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ORIGINAL PAPER

Advances in Plasma Arc Cutting Technology: The Experimental Part of an Integrated Approach

V. Colombo · A. Concetti · E. Ghedini · F. Rotundo · P. Sanibondi · M. Boselli · S. Dallavalle · M. Gherardi · V. Nemchinsky · M. Vancini

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Abstract The experimental part of an integrated approach to design and optimization of plasma arc cutting devices will be presented; in particular results obtained through diagnostics based on high speed imaging and Schlieren photography and some evidences obtained through experimental procedures. High speed imaging enabled to investigate start-up transition phenomena in both pilot arc and transferred arc mode, anode attachment behaviour during piercing and cutting phases, cathode attachment behaviour during start-up transient in PAC torches with both retract and high frequency pulse pilot arc ignition. Schlieren photography has been used to better understand the interaction between the plasma discharge and the *kerf* front. The behaviour of hafnium cathodes at high current levels at the beginning of their service life was experimentally investigated, with the final aim of characterizing phenomena that take place during those initial piercing and cutting phases and optimizing the initial shape of the surface of the emissive insert.

Keywords Plasma arc cutting torches · Diagnostics · Electrode erosion · High speed imaging · Schlieren imaging

Introduction

The plasma arc cutting (PAC) process is characterized by a transferred electric arc that is established between an electrode, that is part of the cutting torch (the cathode), and another electrode, that is the metallic workpiece to be cut (the anode) [1]. In order to obtain a high

V. Colombo (✉) · A. Concetti · E. Ghedini · F. Rotundo · P. Sanibondi · M. Boselli · M. Gherardi
Department of Mechanical Engineering (D.I.E.M.) and Research Center for Applied Mathematics (C.I.R.A.M.), Alma Mater Studiorum—Università di Bologna, Via Saragozza 8, 40123 Bologna, Italy
e-mail: colombo@ciram.ing.unibo.it

S. Dallavalle · M. Vancini
Cebora S.p.A., Via Andrea Costa 24, 40057 Cadriano di Granarolo, Italy

V. Nemchinsky
Keiser University, Fort Lauderdale, FL, USA

quality cut and a high productivity, the plasma jet must be as collimated as possible and must have the higher achievable power density.

State of the art knowledge in PAC is defined more by the huge amount of patents literature than by journal papers; this fact induces a strong need for understanding the physical reasons behind industrially patented successful ideas that, due to patenting rules and strategies, are often not completely and correctly described. The particular approach of this work is in line with the research work done by the Authors in recent years to fulfil the abovementioned need, taking as a starting point either patented solutions or commercial solutions based on those patents in the field of PAC [2–13].

The approach used by the authors in designing and optimizing thermal plasma sources is characterized by the integration of numerical simulation, diagnostics and experimental evidences. Diagnostics enable to investigate significant phenomena, otherwise impossible to recognize, in particular those ones related to start-up and shut-down transients and to the interaction between the plasma jet and the work-piece. Simulative results enable to identify innovative design solutions, addressing specific issues that cannot be fully investigated through experimental tests. Experimental evidences are fundament to validate simulative and diagnostics results and to evaluate plasma arc cutting systems performances, in terms of cut quality and electrode erosion. The integration between diagnostics, experimental evidences and numerical simulation results in designing and optimizing plasma arc cutting torches enables to obtain significant added value and to avoid a try & fail approach, often too expensive, but research is still in the making for finding a link between simulation of the plasma arc and a consistent prevision of cut quality.

In this paper the experimental part of the abovementioned integrated approach will be presented; in particular new insight coming from diagnostics based on high speed and Schlieren imaging and from experimental analysis of the behaviour of electrodes during first starts will be discussed.

High Speed Imaging Investigation of Start-Up Transition Phenomena in Both Pilot Arc and Transferred Arc Mode in Hf Cathodes for PAC

The behaviour of Hf cathodes has been investigated with high speed camera (HSC) imaging techniques during the low current pilot arc phase, to highlight phenomena that take place during the transition from insulating, non-emissive, cold to conductive, emissive, hot for the Hf-based material used in electrodes for PAC of mild steel plates. In particular, the characteristic time scale for the solid hafnium (Hf) oxide layer to be converted into a molten film, enabling the arc root attachment to stabilize itself at the centre of the emissive surface, has been investigated.

The Behaviour of Hf Cathodes During the Start-Up Transient in the Pilot Arc Mode

First results have been obtained in the pilot arc mode [10]. Visualization of the cathode surface during pilot arcing was accomplished by positioning the torch and the camera lens on the same common horizontal axis. These studies have been accomplished for three electrode emitter surface conditions: new electrode with planar emission surface, new electrode with initially concave emission surface, used electrode with a recess spontaneously established on the emission surface after a few cutting cycles. Experiments have been accomplished under operative conditions typically used in cutting of MS plates thicker than 20 mm. In the considered pilot arc phase air is used both as plasma gas and as shield gas, while the arc current is fixed at 25 A; the signal of the voltage drop between the electrode and the nozzle has an average value of 150 V with fluctuations of about ±30 V. The tested electrodes use a press fit Hf insert with a diameter of 2 mm, working in association with a nozzle with a 1.9 mm orifice diameter. Moreover, the use of a plasma diffuser with 3 holes with a diameter of 0.4 mm, enabled to obtain high plasma gas swirl velocity at the inlet of the plasma chamber, with the aim of obtaining a strong constriction of the plasma discharge. The experimental camera recordings for the three conditions of the studied electrode emitter surface show that the pilot arc process is characterized by two subsequent phases (Fig. 1). In the first one, the cathode arc root rotates on the periphery of the emitter surface. This phase is also characterized by the emission of Hf vapours. In the second phase, the cathode attachment is no more rotating at the periphery of the emitter surface and the arc column stabilizes at its centre. The transition from the first pilot arc phase to the second one occurs as a sudden event during which the cathode attachment progresses very fast to the centre of the emitter surface, almost as a collapse, with consequent emission of Hf vapours and, for the case of used electrode, also with the ejection of molten particles. The comparison of the behaviour during pilot arc of electrodes with different emission surfaces shows that the new ones, both with or without the initially

