Advances in plasma arc cutting technology: the experimental part of an integrated approach.

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Abstract: Plasma modeling, numerical simulation and diagnostics can be very useful tools for designing and optimizing plasma arc cutting torches and they should be used in conjunction in order to obtain significant added value from an integrated approach to design, but research is still in the making for finding a link between simulation of the plasma arc and a consistent prevision of cut quality. Diagnostics based on high speed imaging can play an important role for investigating significant phenomena, otherwise impossible to recognize. Schlieren photography can be very useful to better understand the interaction between the plasma discharge and the kerf front. Also, the behaviour of hafnium cathodes at high current levels at the beginning of their service life can be 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 exposed to plasma atmosphere. Experimental evidences can be integrated with simulative results in order to avoid a try & fail approach, often too expensive, to validate models and to identify innovative design solutions, addressing specific issues that cannot be fully investigated through experimental tests.

Keywords: plasma arc cutting torches, diagnostics, electrode erosion, high speed imaging, Schlieren imaging

1. 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 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].

2. 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 (250A) 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. 1). 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. 2). 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 [14], but positively affects the subsequent trend of the Hf erosion rate, improving electrodes service life on the whole.

3. High speed imaging investigation of transition phenomena in the pilot arc phase 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 [10]. 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. 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. 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.3). 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 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. 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.

4. 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]. In particular, a Schlieren Z-type setup connected with a high-speed camera (NAC K3) is used to visualize a 25 A arc discharge of a CEBORA manual torch, cutting 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 have been compared: the windowed standard deviation and the GARCH approach (Fig. 4). Whereas a mean-variance analysis can provide at most time-averaged results, GARCH can model the instantaneous variation of the luminous signal, thus providing new insights on the time evolution of the turbulence around the arc.

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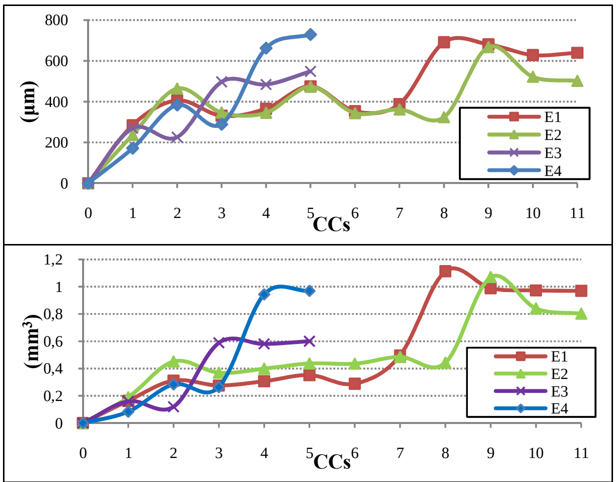

Fig. 1 Trends of *(top)* the maximum recess depth and of *(bottom)* the calculated eroded volumes, as a function of the number of *CCs*, for electrodes with no initial recess (taken from [9]).

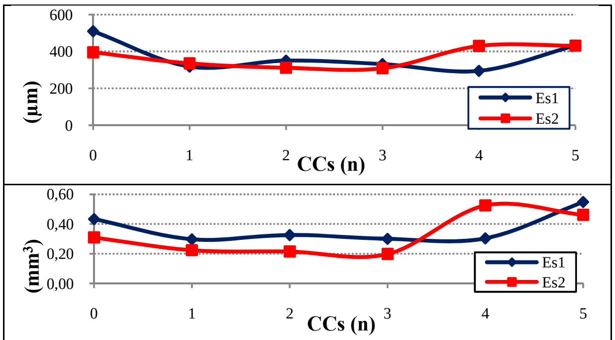

Fig. 2 Trends of *(top)* the maximum recess depth and of *(bottom)* the calculated eroded volumes, as a function of the number of *CCs*, for electrodes *Es1* and *Es2* (taken from [9]).

