Plasma arc cutting technology: simulation and experiments

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Abstract. Transferred arc plasma torches are widely used in industrial processes for cutting of metallic materials because of their ability to cut a wide range of metals with very high productivity. The process is characterized by a transferred electric arc established between an electrode inside the torch (the cathode) and another electrode, the metallic workpiece to be cut (the anode). 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. Plasma modelling and numerical simulation can be very useful tools for the designing and optimizing these devices, but research is still in the making for finding a link between simulation of the plasma arc and a consistent prevision of cut quality. Numerical modelling of the behaviour of different types of transferred arc dual gas plasma torches can give an insight on the physical reasons for the industrial success of various design and process solutions that have appeared over the last years. Diagnostics based on high speed imaging and Schlieren photography can play an important role for investigating piercing, dross generation, pilot arcing and anode attachment location. Also, the behaviour of hafnium cathodes at high current levels at the beginning of their service life can been experimentally investigated, with the final aim of understanding the 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.

1. Introduction
The PAC process [1] is characterized by a transferred electric arc that is established between an electrode, that is part of the cutting torch (the cathode) [2-6], and another electrode, that is the metallic workpiece to be cut (the anode). 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. Plasma modeling and numerical simulation can be very useful tools for the designing and optimizing these devices [7-8, 11,13], but research is still in the making for finding a link between simulation of the plasma arc and a consistent prevision of kerf formation, to predict cut quality. In this frame, qualitative diagnostics based on high speed imaging and Schlieren photography can play an important role for investigating piercing, dross generation, pilot arcing and anode attachment location [9-10]. Also, the behaviour of hafnium cathodes at high current levels at the beginning of their service life can been experimentally investigated [14-15], with the final aim of understanding the 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.

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 paper is in line with the research work done by the Authors in recent years to fulfill the abovementioned need, taking as a starting point either patented solutions or commercial solutions based on those patents in the field of plasma arc cutting.

2. Optimization of plasma arc cutting of mild steel thin plates

PAC processes of mild steel thin plates (thickness in the range 1-3mm), characterized by low current levels (25-45A) and the use of O\textsubscript{2} both as plasma gas and secondary gas, through a Cebora HQC Plasma Prof 164 plasma source, have been studied. The optimization of PAC of mild steel thin plates, both in terms of cut quality and performances of the consumables, have been accomplished in order to achieve cut quality standards and productivity levels usually obtainable through laser cutting processes. The optimization process has been carried out through the simultaneous planning and analysis of experimental tests and numerical simulations, by means of a 2-d FLUENT-based numerical model [7-8].

All the accomplished experimental tests have focused on the investigation of phenomena typically considered to be critical for the cutting process in those conditions: unevenness of the kerf surface, inclination of the cut surfaces and dross formation. The influence of operative parameters on critical phenomena has been studied, mainly changing secondary gas flow and the plasma gas inlet pressure. Also, a better design of consumables, in particular nozzle, electrode and diffusers, and the optimization of current profiles, in particular pilot arc current levels, have been carried out. Modifications that have been finally introduced to the operative parameters and to the torch configuration are:

- the reduction of the secondary gas flow rate (lower than 9 lpm);
- a considerable improvement of the plasma flow rate (from 4 lpm to 6.5 lpm);
- the introduction of a modified nozzle with the conical shape of the orifice end, characterized by an optimum value of the depth of the conical area;
- the introduction of an optimized diameter of the hafnium insert (1.07 mm);
- a reduction of the diameter of the holes of the plasma gas diffuser (0.4 mm);
- the optimization of the current profile during pilot arcing.

Modelling and numerical simulation allowed a better understanding of the physical phenomena concerning the critical aspects initially pointed out and enabled us to detect successful design solutions. In particular, simulation results showed that all modifications that have been introduced, both in terms of operating parameters and consumables geometry, lead to:

- an increase of the axial plasma temperature inside the nozzle (Fig. 1);
- an increase of the plasma swirl velocity in the nozzle orifice region (Fig. 2);
- the removal of turbulent vortexes in the nozzle orifice exit region (Fig. 3).

The integration of the results of these two activities allowed to overcome the critical aspects initially pointed out, improving plasma jet constriction and nozzle cooling and reducing plasma jet instabilities, leading to the improvement of cut quality and the reduction of erosion phenomena of the torch consumables, in particular of the nozzle.

3. High Speed Imaging of transient phenomena and Schlieren photography in PAC

High speed camera (HSC) imaging of pilot arcing and piercing process phases with dual gas torches have been investigated using mild steel and stainless steel plates of various thickness, in various operating conditions. 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 stand-off distance of 1 m from a Cebora (HQC164 for the range 25-120 A and HQC254 for the range 120-250 A) plasma torch, joined
Figure 1. Plasma temperature field [K] for the simulation of the Cebora plasma torch under the following operating conditions: 40 A; plasma gas pressure (O2): 540 kPa (upper half) and 590 kPa (lower half); secondary gas pressure (O2): 40 kPa; nozzle diameter: 0.8 mm.