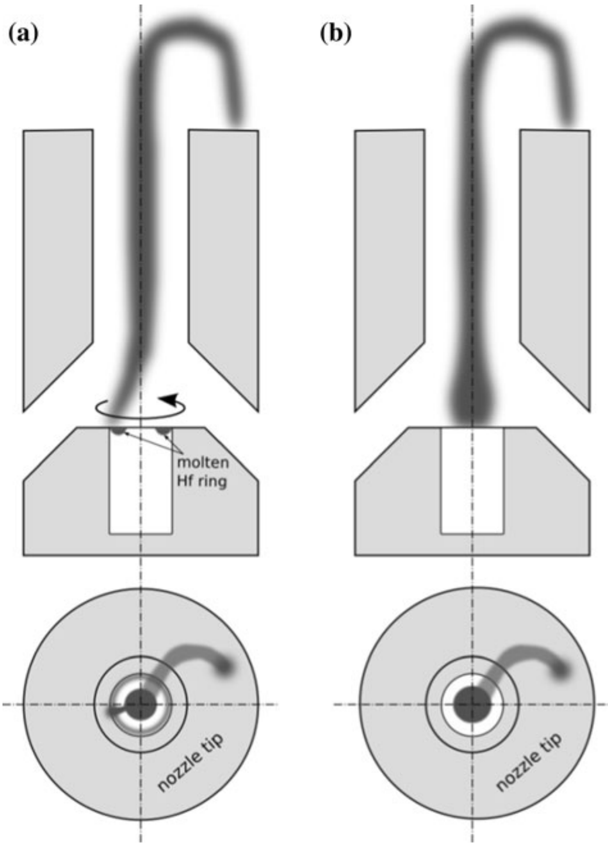

Fig. 1 *Side* and *top* view schematic of the PAC torch in the two start-up pilot arc phases. **a** Rotation of the cathodic arc root on the insert periphery, **b** stable centred arc root (taken from [10])

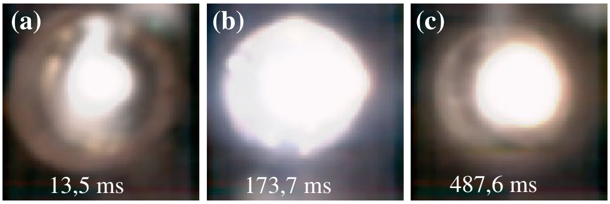

Fig. 2 Pilot arc images, **a** during the first pilot arc phase, **b** during the transition and **c** during the second pilot arc phase, for the case of used electrode (taken from [10])

shaped emission surface, are characterized by a quite short (less than 12 ms) transient towards stabilization of the arc column at the centre of the Hf surface with a smooth transition event without massive ejection of melted Hf based particles. Used electrodes, on the contrary, are characterized by a quite long (almost 175 ms) transient phase with massive ejections (Fig. 2). This experimental evidence, can now support and integrate the qualitative explanation given in [1] for the correlation between a decrease in the erosion rate and a sufficiently gradual increase in arc current during the starting transient. In fact, the experimental evidences shown by high speed imaging can be related to the mechanism [1], which indicates the importance of heating and melting the solid layer of Hf oxide.

The Behaviour of Hf Cathodes During the Start-Up Transient in the Transferred Arc Mode

Subsequent studies have been accomplished investigating the behaviour of Hf cathodes during the start-up transient in the transferred arc mode, in order to obtain more realistic results, with respect to those obtained in the pilot arc mode. The transferred arc mode was obtained using a water-cooled rotating carbon cylinder simulating the anode and replacing the plate. The observation of the cathode surface during transferred arcing was accomplished by removing the shield cup and by using a modified nozzle, as shown in [14], characterized by the presence of a viewing port at one side of the nozzle, positioned at an angle of 45° from the torch/arc axis with the axes centred on the hafnium insert and a diameter of 3 mm; a quartz windows has been suitably positioned into the port and locked through a specific sealing resin. The viewing angle of 45° implies the presence of the round view port in images and an elliptical shape of the hafnium insert. Images have been obtained using a NAC Memrecam K3R HS camera with a 180 mm focal-length lens, protected by a sacrificial neutral filter at a distance of 1 m from the Cebora plasma torch HQC 254, operating in realistic operating conditions for cutting 20 mm mild steel plates with O_2/air as plasma/shield gas and an operating current of 250 A. With respect to the experiments previously accomplished in the pilot arc phase, in this case the plasma gas swirl velocity at the inlet in the plasma chamber was reduced by using a plasma gas diffuser with 6 holes with a diameter of 0.8 mm. The study has been accomplished for a used electrode with a recess spontaneously established on the emission surface after a few cutting cycles. The obtained video shows that the start-up transient in the transferred arc mode is characterized by two subsequent phases, spaced out by a sudden transition event characterized by massive ejections of melted Hf based particles, as for the abovementioned pilot arc mode with a used electrode. In this case, the stabilization of the arc at the centre of the emitter surface occurs after about 15 ms form the arc ignition and the difference in transition time with respect to the pilot arc case can be attributed to the change in operating conditions. Therefore, the obtained result confirm that in the case of used electrodes the start-up transient is characterized by massive ejections of melted Hf based particles before the stabilization of the arc at the centre of the emission surface, independently of swirl

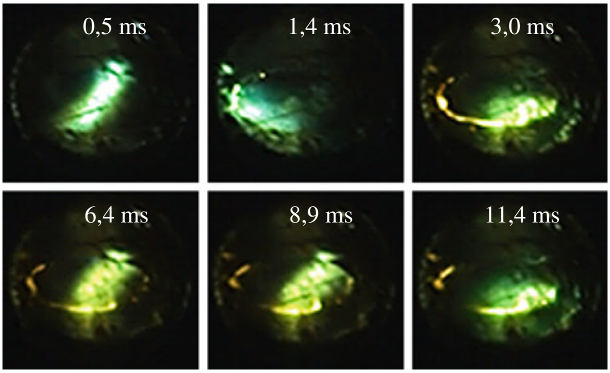

Fig. 3 Transferred arc images, at different time steps, during the first start-up transient phase

