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REVIEW

Multiple Electrodes and Cascaded Nozzles: A Review of the Evolution of Modern Plasma Spray Torches

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Abstract Conventional one-cathode/anode plasma spray guns are susceptible to aging. One reason is the large power density, especially at the arc roots on the cathode tip and the anode wall. Anode wear results in a thinner boundary layer and a reduced arc root motion, which increases the local thermal load. This also results in a voltage drop, and thus a reduction in power level when the power source is operated in a constant current mode. In addition to electrode wear, the instantaneous arc morphology and the time-dependent voltage waveform are strongly correlated to each other, especially when hydrogen or nitrogen is used as secondary plasma gas. Such arc dynamics are a major phenomenon that broadens the distribution of particle in-flight characteristics. The inevitable wear of electrodes and the inherent power fluctuations were the starting point for the development of new concepts for modern plasma spray guns. Multi-electrode plasma torches were developed to improve operational stability and lifetime. They became popular due to their good stability and high-power plasma jet, even when operated with inert gases only. In this context, cascaded torch nozzles were introduced, which effectively limit the axial movements of the anodic arc attachment. Such a design includes a stack of neutrodes in front of the anode, which are electrically insulated from each other. Since the arc is more stable, the power demand is virtually constant and the treatment of the feedstock particles is more uniform than with the conventional non-cascaded torches. In this review, the mechanisms leading to electrode wear and arc fluctuations in single-cathode/anode plasma guns are explained. Some concepts of multi-electrode torches and cascaded torch nozzles are presented. Examples of experimental results obtained by diagnostic methods are also given.

Keywords Plasma Spray Torch · Multiple electrodes · Cascaded nozzle · Arc fluctuation · Electrode wear

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Introduction

It is well known that conventional one-cathode/anode thermal spray guns are susceptible to *aging*. The performance of such torches degrades continuously. One reason is the large power density, especially at the arc roots on the cathode tip and the anode wall. In addition to electrode wear, arc *fluctuation* is a typical problem in plasma torches (Ref 1). The instantaneous arc morphology and the time-dependent voltage waveform were found to be strongly correlated to each other. Thus, the dynamics of the arc is an important phenomenon that broadens the distribution of the characteristics of the particles in flight. As a result, the deposition rate and the microstructure of the sprayed coating are affected.

In conventional one-cathode/anode plasma torches, the inevitable wear of the electrodes on the one hand and the inherent power fluctuation induced by the arc movements on the other hand have been the starting points for the development of novel concepts for modern plasma spray guns. Thus, *multi-electrode plasma torches* were developed to improve the operation stability and lifetime (Ref 2, 3). Such kind of plasma sources became popular because of their good stability and high-power plasma jets, some of them even when operated with inert gases only.

In this context, *cascaded plasma torches* (CPTs) have been introduced which effectively limit the axial movements of the anodic arc attachment in (Ref 4). As a result of the more stable arc behavior, the power demand is virtually constant and the treatment of the feedstock particles is more uniform compared to the previous non-cascaded torches.

In this review, the mechanisms leading to electrode wear and arc fluctuations in legacy single-cathode/anode plasma guns are recalled leading to the development of modern plasma spray torch concepts. They are modern in the sense that those plasma torches are increasingly used today although their concepts are not really new. Some of these concepts, namely multi-electrode torches and cascaded torch nozzles, are presented. Furthermore, some examples of experimental results obtained by diagnostic methods are given to visualize the performance of some torches.

Performance of Conventional Single-Cathode/Anode Plasma Torches

Aging

Anode erosion is a common problem in DC plasma spray torches. Figure 1 shows a typical example of a worn cathode (top) and anode (bottom, cross section) of a conventional single-cathode/anode F4 plasma torch. The tip of the cathode has molten spots, and some cracks are visible. The anode wall shows a deep crater that anchors the arc root, suggesting a non-axisymmetric arc morphology. Such wear has been studied in (Ref 5) and shown to result in a thinner boundary layer and a reduced movement of the arc root, which increases the local thermal load. This also results in a voltage drop, and thus a reduction in power when the power source is operated in a constant current mode (Ref 6). Figure 2 shows the evolution of the deposited coating thickness and of the plasma torch input power during the processing of a small batch of 38 gas turbine components with an F4 single-cathode/anode plasma torch.

The deposition rate drops by 12% and the power drops by almost 5%. In such cases, it is common practice to increase the secondary plasma gas flow, but this can only be help so much. Thus, in (Ref 8) it was found that it is more preferable to maintain the in-flight particle temperature around a constant value to obtain more consistent and reproducible deposition efficiencies and microstructures rather than to maintain a constant input power by adjusting the secondary hydrogen flow rate.

