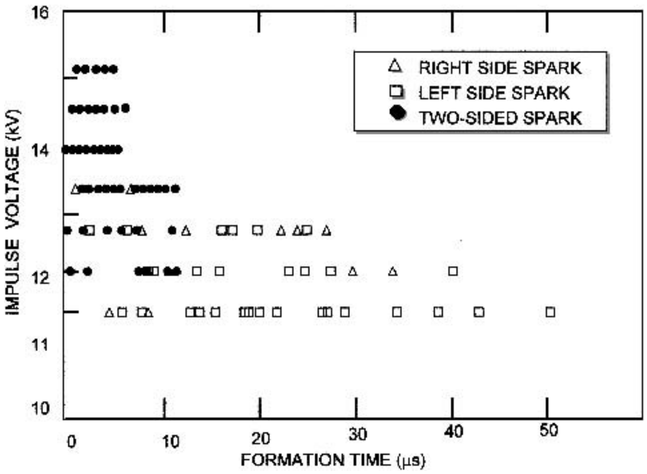

Fig. 4 Impulse voltage vs formation time for cascaded trigger sparks

with these secondary electrodes results in a momentary connection between the high-voltage dc supply and electrode 4. This arrangement produces an impulse voltage of very fast rise time. The latter is a necessary condition for the rapid onset of parallel spark discharges around both sides of the electrode array. The measured rise and fall times of the impulse voltage were 70 ns and 1 ms, respectively. The needle rotation speed was set to 1800 rpm, or 30 Hz.

The onset of parallel triggering sparks around the electrode ring relies on the establishment of electron avalanches within every electrode gap. The probability and formation time for such sparks depends strongly on the peak value of the impulse voltage applied to electrode 4. A spark discharge can be characterized by the product of its onset voltage and the time duration needed to form the spark, otherwise known as the spark's *v-t* characteristic.[19] In general, the higher the applied voltage, the shorter the formation time of the spark. Figure 4 shows the *v-t* characteristic of the trigger sparks in our system, measured without argon gas present. The ±170-V dc supply was not connected to the electrodes during these measurements. The black circles correspond to desirable parallel sparks that travel simultaneously down both sides of the electrode array and terminate on electrodes 1 and 7. The white squares and triangles correspond to undesirable single sparks that travel down the left or right side only of the electrode array. As these data show, impulse voltages above about 14 kV reliably produce desirable; "two-sided" sparks of formation time less than 10 μs. At impulse voltages smaller than 14 kV, however, undesirable, "one-sided" sparks begin to appear with formation times widely scattered up to 50 μs. These data also suggest that a two-sided trigger spark will not occur if the formation time of the impulse voltage is longer than about 12 μs.

Note that a trigger voltage that rises too slowly may cause a one-sided spark to occur before the trigger voltage reaches the peak value needed to initiate a two-sided spark. A conventional plasma torch uses a radio frequency (rf) high voltage source, typically an ignition coil, for triggering the arc. The rise time of such a voltage source is usually longer than ten microseconds. Hence, it might be impossible to obtain a two-sided trigger spark using a conventional rf-triggered voltage source.

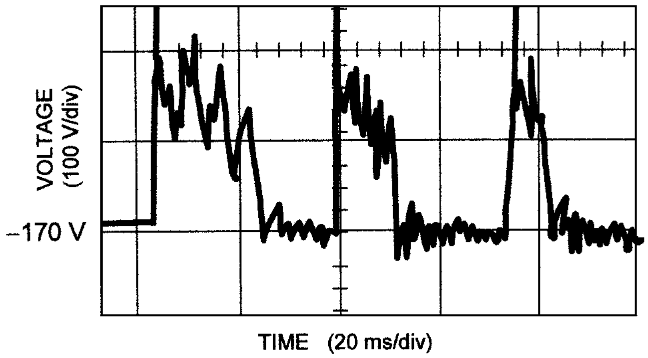

Fig. 5 Voltage between electrode 7 and ground vs time showing periodic arc formation

4. Results

As an initial test of the system, the ±170-V dc source was connected between electrodes 1 and 7, with the triggering voltage set to 14 kV. Each trigger spark caused a high-current cascade of six arcs to flow around the inner ends of the rod electrodes. The arc current was adjusted by setting the series resistor to 10, 15, 20, or 25 ohms**.**

At argon injection pressures less than about 35 kPa, the arc discharge directly bridged electrodes 1 and 7, essentially short-circuiting the cascade arc. At injection pressures in excess of 70 kPa, however, a cascade arc lasting for a few tens of milliseconds could be sustained. Figure 5 shows the voltage at electrode 7 versus time (measured relative to ground) as recorded by a digital oscilloscope. After the large initial spike caused by the trigger impulse, the voltage of electrode 7 moved from –170 V to about 50 V, signifying the onset of the main arc. Small voltage fluctuations at 180 Hz associated with the ripple of the three-phase ac voltage source is also evident during this interval. After about 20 ms, the arc extinguished and the voltage of electrode 7 returned to –170 V. The trigger sparks allowed the cascade arc discharges to be reproduced repeatedly.