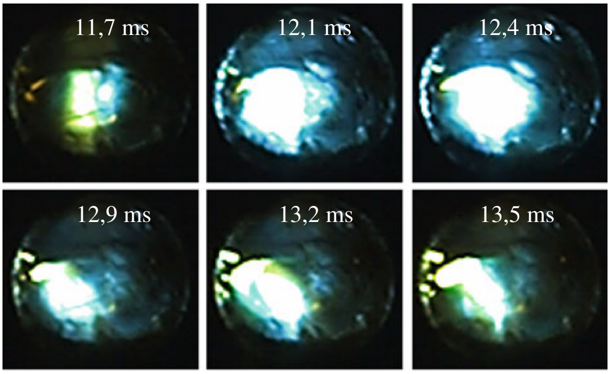

Fig. 4 Transferred arc images, at different time steps, during the transition event

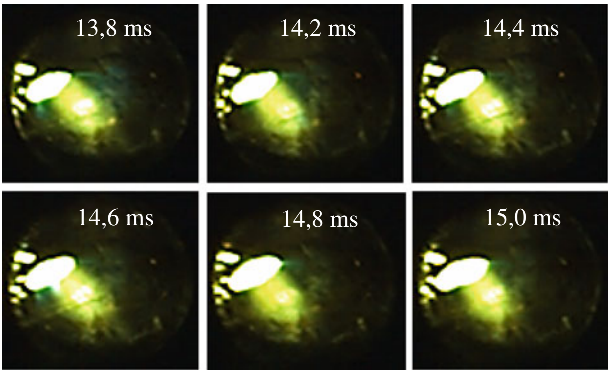

Fig. 5 Transferred arc images, at constant time steps of 0.2 ms, during the second start-up transient phase

velocity operating conditions; which otherwise influence the transition time. This evidence must be taken in due consideration during the optimization of the start-up transient phase, since swirl velocity operating conditions, together with torch geometry, are significant design parameters for the optimization of cut quality and consumables service life. Figures 3, 4 and 5 show some significant frames of the recorded video referred, respectively, to the first start-up transient phase, the transition event and the second start-up transient phase.

Comparison Between Cathode Attachment Behavior During Start-Up Transient Between PAC Torches with Retract and High Frequency Pulse Pilot Arc Ignition

The behaviour of Hf cathodes has been investigated with high speed camera (HSC) imaging techniques during the low current pilot arc phase, to highlight the different behaviour of the cathodic attachment in torches with retract starting and high frequency pulse pilot arc ignition, with electrodes for plasma arc cutting (PAC) of mild steel plates. The importance of early stages of the pilot arc phase for the electrode erosion phenomena has been, in the past and more recently, highlighted. But no one has ever studied in detail the differences in the behavior of the cathodic attachment in the pilot arc early stages, due to these two methods for the ignition of the pilot arc, and their influence on the electrode wear phenomena.

We provide results of our experimentation on start-up erosion in two PAC torches with Hf cathode and air plasma gas, in both cases of retract starting and high frequency pulse pilot arc ignition.

For the case of retract starting [1], the most common form of retract starting uses the pressure of the air supplied to the torch to drive back a piston to which the electrode is ultimately connected. The electrode and nozzle start out in contact with an electric current running through them. When the electrode retracts a pilot arc is created.

For the case of high frequency pulse pilot arc ignition [8], a high frequency signal breaks down electrode-nozzle gap, as shown in Fig. 1a. After that, a relatively low-current (say 20 A) pilot arc between electrode (negative) and nozzle (positive) is established.

Traces of the arc on the cathode surface show that the arc initially starts at the copper holder and then moves to the holder-emissive insert boundary. From there, it reaches its final position at the center of the insert. The way the arc reaches its final position at the center of the cathode is very important for erosion phenomena. Therefore, it is important to know the mechanisms and the time scale that leads the emitter surface from solid to melting phase. As previously mentioned and described in detail in [10] for the case of high frequency pulse pilot arc ignition.

However, many torches today on the market provide an retract starting, in which the mechanisms for the pilot arc ignitions are very different from those that occur during pilot arc ignition by a high frequency pulse. These differences can lead to a substantially different behavior of the cathodic attachment during this phase. To optimize the control of the cathodic attachment behavior, in order to reduce the electrode wear phenomena, it is important to know what happens in case of retract starting. The aim of this work is to understand the differences in the time and space evolution of the arc attachment during pilot arc phase, in both pilot arc ignition ways, to understand if one of these two arcing modes can be regarded as absolutely better than the other and to highlight what differences should be considered in managing the ignition transient in both cases.

Visualization Set-Up

A NAC Memrecam GX-3 camera has been used, with a maximum acquisition speed of 200,000 fps and a 180 mm focal-length lens, protected by a sacrificial neutral filter, at a distance of about 0.5 m from the plasma torch, joined with a digital oscilloscope (LeCroy LT374M).

Visualization of the cathode surface during pilot arc was accomplished by positioning the torch and the camera lens on the same horizontal axis. The camera set-up has been selected, for all pilot arc experiments, with 100,000 fps and 1/333,000 s shutter time, in order to achieve the best compromise between a suitable camera acquisition speed and a suitable image resolution. In all experiments auxiliary lighting has been used only in the setting phase, in order to optimize each focusing procedure, while the images have been captured without any filtering.

For both cases, the image acquisition was synchronized with operating current waveform acquisition in order to create an evident link between the typical behaviour of the pilot arc and the arc current waveform construction in the HF and retract starting modes.