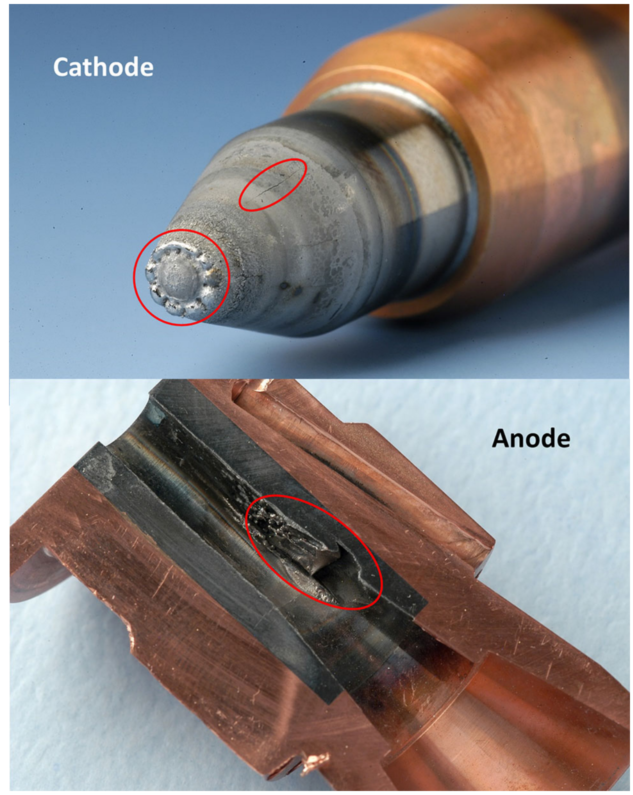


Fig. 1 Worn cathode (top) and anode (bottom, cross-sectioned) of a single-cathode/anode conventional F4 plasma torch

Figure 3 illustrates how severe the heating of the feedstock particles is affected by electrode wear. Here, the in-flight temperature distributions measured at the spray-distance are plotted using a conventional single-cathode/anode F4 plasma torch with a new set of electrodes and a worn set, respectively. In the latter case, the temperatures are generally lower, and the distributions are shifted off-axis and distorted. This can be expected to have a serious effect on the coating properties.

Arc Fluctuation

Due to the viscous force of the gas flow and to the self-magnetic force of the arc, the anode attachment moves along the smooth anode wall toward the torch exit. This extension of the arc is accompanied by an increase in voltage. The subsequent re-ignition of the arc at a point on the anode closer to the cathode causes the voltage to drop. The dynamics of the arc core are particularly dependent on

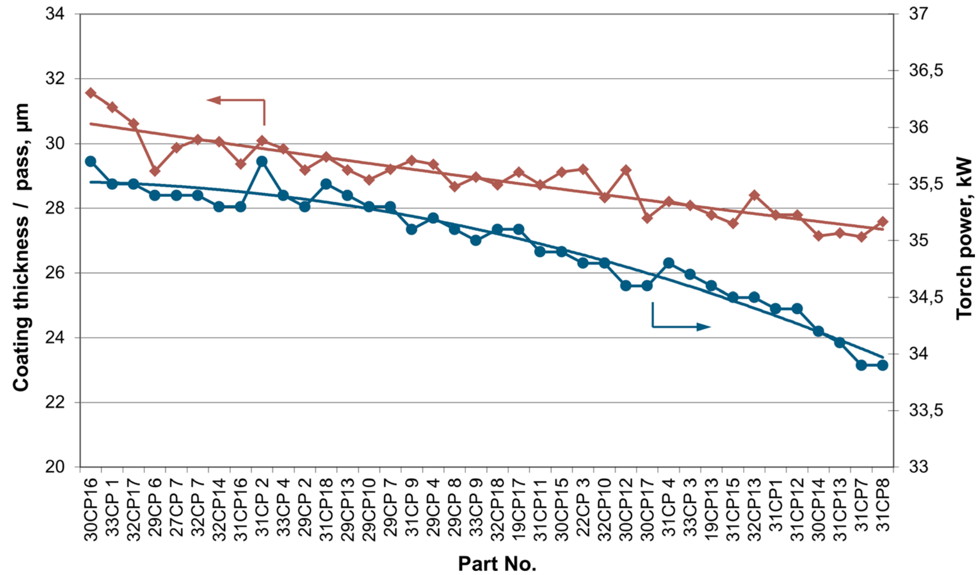


Fig. 2 Evolution of the deposited coating thickness and the plasma torch power during the processing of a small batch of 38 gas turbine components with an F4 single-cathode/anode plasma torch (data points are plotted in sequence of spraying); reproduced with permission from Springer Nature: Georg Mauer et al., Monitoring and Improving the Reliability of Plasma Spray Processes, Journal of Thermal Spray Technology, **26**(5), p 799-810, 2017, Springer Nature (Ref 7)

the arc current and on the plasma gas flow rate and composition. With respect to the latter, molecular gases such as hydrogen and nitrogen play an important role because their thermal conductivity exhibits peaks not only at ionization temperatures above 10,000 K, but also at lower temperatures between 3000 K and 7000 K due to their dissociation. This gives an additional contribution to the reactive part of the thermal conductivity (Ref 10, 11).

Three basic dynamic modes of the arc operation can be defined (see Fig. 4): with an overall increasing mean voltage, from a nearly constant voltage (steady mode 1), passing through a sinusoidal waveform of low amplitudes (takeover mode 2) up to the random, intensely fluctuating restrike mode 3 (Ref 5). Depending on the torch design, pressure effects (Ref 12) can also be mixed with the restrike mode. It is also reflected in significant fluctuations in the length of the plasma jet as shown in Fig. 5.