Figure 2. Plasma swirl velocity [m/s] for the simulation of the Cebora plasma torch under the following operating conditions: 40 A; plasma gas pressure (O2): 540 kPa; secondary gas pressure (O2): 40 kPa; nozzle diameter: 0.8 mm with a nozzle orifice end cylindrically shaped (upper half) and conically shaped (lower half).

Figure 3. Plasma velocity [m/s] for the simulation of the Cebora plasma torch under the following operating conditions: 40 A; plasma gas pressure (O2): 540 kPa; secondary gas pressure (O2): 40 kPa; nozzle diameter: 0.8 mm with the nozzle orifice end cylindrically shaped (upper half) and conically shaped (lower half).
with a digital oscilloscope (LeCroy LT374M). Synchronizing the start acquisition time of both instruments, the images captured by the HSC have been time-correlated to the oscilloscope waveforms of voltage, current and pressure inside the nozzle. Pilot arcing images have been obtained with air as pilot arc plasma gas, with a 1.9 nozzle diameter and in the absence of the torch shield cup (without secondary gas) in order to observe the arc loop attachment on the nozzle tip. Pilot arcing duration has been extended with respect to real cutting conditions in order to fully observe arc loop attachment phenomena. All images have been acquired at 10000 fps and 1/200000 s shutter time without any filtering.

The technique has provided new insight of the PAC process and some interesting phenomena have been highlighted.

### 3.1. Effects of different operating parameters on pilot arc behaviour

A study of the influence of different parameters on the rotation of the arc loop attachment on the nozzle tip during pilot arcing has been carried out through a series of experiments at different operating conditions. The influence of the current level on pilot arcing has been studied setting a current waveform with two different current levels: a first phase at 45A, with a second phase at 25A. As shown in Fig.4, an increase in arc current level induces an increase of both the pilot arc cross section and its visible light emission, while inducing an enhanced random jumping arc attachment behavior on the nozzle tip. Fig. 5 shows three high speed imaging experiments carried out with different plasma gas flow rates (21, 28 and 36 slpm). This comparative analysis has shown that an increase in the flow rate leads to the reduction in the pilot arc rotational speed on the nozzle tip; the rotational speeds have been evaluated analyzing the single frames for the three cases and the frequencies are about 2000 Hz, 1000 Hz and 400 Hz, respectively. A series of results that will not be detailed here shows how different swirl strength conditions for the plasma gas flow also have an impact on the rotation of the arc root attachment. In the case of higher swirl strength the arc loop attachment...
attachment experiences an entire (360°) rotation along the nozzle tip without any erratic or discontinuous moving. The total time for a complete rotation of the arc around the nozzle tip is 11.5 ms. The case of lower swirl strength is characterized by erratic and discontinuous movements of the arc attachment on the nozzle tip experiencing an incomplete (180°) rotation on the nozzle tip.

3.2. Cathode surface images during pilot arcing
Visualization of the cathode surface during pilot arcing with high time resolution was accomplished by positioning the torch and the camera lens on the same horizontal axis. Four different sequences (with different focal ratios in the camera set-up) of pilot arc images coming from four different experiments carried out in the same operative conditions have been obtained. Realistic conditions for the cutting of MS plates with 250 A and O₂/air as the plasma/secondary gas have been used. Every sequence of images shows at best a particular phenomenon that takes places during a pilot arcing.

Images of Fig. 6 were obtained with a focal ratio of f/16; they concern the phase in which the pilot arc, once initiated, is blown out of the nozzle by the plasma gas flow, with a swirling motion due to the swirl component of the plasma flow. The increase in the voltage can be associated to the increase in the arc axial length.

Images of Fig. 7 were obtained with focal ratio of f/32 and they refer to the phase in which the arc has already exited the nozzle, creating an arc loop protruding out of it. The bright areas between the arc root and the copper holder of the electrode, that appear in some frames, are interpreted as electron emission spots on the molten hafnium surface of the electrode; their movement is ruled by the drag of the swirling plasma gas flow.

Images of Fig. 8 were obtained with focal ratio of f/5.6, aimed at obtaining information on conditions on the nozzle tip. The torch operative conditions used in these movies are the same as those
characterized by lower swirl strength and induce an intermittent motion of the arc loop attachment on the nozzle tip. The intermittent root attachment of the pilot arc induces the formation of dark dots on the nozzle tip, even though the arc maintains its non-moving and localized attachment on the same point for less than 0.4 ms.