High Frequency Pulse Pilot Arc Ignition

During experimental tests a Cebora S.p.A. plasma cutting system has been used; comprising the power supply Cebora Plasma 100, together with a prototype mono-gas plasma torch. The system can operate in the range 25–100 A in controlled current mode. Experiments have been accomplished under operative conditions typically used in cutting of MS plates thicker than 20 mm with an operating current of 100 A and with air as both plasma and shield gas. In the considered pilot arc phase the arc current is fixed at 25 A. The tested electrodes use a press fit Hf insert with a diameter of 1.6 mm working in association with a nozzle with a 1.37 mm orifice diameter.

As shown in Fig. 6, the start-up transient phase is characterized by two subsequent phases separated by a transition event, described in detail in [10]. The arrival of the cathodic attachment on the periphery of the emissive surface takes place after 3.19 ms and the stabilization of the cathodic attachment at the center of the emitter surface takes place after 14.36 ms, whereas 0 ms is the time in which the pilot arc ignition takes place. During the transition event massive Hf vapours and Hf particles emissions takes place.

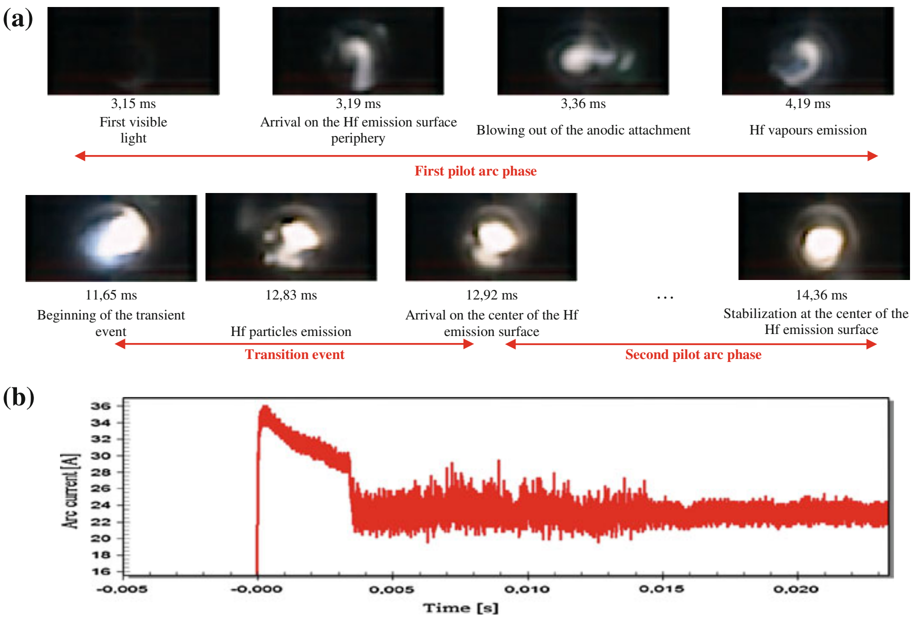

Fig. 6 **a** Pilot arc images, at different time intervals, and **b** waveform of the operating current for the case of HF starting

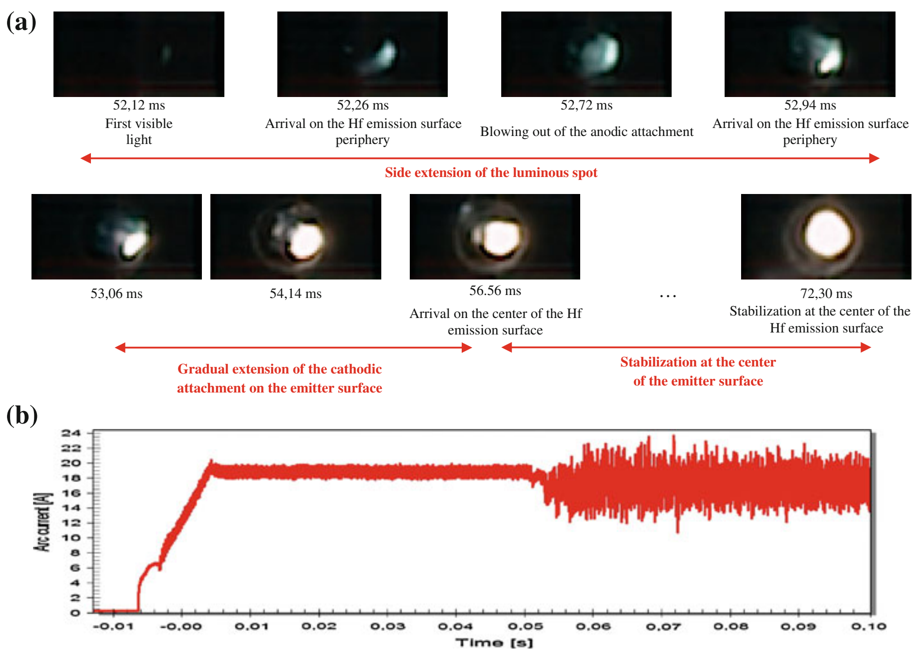

Fig. 7 **a** Pilot arc images, at different time intervals, and **b** waveform of the operating current for the case of retract starting

Retract Starting

During experimental tests a Hypertherm Inc. plasma cutting system has been used; comprising the power supply PM1650 together with the mono-gas plasma torch T100. The system can operate in the operating current range 30–100 A. Experiments have been accomplished under operative conditions typically used in cutting of MS plates thicker than 12 mm, with an operating current of 100 A and with air as both plasma and shield gas. In the considered pilot arc phase the arc current is fixed at 20 A. The tested electrodes use a press fit Hf insert with a diameter of 1.3 mm working in association with a nozzle with a 1.52 mm orifice diameter.

As shown in Fig. 7, the start-up transient phase is characterized by a side displacement of the cathodic attachment from the copper holder to the periphery of the emissive surface followed by a gradual extension of the cathodic attachment on the emission surface, without sudden events and Hf massive ejections. The current reaches its nominal value before the electrode detachment from the nozzle; when the gap is formed at 52.12 ms, the current becomes more unstable and the first visible light is detected by HS imaging (see Fig. 7). Moreover, the transition is much more extended in time: the arrival of the cathodic attachment on the periphery of the emissive surface takes place after 52.9 ms and the stabilization of the cathodic attachment at the center of the emitter surface takes place after 72.30 ms, whereas 0 ms is the time in which the pilot arc ignition takes place. Some Hf vapours and Hf particles emissions takes place during the extension of the arc root cathodic on the emission surface.