In (Ref 13), it was found that in a single-cathode torch and for all the argon gas flows considered, the low-frequency (300/360 Hz) arc fluctuations are mainly caused by the rectification of the power supply. In contrast, when using hydrogen or nitrogen as secondary plasma gas, the influence of the arc restrike mode (3-4 kHz) dominates the voltage waveform.

Time-resolved diagnostic measurements of the individual particle temperatures and velocities were correlated with the instantaneous voltage difference between the electrodes (see Fig. 6) (Ref 14). These time-dependent variations in particle temperature and velocity due to the power fluctuations induced by the arc movements were found to be very large when the plasma torch is operating under the restrike mode ($\Delta P/P \approx 100\%$, where P denotes the electrical power). When operating under the takeover mode, those fluctuations decrease but still remain quite high ($\Delta P/P \approx 30\%$) (Ref 14). This type of power fluctuations results in an increased porosity, a higher content of partially melted or non-melted particles, and lower deposition rates (Ref 15).

In addition to experimental testing, arc fluctuations have been also the subject of simulation model development. This has shown that the prediction of arcing is influenced by the choice of arc models, with the two-temperature model providing closer predictions to actual voltage and arcing (Ref 16).

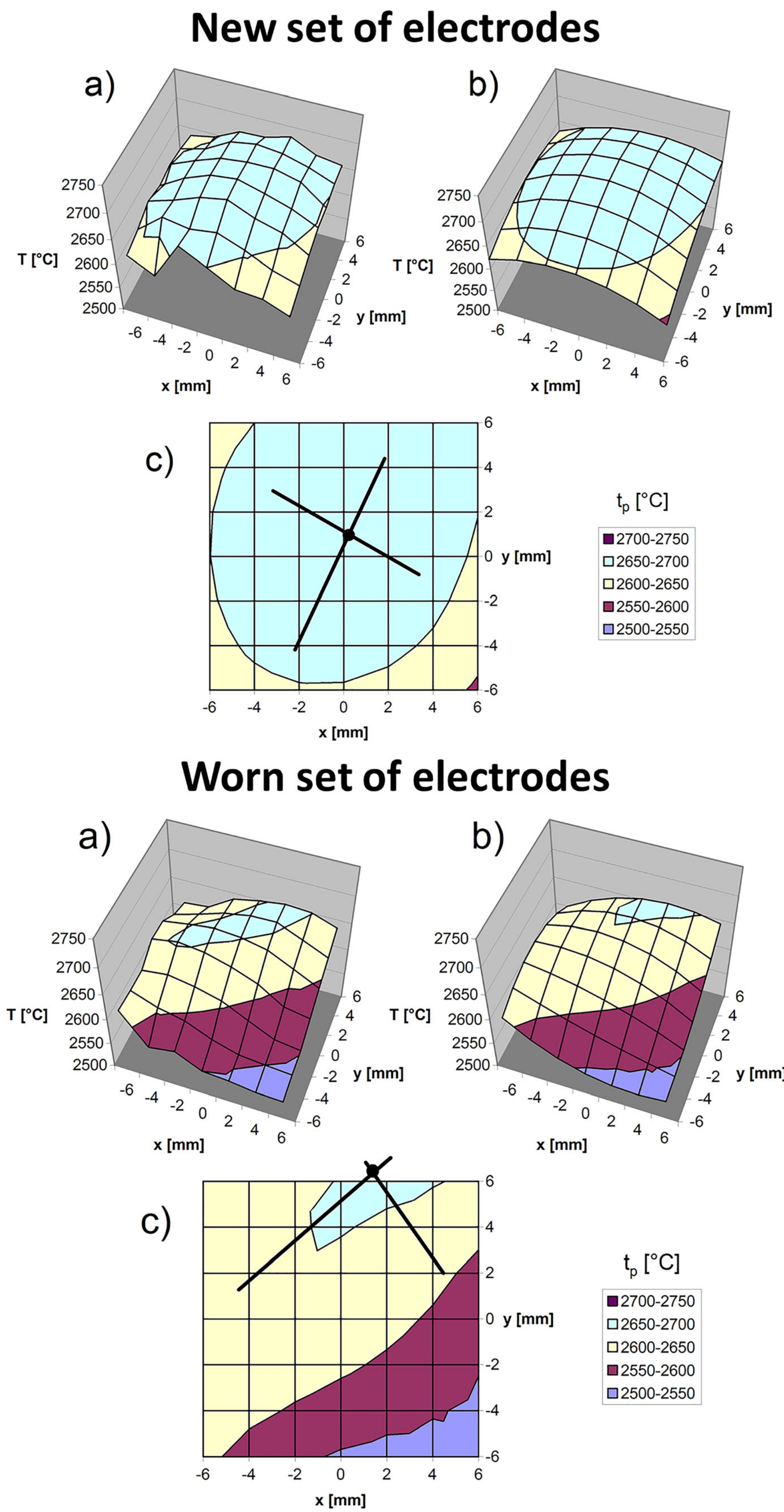
Evolution of Modern Plasma Spray Torch Concepts

Multi-electrode Plasma Torches

Multi-electrode spray systems have significantly improved the process stability and uniformity of atmospheric plasma spraying (Ref 17). In addition, such designs allow arc voltages and plasma powers to be increased by extending the arc length, potentially improving thermal efficiency (Ref 18).