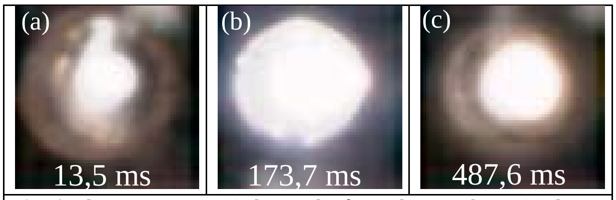

Fig. 4 Pilot arc images, (a) during the first pilot arc phase, (a) during the transition and (c) during the second pilot arc phase, for the case of used electrode.

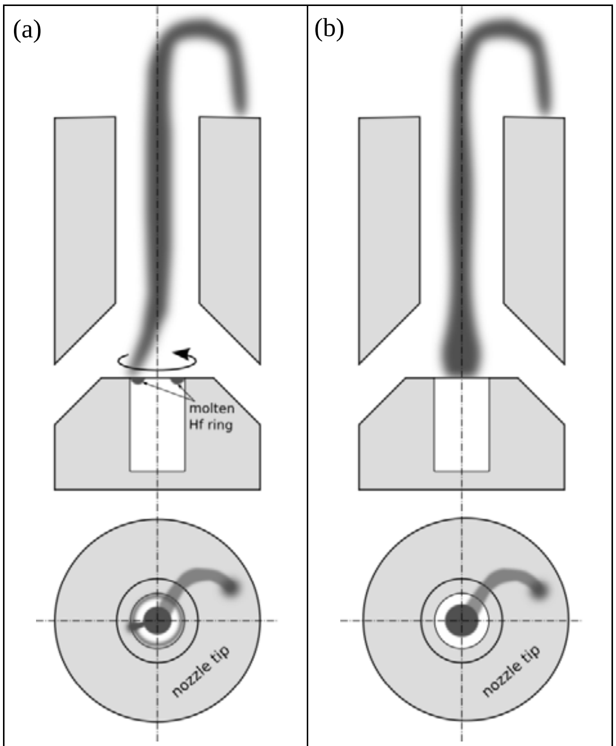

Fig. 3 Side and top view schematic of the PAC torch in the two start-up pilot arc phases: (a) rotation of the cathodic arc root on the insert periphery; (b) stable centred arc root (taken from [10]).

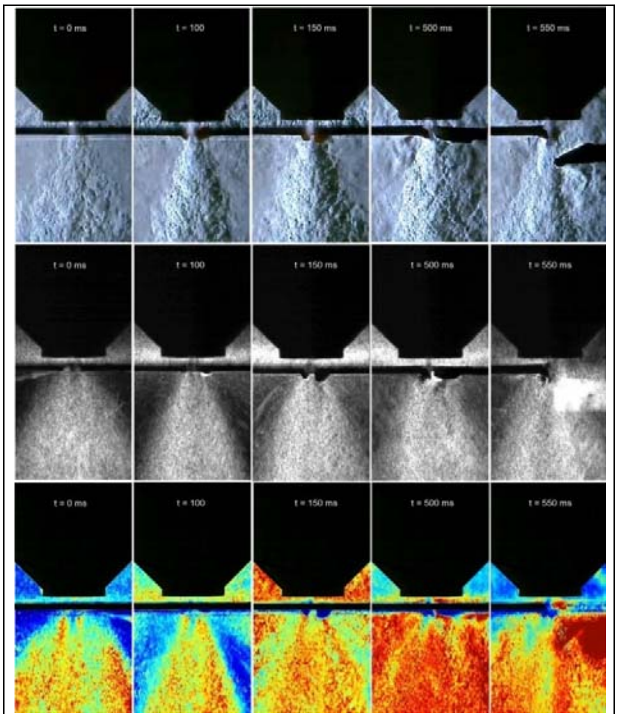

Fig. 5 Schlieren field (*top*), windowed standard deviation (*middle*) and GARCH volatility of the Schlieren field (*bottom*) at different time steps (0, 100, 150, 500, 550 ms from left to right) in realistic cutting conditions. The scale for the windowed standard deviation is from black (low) to white (high). The scale for GARCH volatility is from blue (low volatility) to red (high variance of the Gaussian noise).