Conclusions can be drawn concerning the particular conditions in which heat transfer transients in the cathode tip during PAC pilot arc take place in both pilot arc ignition ways;

giving additional useful information for future design oriented simulation of such phenomena in different geometric and operating conditions, with the final aim of optimizing cathode expected service life.

Experimental Analysis of the Behavior of High Current Electrodes in PAC During First Cycles

The behaviour of Hf cathodes at the beginning of their service life when operating at high current levels (250 A) in the PAC process has been experimentally investigated with the final aim of describing the phenomena that take place during those initial cutting cycles (CCs) and optimizing, with respect to expected service life, the initial shape of the electrode emissive surface [9]. The experimental tests were carried out in realistic operative conditions for cutting mild steel plates with oxygen/air as plasma/shield gas. An iterative experimental procedure for the optimization of the initial recess shape of the Hf insert have been validated, starting the investigation with an initially planar emission surface and defining subsequent optimization steps on the basis of the evolution of the recess depth naturally created during the first few CCs. The process of cathode erosion at this stage was found to be only partially deterministic. Thus, 3-D morphology of a set of electrodes (E1–E4) was reconstructed after each of 5 cutting cycles (Fig. 8). The results obtained during tests with electrodes characterized by an initially planar emission surface were a reference point for the design of two spherical recess shapes (Es1–Es2), also tested on erosion during first cutting cycles. Results obtained from tests on electrodes Es1 and Es2 enabled us to identify optimal values for both the maximum recess depth and the erosion volume of the initial recess, for the specific geometrical and operative conditions under which erosion tests were accomplished (Fig. 9). The identified experimental procedure developed in the present work showed that the optimization of the initial recess shape of the Hf emitter surface not only minimizes the deposition of HfO_2 on the nozzle, as affirmed in [15], but

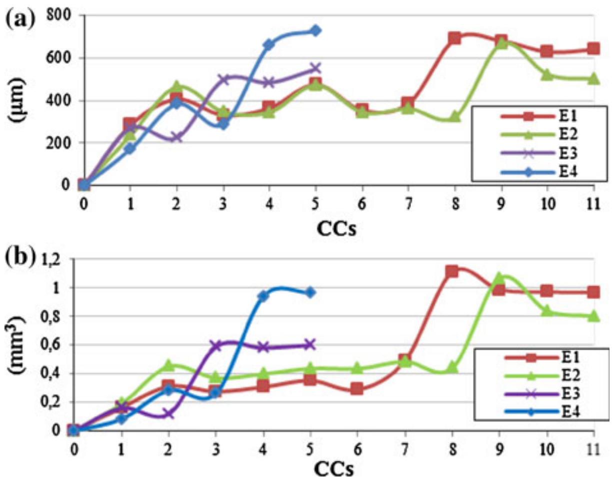

Fig. 8 Trends of (*top*) the maximum recess depth and of (*bottom*) the calculated eroded volumes, as a function of the number of *CCs*, for electrodes with no initial recess (taken from [9])

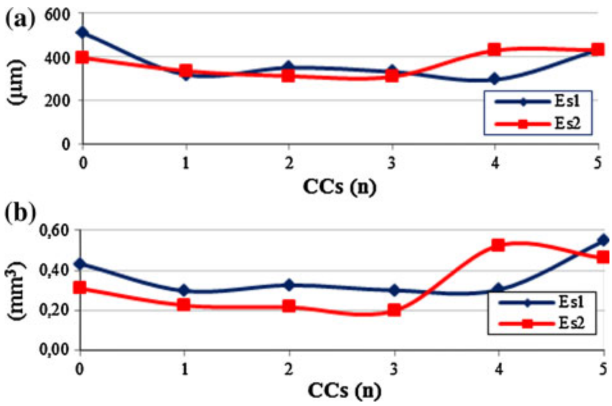

Fig. 9 Trends of (*top*) the maximum recess depth and of (*bottom*) the calculated eroded volumes, as a function of the number of *CCs*, for electrodes *Es1* and *Es2* (taken from [9])

positively affects the subsequent trend of the Hf erosion rate, improving electrodes service life on the whole.

Anode Attachment Behavior During Piercing and Cutting Phases

The visualization of the anode attachment behavior have been accomplished during the piercing and cutting of the edge of a 20 mm mild steel plates, through a Cebora plasma torch HQC 254 operating in realistic conditions, with O_2/air as plasma/shield gas and an operating current of 200 A. For the piercing phase, A NAC Memrecam GX-1 camera a with a 180 mm focal-length lens has been used, at a distance of about 0.5 m from the edge of the plate; the camera set-up has been selected with 30,000 fps and 1/200,000 s shutter time, in order to achieve the best compromise between a suitable camera acquisition speed and a suitable image resolution. For the cutting phase, a K3R HS camera with a 180 mm focal-length lens has been used, at a distance of about 0.5 m from the edge of the plate; the camera set-up has been selected with 10,000 fps and 1/200,000 s shutter time. Figure 10 shows the schemes of the recorded images, for both piercing and cutting phases. The recorded video related to the edge piercing phase shows that the anode attachment is characterized by single and multiple arc root attachments on the *kerf* sides moving from the top to the bottom of the plate, as shown in Fig. 11. The cutting phase was studied in realistic operating conditions and in modified operating conditions, for what concerns the cutting speed. In particular, four different videos were accomplished, characterized by different cutting velocities: 0.3, 1, 3.5 and 4.5 m/s. The comparison of the behaviour of the anode attachment for different cutting speeds shows that, with a very low cutting speed the anode attachment is characterized by single and multiple arc root attachments on the cutting front moving from the top to the bottom of the plate, as for the piercing phase, as shown in Fig. 12. Increasing the cutting speed the arc root attachment disappears from the cutting front and the arc length reduces and becomes constant, as shown in Fig. 13. The arc length was measured considering the more luminous area inside the *kerf* as the arc, and the less luminous area as the plasma column, as shown in Fig. 10. The qualitative analysis of images obtained with different cutting velocities has been also supported by a quantitative analysis obtained calculating, for each image, the mean value and the standard deviation