Figure 7 shows examples of multi-arc plasma generators (Ref 3). They have either merging or separate arcs and all of them allow for central feedstock injection. In addition to the reduction of power density and thus torch degradation, these concepts were intended to pave the way for central powder injection. The latest development shown in this figure is the basis of the Axial III™ plasma torch (Northwest Mettech Corp., Surrey, BC, Canada). It is a spray gun with a set of three single cathode–anode units, thus providing three separate arcs. It is based on the patent granted in 1996 to Ross and Burgess (Ref 19). The three

Fig. 3 In-flight temperature distributions at spray-distance using a conventional single-cathode/anode F4 plasma torch with a new set of electrodes (top) and a worn set (bottom), respectively; (a) as measured, (b) smoothed, (c) main curvature analysis; reproduced with permission from Springer Nature: G. Mauer et al., Detection of Wear in One-Cathode Plasma Torch Electrodes and its Impact on Velocity and Temperature of Injected Particles, J. Therm. Spray Technol., 16(5-6), p 933-939, 2007, Springer Nature (Ref 9)



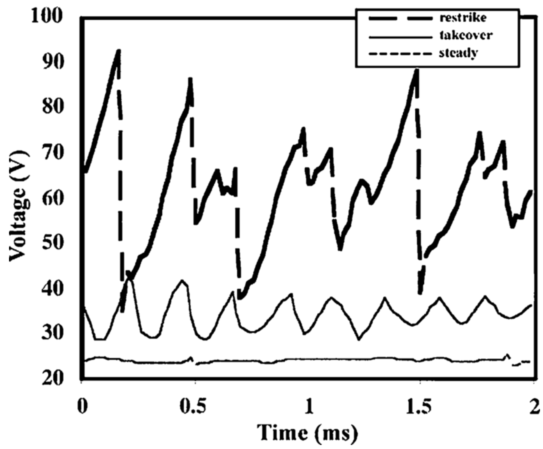


Fig. 4 Basic arc operating modes using a conventional single-cathode/anode SG-100 plasma torch; restrike mode (100 A, 12/40 Ar/He), takeover mode (500 A, 40/20 Ar/He), steady mode (900 A, 60 Ar); reproduced with permission from Springer Nature: Z. Duan, J. Heberlein, Arc instabilities in a plasma spray torch, J. Therm. Spray Technol., **11**(1), p 44-51, 2002, Springer Nature (Ref 5)

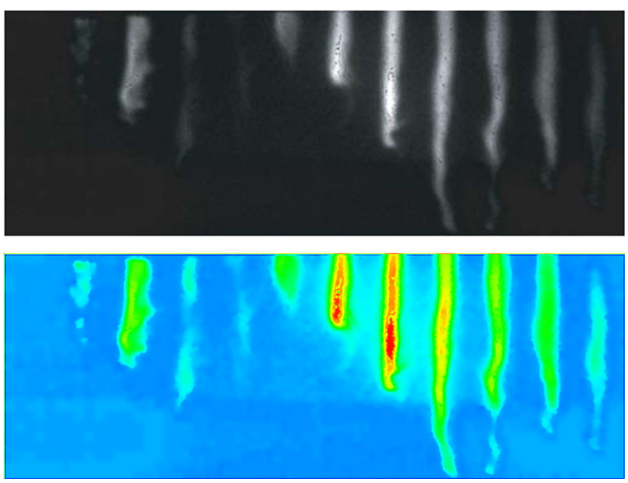


Fig. 5 Jet fluctuations using a conventional single-cathode/anode F4 plasma torch (540 A, 45 slpm Ar, 12 slpm N_2, exposure time 5 ns); top: reproduced with permission from Wiley: J. Schein et al., Improved Plasma Spray Torch Stability Through Multi-Electrode Design, Contrib. Plasma Phys. **47**(7), Wiley (Ref 2); bottom: transformation to pseudo-colors to enhance the contrast