Images of Fig. 9 were obtained with focal ratio of f/5.6 and with a 2.5 mm diameter nozzle while in Figs. 6, 7 and 8 the nozzle diameter was 1.9 mm. Images obtained during this experiment show both the detachment from the hafnium molten pool of molten hafnium particles and their trajectories. The HS images clearly show that the presence of centrifugal forces due to the plasma gas swirling, plays a leading role in electrode erosion. The time correlation between HS images and current waveform shows that the detachment of molten hafnium particles from the emissive surface begins when the arc current drops to zero with current going from 25 A to 0 A in less than 0.1 ms.

3.3. Images of double arcing in transferring arcs

Fig. 10 shows images of a realistic phase of arc transferring during the piercing of a MS plate 20 mm thick at 200 A and O2/Air as plasma/secondary gas, respectively. Gas flow rates and torch stand-off have been set to increase the probability of double arcing taking place during piercing. The sequence of images shows different phenomena that can be associated to the double arcing. In particular green vapours and silver grey vapours appear in most of the image frames and can be correlated to copper (due to arc attachment on the nozzle) and on the shield) and hafnium (due to arc root attachment instability on the electrode emissive surface) vapour emissions, respectively.
The hypothesis of arc root attachment instability is also supported by the evidence in some of the frames of Fig. 10 of traces of solid particles (probably hafnium oxide) exiting the nozzle. Some other image frames show the presence of an arc attachment on the nozzle, the arc having disappeared from its usual position along the torch axis. The correspondence between arc instabilities showed by the images and the spikes in the oscilloscope waveform of arc voltage leads to a hypothesis where the arc voltage between electrode and nozzle can be assumed as an arc stability indicator: the isolated peaks can be related to hafnium vapors emission while continuous spikes to arc attachment on the nozzle and the shield, respectively.

Non-destructive double arcing phenomena during piercing probably occur as a consequence of the deposition of a small amount of hafnium oxide on the nozzle orifice wall, inducing a local increase of the radial electric field and an increase in the probability of double arcing. When double arcing occurs, rapid [<1 ms] evaporation of the hafnium oxide with vapor emission from the nozzle restores the previous and normal arc behavior. Due to their very short duration, the described phenomena can assume a non-destructive character.

Two more phenomena, not detailed here, were investigated by some of the authors [10]. The first study concerning the tracking of trajectories and velocities of ejected particles from the nozzle orifice during pilot arcing, on a shorter time-scale than the one typical for the ejection of liquid metal droplets during transients [4], probably coming from cracking of the solid layer of HfO$_2$ on the emitter during arc re-start [1].

The second one concerning the influence of the level of alignment of torch head components on the plasma arc behavior during piercing phases. In particular, it was found that a relative non-alignment between shield and electrode grater then 0.025 mm can induce destructive piercings at high current (>200 A). Schlieren photography has also been used by some of the authors to visualize density gradients due to turbulence and temperature in real cutting conditions, in order to investigate plasma and secondary gas interactions and their impact on cut quality with feedback on torch design.

4. Experimental analysis of the behaviour of high current electrodes in pac during first cycles

Cathode erosion phenomena put still a limit in the improvement of the performances of PAC process, with respect to its main competitors; in particular for the operative conditions in which oxidizing plasma gases (oxygen and air) and high current levels (> 200 A) are used in presence of an Hafnium (Hf) emitter. Several studies [2-6] have been accomplished in order to understand phenomena that give rise to Hf erosion in different phases of the PAC operative cycle.

The behaviour of Hf cathodes at the beginning of their service life when operating at high current levels in the PAC process has been experimentally investigated with the final aim of understanding the phenomena that take place during those initial piercing and cutting phases and optimizing, with respect to expected service life, the initial shape of the surface of the emissive insert exposed to plasma atmosphere. Hf erosion mechanisms on the emitter surface, modifications of the Hf insert morphological structure, together with the effect of deposition of molten emissive material on the nozzle inner surface have been studied in realistic operative conditions for cutting mild steel plates with oxygen as plasma gas and air as shield gas at relatively high current level (250 A).

A new experimental procedure have been proposed, starting the investigation with an initially plane insert emission surface, subsequent cutting phases have been accomplished checking each time the dimension of the growing concave recess on the insert and the amount of Hf oxide collected on the nozzle surface during the first few cutting cycles while using these information for defining subsequent optimization steps.

Morphological and compositional analysis of the tested electrodes and nozzles led to a detailed description of Hf erosion phenomena and of the trend of modification of the emission surface and of the interface between the Hf insert and the copper holder.

High speed imaging during piercing phases has been used to highlight the possible presence of non destructive double arcing phenomena taking place at the beginning of electrode-nozzle service life as a consequence of deposition of Hf based material on the nozzle. Also for highlighting the different behavior during start-up phases of new or used electrodes.
Fig. 10 (a) Transferring arc images, at different time steps, for a torch with 1.6 mm nozzle diameter and 3 mm shield diameter, at 200A. (b) Images are time-correlated to the oscilloscope waveform of the electrode-nozzle voltage.