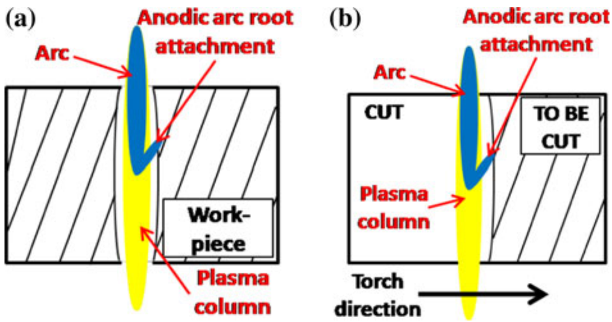

Fig. 10 Schemes of the recorded images, for **a** edge piercing, and **b** edge cutting phases

value of the voltage drop between the cathode attachment and the anode attachment as indicating the anode attachment location and its moving along the *kerf* side. The calculated values are in agreement with the qualitative observations: the mean value of the voltage drop varies from 219 V (for 0.3 m/s cutting speed) to 140 V (for 4.5 m/s cutting speed), while the standard deviation varies from 12.27 V (for 0.3 m/s cutting speed) to 2.8 V (for 4.5 m/s cutting speed).

Statistical Analysis of High-Speed Schlieren Imaging in PAC

The interaction of plasma gas with the surrounding atmosphere in PAC has been investigated using high-speed Schlieren imaging [13]. This visualization method has been applied in the past to cutting torches to visualize the turbulent patterns created by strongly fluctuating temperature field [16] and to highlight the arc width fluctuations [17]. In [17], a spatial FFT transformation with wavelet analysis of the Schlieren image has been used to estimate the arc symmetry. Prevosto et al. [18] has used Schlieren methods to estimate the radial temperature profile of a 30 A commercial torch.

In this work, a Schlieren Z-type setup connected with a high-speed camera operating at 10,000 fps (NAC K3) is used to visualize a 25 A arc discharge of a CEBORA manual torch. A motorized stage has been used to move the workpiece and to hold the torch in the recording area. With this setup it was possible to record the real cutting process of a 2 mm mild steel workpiece, using O_2 both for primary and secondary gas. The time-series corresponding to the recorded intensity of each pixel have been post-processed using two different methods for statistical analysis that highlight the time variation of the amplitude of the fluctuations in the density field: the "windowed standard deviation" and the GARCH approach. In the first one, the "windowed standard deviation", the raw video was divided into 25 frames sub-videos. Each of these was collapsed in a unique frame, where the value of each pixel represents the standard deviation of its corresponding 25 values in the sub-video. A 400 fps video was then constructed using the post-processed frames. The 25-frame window was chosen as a compromise between time-resolution and accuracy of the estimated standard deviation. Since most of the values were truncated due to over-exposure, the calculated standard deviation was adjusted hypothesizing an underlying Gaussian distribution. In the second method, the GARCH (Generalized Autoregressive Conditional Heteroskedasticity) analysis [19], the intensity of each pixel was extracted frame-by-frame from the raw video, yielding a time series of values. Each time series was

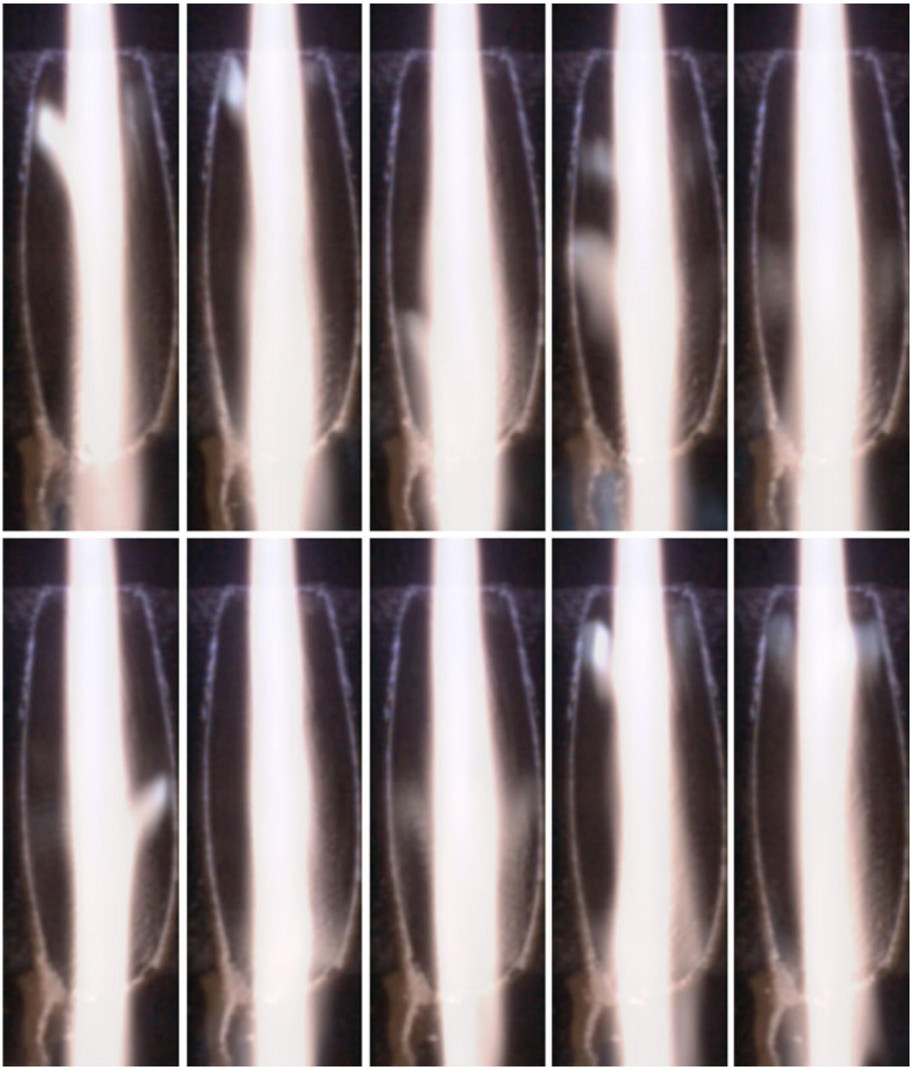

Fig. 11 Selected images of the edge piercing phase, at constant time steps of 0.033 ms