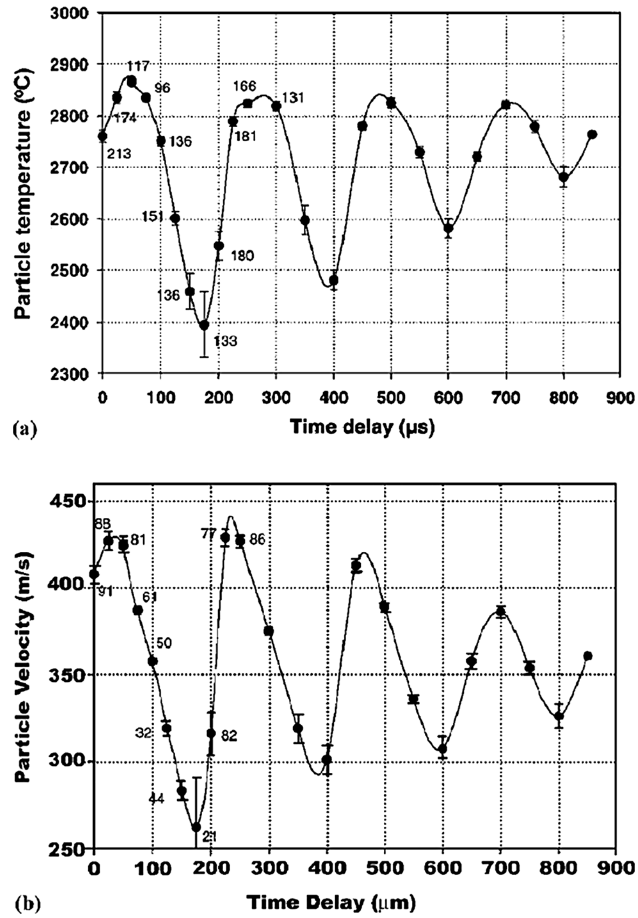


Fig. 6 Time-resolved diagnostic measurements of the fluctuating (a) average particle temperature and (b) velocity using a conventional single-cathode/anode F4 plasma torch (alumina, 550 A, 35 slpm Ar, 10 slpm H_2); the error bars represent the 1•σ confidence interval on the mean value, the numerical data indicate the sample standard deviations; reproduced with permission from Springer Nature: J.F. Bisson et al., Effect of plasma fluctuations on in-flight particle parameters, J. Therm. Spray Technol., **12**(1), p 38-43, 2003, Springer Nature (Ref 14)

plasma jets generated by three independent DC arcs converge to form a unified plasma jet inside the torch. Thus, this torch essentially consists of three plasma generators, each with single cathode and anode.

Figure 8 shows the tomographic 3D reconstruction of the temperature distribution in the plasma jet of an Axial III™ plasma torch when using three different nozzle diameters. It is obvious that the three individual plasma jets are not completely merged but form three separate hot lobes.

The fluctuations of the three individual single-cathode/anode units are also not smoothed out by merging the plasma jets. Figure 9 shows the radial intensity line scans of the Axial III™ plasma jet of three consecutive high-speed images. The intensity fluctuations are obvious and are also reflected in the corresponding instantaneous values of the total torch power. See (Ref 20) for an example of the variation in performance of each unit and the overall performance of this gun over time.

In 1991, Landes et al. (University of the Federal Armed Forces Munich, Germany) introduced the Triplex I gun with three cathodes and one anode, see Fig. 10 (Ref 21). It was turned into a commercial product by Sulzer Metco (Wohlen, Switzerland, today Oerlikon Metco). Three cathodes were insulated against each other and biased separately to produce three different arcs with fixed anodic arc root attachments. The arc voltage was adjusted by varying the anode/cathode distance, and the enthalpy of the

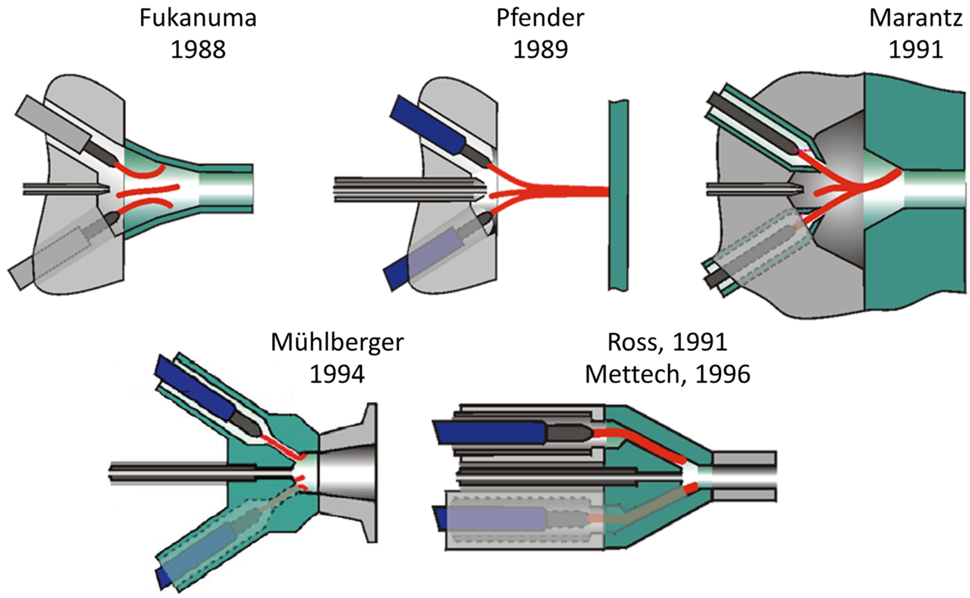


Fig. 7 Examples of multiple-arc plasma generators; reproduced from (Ref 3), licensed acc. to the terms of the Creative Commons Attribution Non-Commercial License CC BY-NC 3.0 (https://creativecommons.org/licenses/by-nc/3.0/)