From the voltage and current measurements of the cascade arc, the relationship between the cascaded arc voltage and current could be estimated. Figure 6 shows the relationship between the cascaded arc voltage and current at argon injection pressures of 70 kPa and 100 kPa. The relatively constant nature of the arc voltage over a wide range of arc currents is evident in this plot. The *v-i* curve of the cascade arc resembles the widely cited "negative characteristic" of a simple two-electrode arc.[20,21] In this case, however, the voltage across the entire arc cascade is much larger than the voltage across a single arc. This result suggests that each arc sustains its own cathode drop, and that the total voltage across the cascade will be equal to the voltage drop of a single arc times the number of arcs in the cascade. For our six-arc cascade, the voltage across the entire cascade at 20 A was about 130 V, with each arc sustaining a voltage drop of about 22 V. At a total cascade voltage of 130 V and an arc current of 20 A, the total electrical energy dissipated in the arc was approximately 2.6 kW.

Figure 7 shows the mean value of the arc duration as a function of arc current. The duration of the cascade arc increases with the arc current and becomes shorter at higher argon injection

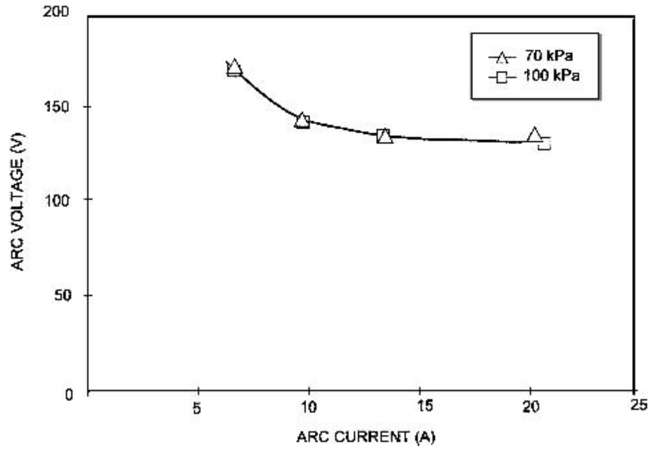

Fig. 6 Relationship between arc voltage and current for two values of argon inlet pressure

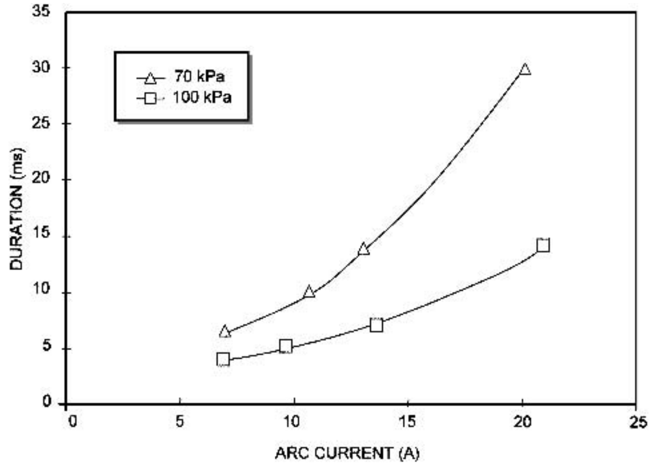

Fig. 7 Relationship between arc current and duration for two values of argon inlet pressure

pressure. One explanation for this result could be that the cascade arc is extinguished by the moving argon stream.

Photographs of the circular-shaped cascaded arc discharge confirm that the brightest region of the plasma plume has a diameter of about 40 mm and a length of about 60 mm with the plasma plume extending upward. These dimensions characterize the laboratory-scale experiment only and are not indicative of those achievable in a commercial-scale system. The circular cascade arc is inherently scalable, such that a wide range of arc plume dimensions should be achievable. The upward extension of the plasma plume described above is likely due to the streaming of the argon gas as well as the tendency of the hot plasma gases to rise. In a practical plasma torch system, the outward flow of the argon stream could be used to direct the plasma plume in any desired direction, as in a conventional, single-electrode system. The experiments suggest that, in contrast to a conventional single plasma torch, the stability of the arc in a circular cascaded plasma torch array depends on the argon gas flow rate. This dependency is evident in the data of Fig. 7, where higher pressure results in increased gas flow rate. Because the arc column tends to deform or be extinguished by any turbulence in the argon gas flow, the latter must be nearly laminar in the region surrounding the arc electrodes if the arc is to be stable.

5. Summary

A laboratory-scale circular cascade arc torch array has been designed and experimentally verified using seven tungsten rod electrodes mounted radially around a stream of argon gas and fed by a single high-current voltage source. The cascade arc discharge is repetitively triggered using a spark gap that initiates a bi-directional cascade spark discharge. The ensuing arc discharge forms a cylindrical plasma plume into which particles can be injected for the purposes of plasma spray operations. The system has the potential to be incorporated into a commercial grade plasma torch system using conventional power supplies and only modest design of the plasma gun itself. The principal advantage of such a system would be better center injection of powder feedstock, leading to improved uniformity of the coating as a function of radius from the center of the plasma plume. Future work will include the measurement of arc temperature and velocity distribution in the plasma plume under a variety of operating conditions, and the construction of a commercial scale-working prototype.

Acknowledgments

We wish to thank Donald Wroblewski and Michael Gevelber for their many helpful suggestions regarding the uses and need for a circular plume plasma torch system; Thomas Bifano for use of his laboratory facilities; and Joseph C. Crager and Paul Bierden for their help in running the experiments. Susan Mitchell assisted in the preparation of the figures.

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