normalized to zero mean and unit variance and fitted with an AR(1) + GARCH(1,1) model, interpreting each value as the sum of a deterministic trend plus a random noise drawn from a Gaussian distribution with time-dependent variance. For each frame, the value of each pixel in the raw video can be substituted with the value of its corresponding GARCH volatility, the standard deviation of the Gaussian noise, yielding a video representing the instantaneous turbulence in the plasma flow. Whereas a mean–variance analysis can provide at most time-averaged results, GARCH can model the instantaneous variation of the luminous signal.

In Fig. 14, selected frames of the Schlieren video of the cutting process have been reported together with their statistical elaborations. At t = 0 ms, the arc is transferred to

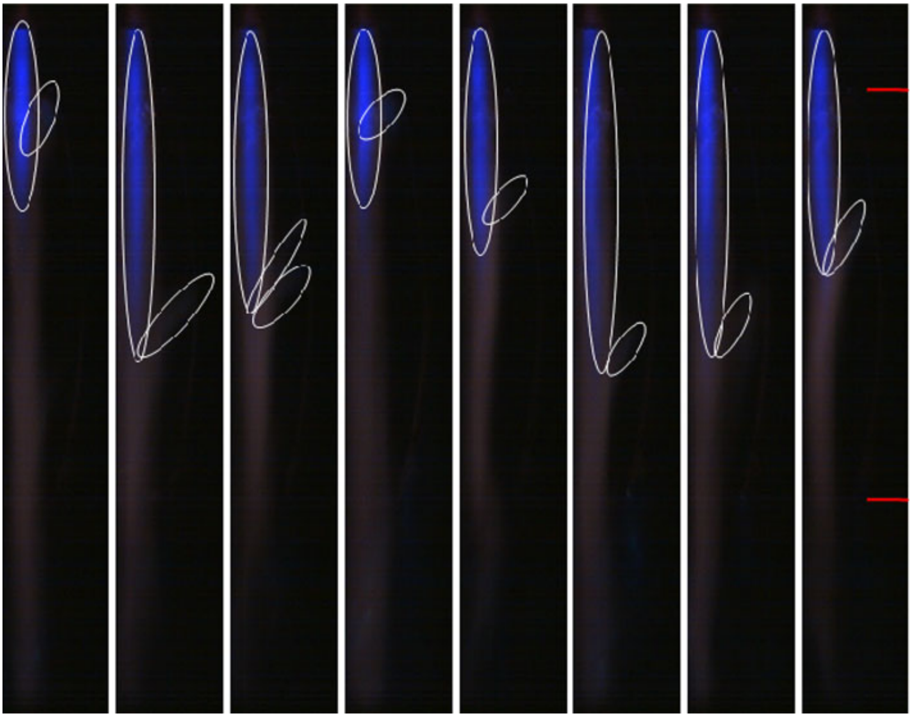

Fig. 12 Selected images of the edge cutting phase, with cutting speed of 0.3 m/s, at constant time steps of 0.1 ms. *Red lines* indicate the workpiece, the *white circles* indicate the main arc and the anodic arc root attachment

the workpiece; in this frame, the turbulence pattern is very similar to the one of a hot jet discharging in atmosphere. From t = 100 ms to t = 150 ms the turbulence arc above the workpiece increases as the torch moves into the workpiece and the turbulence jet below the workpiece becomes narrower; as expected, both "windowed standard deviation" and GARCH analyses highlight the increase in turbulence intensity above the workpiece. At t = 150 ms, the maximum of turbulence intensity has been obtained. When the torch reaches the final end of the workpiece (t = 500 ms), turbulence decreases and the pattern assumes the typical shape of a hot jet at t = 550 ms where the cut part of the workpiece is detached.

Schlieren methods seem to be a very promising for the visualization of turbulence patterns around plasma cutting torches and for the optimization of such systems.

Conclusions

Presented results are the experimental part of an integrated approach to design and optimization of plasma arc cutting torches.

Some HS imaging results were shown in order to describe phenomena taking place in PAC and that are typically characterized by a very small time scale (less than 1 ms). Results coming from this kind of investigation are mostly qualitative; still, they can give

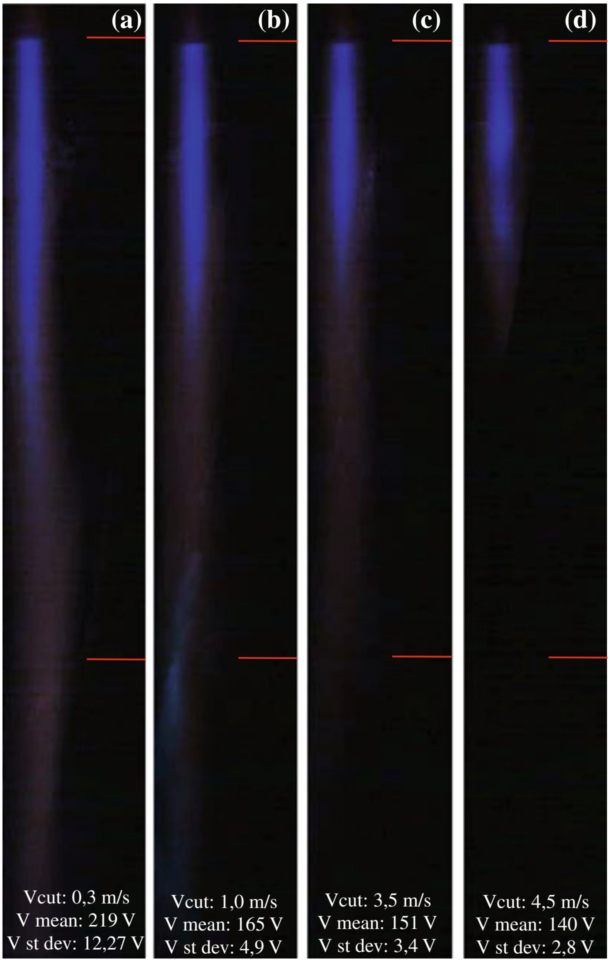

Fig. 13 Selected images of the edge cutting phase, with cutting speed of **a** 0.3 m/s, **b** 1.0 m/s, **c** 3.5 m/s, and **d** 4.5 m/s