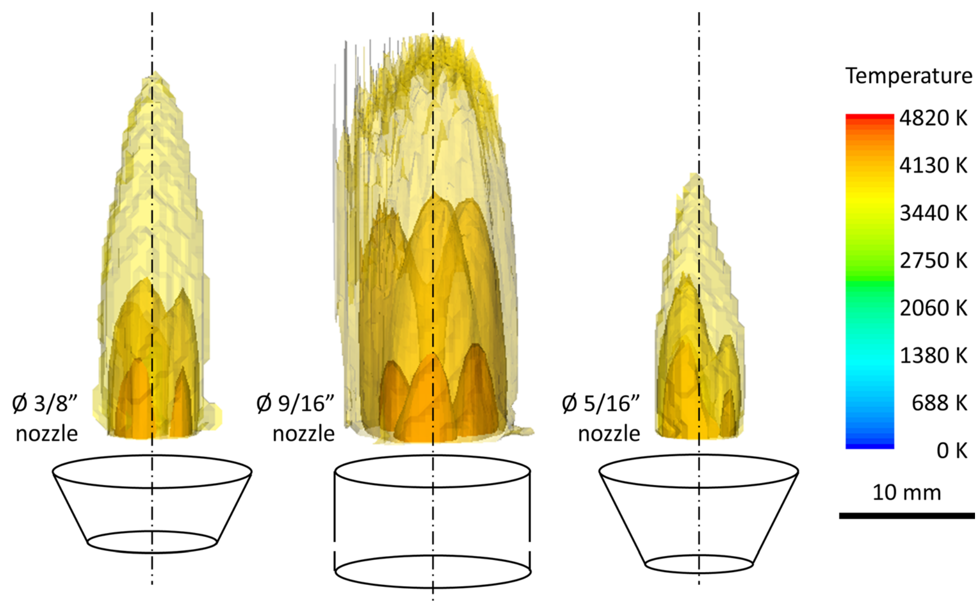


Fig. 8 Tomographic 3D reconstruction temperature distribution in the plasma jet of an Axial III™ plasma torch when using three different nozzle diameters (3 x 230 A, 112 slpm N_2, 38 slpm H_2, nozzle Ø 3/8“); reproduced and rearranged from (Ref 20), licensed acc. to the terms of the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by-nc/4.0/)

plasma jet could be increased without the need of operating with molecular gases. The successor models Triplex II and TriplexPro™-200/210 allowed operation at higher capacities; the latter can also be equipped with nozzles of different diameters.

Later, in 2007, it was again Landes et al. who introduced the Delta gun (Ref 22) (see Figure 11). It was marketed by GTV Verschleißschutz GmbH (Luckenbach, Germany). Three anode segments are insulated against each other and separately connected to a triple power supply. The anode segments are shrouded by a lateral argon gas flow. The discharge current is forced to flow down the centerline of the torch up from the cathode tip to an arc separation point. At this point, the single arc splits into three short arcs that are fixed to the anode segments. As a result, the anodic arc roots are well defined axially and azimuthally and are not displaced. Thus, the torch fluctuations are small as illustrated by high-speed camera images in the kind of Fig. 5 for the Triplex and Delta torches by Schein et al. (Ref 2).

In principle, fixing the attachment of the arc also can mean the risk of greater anode erosion. In the case of multi-electrode concepts like Triplex and Delta, however, the plasma power is divided between several arcs, resulting in lower power densities.

The operation of plasma torches is controlled by coupled dynamic, thermal, chemical, electromagnetic, and acoustic phenomena (Ref 24). Computational modeling is used to gain insight into torch characteristics, such as the dynamics

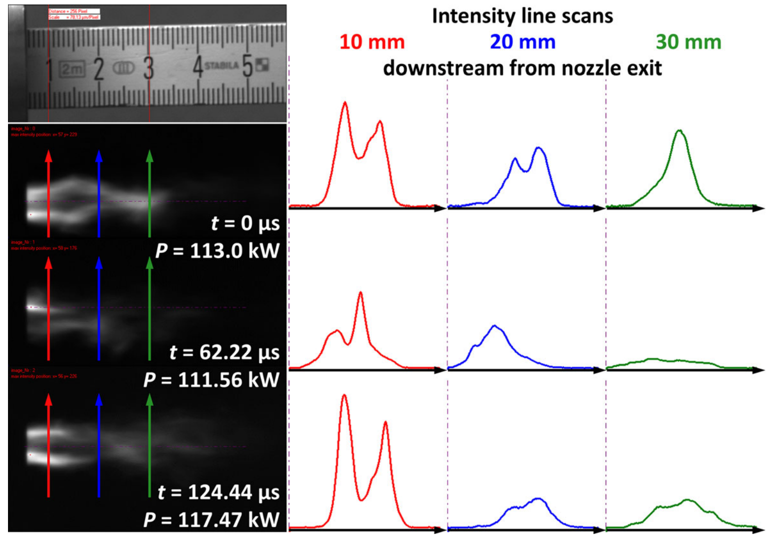


Fig. 9 Radial intensity line scans of the Axial III™ plasma jet (3 x 230 A, 112 slpm N_2, 38 slpm H_2) of three sequential high-speed images; reproduced and rearranged from (Ref 20), licensed acc. to the terms of the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by-nc/4.0/)

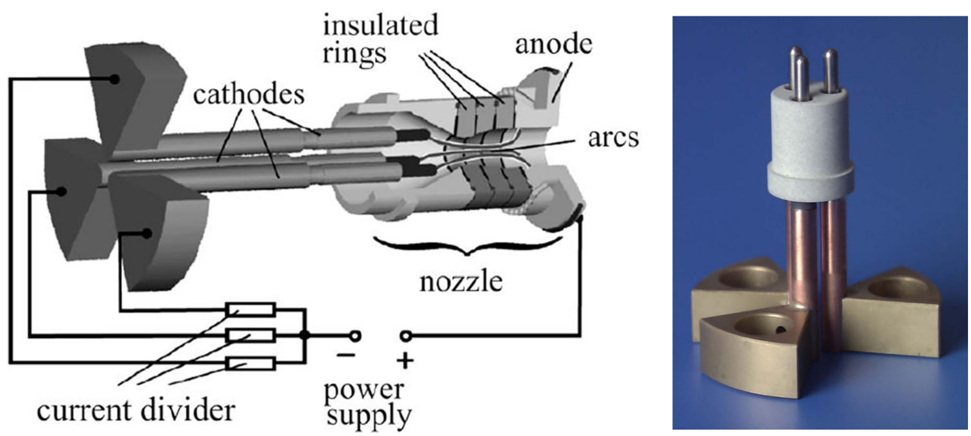


Fig. 10 Design of the Triplex I gun with three cathodes and one anode, left schematic reproduced from (Ref 3), licensed acc. to the terms of the Creative Commons Attribution Non-Commercial License CC BY-NC 3.0 (https://creativecommons.org/licenses/by-nc/3.0/)

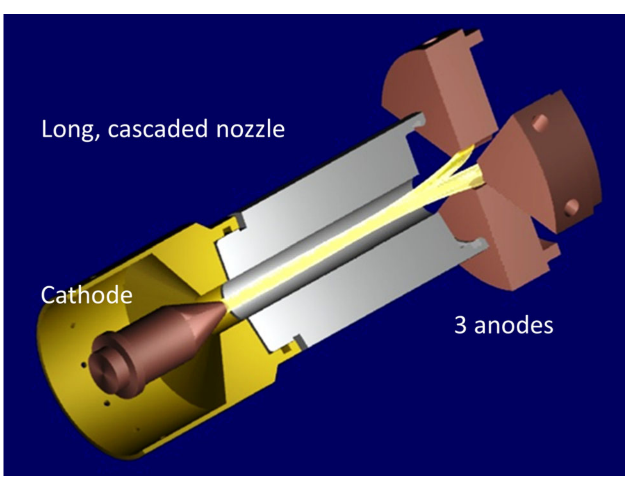


Fig. 11 Design of the Delta gun with one cathode and three anode segments; reproduced with permission of Universität der Bundeswehr München (Ref 23)

of the arc inside the plasma torch, that are practically inaccessible to experimental observations. This helps to understand and control these processes. However, it presents challenges such as non-equilibrium conditions and rapid transient events, which require advanced diagnostic methods for verification (Ref 25, 26). Such numerical models have been developed to study flow characteristics and to perform free-jet simulations also in multi-electrode torches; they have been refined with respect to the meshing and the applied turbulence model (Ref 27, 28).

Cascaded Plasma Torches

Wall-stabilized, cascaded plasma torch (CPT) concepts consist of a stack of metallic neutrodes in front of the anode, which are electrically insulated from each other. Reducing the inner diameter of the segments (arc constriction), while keeping the other arc parameters the same, leads to a significant increase in the field strength and consequently to higher energy losses by heat conduction. In order to maintain the wall stabilizing effect, it is essential that the diameter of the channel containing the arc is smaller than the diameter of a free-burning arc operated under the same conditions. If the channel diameter is too large, the stabilizing effect of heat conduction is lost (Ref 29).

CPTs make it possible to achieve an arc length that is longer than the average so-called self-setting length (dependent on the arc current, plasma gas composition and flow rate, and electrode geometry) (Ref 30). This reduces arc motion and plasma jet fluctuations, resulting in longer and more stable plasma jets with higher specific enthalpy than conventional plasma torches (Ref 31). Thus, CPTs help eliminate their major drawbacks, such as plasma parameter drift and excessive erosion of electrodes (Ref 32), resulting in improved melting capability, overall process reliability, and extended and more uniform particle treatment at higher feed rates (Ref 33).

The cascaded arc was introduced in 1956 by Maecker (Ref 34). Further fundamental work was done at the Eindhoven University of Technology (Ref 35). An early plasma torch concept with a fixed length arc forced by the insertion of neutrodes between the cathode and anode was the advanced plasma gun (APG) (former Metco-Perkin-Elmer, 1968) (see Fig. 12). However, this torch did not provide sufficient stability of the plasma jet, because an azimuthal motion of the arc root on the cylindrical anode wall could not be avoided (Ref 3). Another development with a fixed minimum arc length was the PJ-100 torch (Plasma Jet Co., 2001), which can be operated with an electrical input power of up to 100 kW. The design goals were a high thermal efficiency, a plasma plume with less turbulence and eddies, and a homogeneous temperature and velocity distribution of the plasma (Ref 36).

The Debye-Larmor™ cascade gun family was developed based on the single-cathode/anode F4 torch technology and combined it with a cascaded nozzle (Gulhfi AG, Wohlen, Switzerland). The modular torch concept allows to control the arc length and thus the output power, the plasma gas velocity and enthalpy (Ref 37). The Debye-Larmor plasma gun can be used for both atmospheric and low-pressure plasma spraying. It can be operated with argon only (Ref 38).