important additional information on solving problems that have been otherwise investigated mainly from the theoretical or computational point of view. They can help in optimizing the design of torch components, of process characteristics and of plasma operative conditions (e.g. cathode erosion mechanism, double arcing, effect of anode attachment location, dross formation, effects of non perfectly aligned torch head components, etc.). In particular, some new HS imaging results have been presented, enabling to study phenomena that cannot be investigated with other diagnostic methods.

Moreover, results obtained investigating fluid dynamic instabilities in PAC using statistical analysis of high speed Schlieren images have been shown. The presented results are only an initial stage that allowed to study the possibility of transforming into quantitative data the typically qualitative information achievable with the Schlieren technique. Future developments will allow to apply these methods to real cases to obtain quantitative information on axial symmetry and stability of the arc, showing how even slight imperfections of the nozzle caused by erosion or non perfect alignment can influence arc

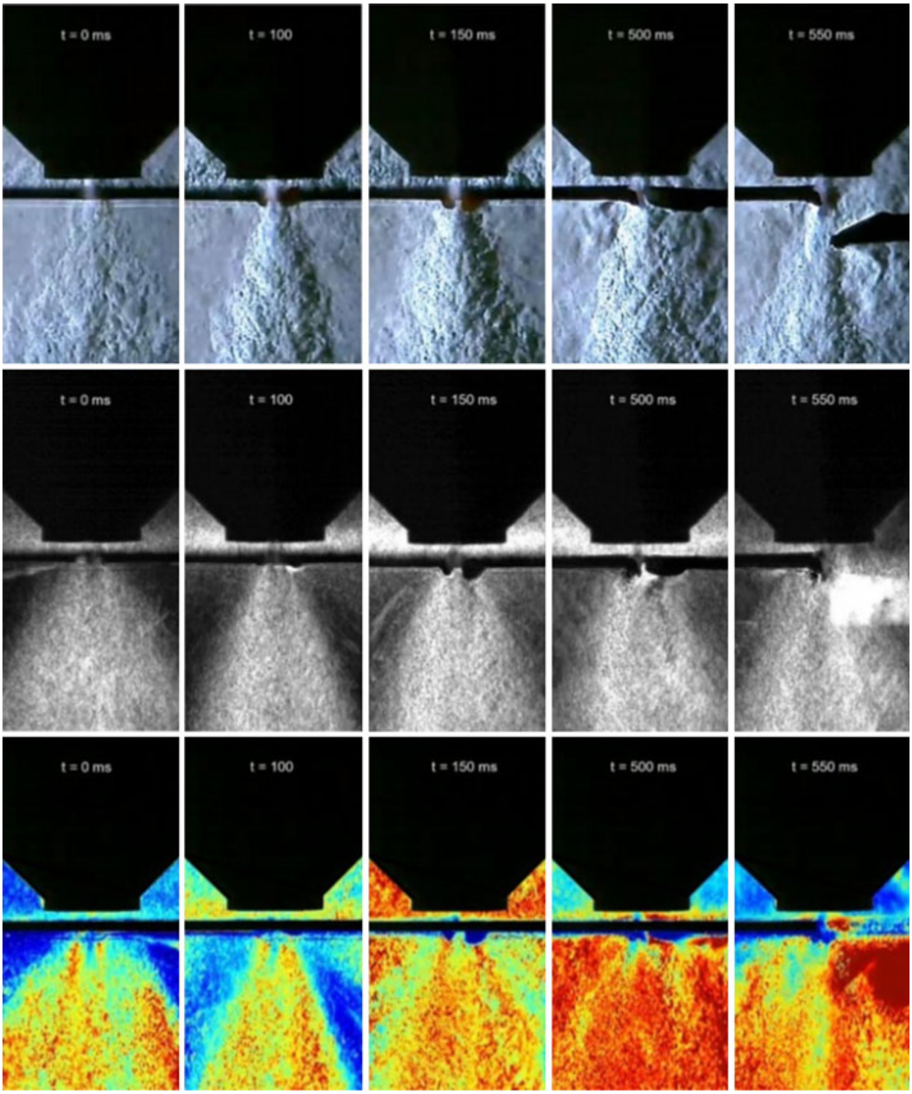

Fig. 14 Schlieren field (*top*), windowed SD (*middle*) and GARCH volatility of the Schlieren field (*bottom*) at different time steps (0, 100, 150, 500, 550 ms from *left* to *right*) in realistic cutting conditions. The scale for the windowed SD is from *black* (low) to *white* (high). The scale for GARCH volatility is from *blue* (low volatility) to red (high variance of the Gaussian noise). (taken from [13])

symmetry and stability, and on the interaction between the plasma jet and the secondary gas, for different secondary gas injections.

Finally, erosion phenomena that take place during different stages of electrodes service life at high currents were described without the pretence of clarifying the mechanisms underlying them. Up to now, the causes that produce such a strong erosion of the emitter surface are not exactly known and it would be an interesting topic for future work in this field.

Further developments will be aimed at defining an efficient link between simulations of the plasma arc, experimental evidences coming from HS and Schlieren imaging and experimental results related to *kerf* formation and cut quality.

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