Besides wall stabilization, the use of a strong vortex motion, with or without magnetic field enhancement, was the subject of extensive studies (Ref 29), e.g., by Zhukov who introduced a cascaded plasma torch with inter segment gas injection in 1979 (Ref 39). Belashchenko et al. developed a high-voltage—low current APS process and torch that is based on combined wall and gas stabilizations (C^+Plasma) in 2015 (Ref 40, 41).

The concept of CPTs has been widely applied to multi-electrode plasma torches, such as the Triplex torch series, Triplex I, Triplex II, TriplexPro™-200/210 (Oerlikon Metco, Wohlen, Switzerland, all mentioned above), and also for the Delta gun (GTV Verschleißschutz, Luckenbach, Germany) (see Fig. 11). In addition, the SinplexPro™ (Oerlikon Metco, Wohlen, Switzerland) is an approach to bring the benefits of the cascaded arc technology likewise to a single-cathode gun (Ref 42) (see Fig. 13). The SinplexPro™ 03C is its low-pressure compatible variant, capable of operating at chamber pressures down to 3 kPa. It was launched in 2022 intended to replace the conventional F4-VB torch and 03CP single-cathode/anode torches at low-pressure plasma spraying (all Oerlikon Metco, Wohlen, Switzerland).

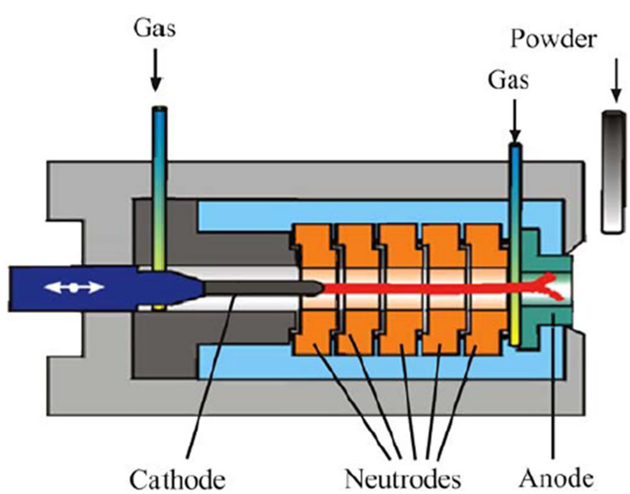


Fig. 12 Schematic of APG plasma torch; reproduced from (Ref 3), licensed acc. to the terms of the Creative Commons Attribution Non-Commercial License CC BY-NC 3.0 (https://creativecommons.org/licenses/by-nc/3.0/)

Fig. 13 SinplexPro™ single-cathode plasma torch with cascaded nozzle, reproduced by permission of Oerlikon Metco

The following are a few examples of the diverse uses of CPT technology. For the spheroidization of metallic powders with wide size distribution, the introduction of such a triple-cathode cascaded plasma torch has allowed for plasma spheroidization with relatively small arc voltage fluctuation, high arc voltage, and low gas flow rate range, demonstrating an increased effectiveness (Ref 43). Another study compared a conventional torch and a cascaded arc plasma torch and found that the latter had improved melting capability and more uniform particle temperature at higher feed rates (Ref 33). The influence of the nozzle's diameter of CPTs on electric arc dynamics and coating properties has been studied, showing that reducing the nozzle's diameter results in higher arc voltage fluctuations and lower thermal efficiency of the plasma torch, potentially leading to higher coating porosity (Ref 44).

Conclusions and Perspectives

The development of multi-electrode plasma guns and wall-stabilized cascade arc torches has been stimulated by two key phenomena: the early degradation of conventional single-cathode/anode torches and their strong arc fluctuations. In this review, the underlying mechanisms were recalled. Some examples of experimental results obtained by diagnostic methods were given to demonstrate their significant impact on the properties of the deposited coatings. In addition, some designs of multi-electrode guns and cascaded torch nozzles were presented. Such multi-electrode plasma and wall-stabilized cascade arc torches have become mainstream in the thermal spray industry, offering improved melting capability, overall process reliability, and extended and more uniform particle treatment at higher feed rates.

One remaining limitation is that the only commercially available multi-electrode torch that allows axial feedstock injection does not have cascaded nozzles and is therefore still prone to fluctuations. On the other hand, the available CPTs, which show a more stable operation, are equipped only with radial feedstock injectors. Depending on the feedstock (powders or suspensions), this can lead to a wide fan-out of the plume, which has a detrimental effect on the deposited microstructures. In order to achieve improvements in this respect, the University of the Federal Armed Forces in Munich, in cooperation with Forschungszentrum Jülich, is currently assembling an experimental test rig that can be equipped with three plasma generators (legacy torches and/or CPTs). Their relative position and orientation can be adjusted, and an axial feedstock injection will be provided. It is expected that the interaction of the three plasma generators can be studied in detail, since the merging area of the jets is accessible for diagnostic systems. In particular, the performance of suspensions will be investigated to improve the efficiency and reproducibility of the spraying process. In addition, stabilization measures in multi-electrode torches and CPTs, such as the introduction of additional magnetic fields or electrodes, are conceivable.

The advances in plasma torch technology have been accompanied by other activities to improve thermal spray processes. Examples for this include the development of sensors, testing, modeling and machine learning techniques, and the production of precursors to increasingly stringent specifications (Ref 45).

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