Fig. 11 Trends (a) of the maximum recess depth and (b) of the calculated eroded volumes, as a function of the number of CCs, for electrodes with no initial recess.

Fig. 12 Trends (a) of the maximum recess depth and (b) of the measured eroded volumes, as a function of the number of CCs, for electrodes Es1 and Es2.

4.1. Experimental procedure
In general terms, the optimal shape of the initial recess of the Hf insert is strongly dependent upon “typical operating and geometric conditions” of the torch being optimized. For these reasons, an experimental procedure is proposed here, starting the investigation with an initially plane insert emission surface and analyzing the evolution of the recess depth naturally created during the first few cutting cycles (CCs) while using these information for defining subsequent optimization steps.

The proposed experimental procedure can be divided into different stages. The first stage is characterized by a series of tests accomplished on electrodes having an initially plane insert emission surface. The erosion tests were stopped after every cutting cycle to check the Hf eroded volume and the overall nozzle condition. Modifications of the Hf insert morphological structure were also monitored and this first test was stopped when the emissive surface morphology reached a stabilization phase as a function of the number of CCs. The dimension of the recess that was naturally created on the emissive surface at the end of the first stage was taken as reference point to design some intermediate spherical recesses to be tested on erosion during CCs in the second stage of the
procedure. The Hf eroded volume, the overall nozzle condition and the Hf insert morphological structure evolution over CCs were monitored, in order to identify the stabilization phase for each tested electrode. The modifications occurred on the emissive surface morphology of tested electrodes allowed to identify the optimal spherical recess.

4.2. Behaviour and analysis of electrodes with no initial recess

Four experimental tests (E1÷E4) were accomplished. For each test, 1 electrode with no initial recess underwent 5 CCs; a new nozzle was used for every CC. 3-D topographies and volume measurements were accomplished for each electrode after every CC. After the first arc ignition, all the tested electrodes evidenced the presence of a concave recess in the Hf emissive insert and an annular zone with Hf deposit surrounding the insert boundaries on the cathode surface. Moreover, SEM macrographs exhibit the presence of a fine dispersion of Hf oxide surrounding the massive Hf deposit, together with HfO$_2$ droplets. Finally, part of the Hf based particles ejected from the insert is deposited on the inner nozzle surface.

The evolution of the eroded volumes (Fig. 11 (a)) at the first stage (which show a trend similar to the one of the maximum cavity depth, Fig. 11 (b)) suggests how the erosion behaviour of each insert is only partially determined by the morphology of the emitting surface as measured at the previous step. Electrodes E1 and E2, between 2 and 5 CCs, maintained their cavity depth and erosion volume almost constant, while no or extremely limited Hf emission and deposition on the nozzle inner surface was detected proving how the Hf volumes eroded during first 2 CCs could be removed from an optimized emissive insert. Due to this particular behaviour, they have been tested for an increased number of starts, in order to better study the evolution of the recess spontaneously established, and they have been considered as a reference point to start an experimental procedure for the optimization of the recess shape.

Electrodes E1 and E2, subjected to 11 CCs, are both characterized by massive Hf ejection events after the first 5 CCs, in particular: the eroded volumes skip from 0.31 – 0.43 mm$^3$ to 1 mm$^3$ and the maximum recess depth reaches a level of about of 0.7 mm (Fig.11). The levels of eroded volume and maximum recess depth that electrodes E1 and E2 reach, after 11 CCs are similar to those ones that electrodes E3 and E4 reached, with an non linear trend, after 5 CCs. They both reach the stabilization of the emissive surface morphological structure after 9 CCs.

4.3. Behaviour of electrodes with initially optimized recess

On the basis of the results obtained from tests on electrodes E1 and E2 after 5 CCs, two (non-trial) spherical recess shapes have been designed:
- from electrode E1 a spherical recess with an initial recess depth of about 400 μm and an initial recess volume of 0.31 mm$^3$ (electrode Es1);
- from electrode E2 a spherical recess with an initial recess depth of about 500 μm and an initial recess volume of 0.43 mm$^3$ (electrode Es2).

Experimental evidences showed that both for electrode Es1 and Es2 the eroded volume levels and the recess depth were significantly reduced with respect to the ones reached on E1 and E2 after 10 CCs (Fig. 12). Moreover, both eroded volume and maximum recess depth levels of Es1 and Es2 reach a similar value after accomplished erosion tests, although fresh electrodes were designed with a slightly different initial shape of the spherical recess. This result enabled us to consider the recess shape obtained at this stage with electrodes Es1 and Es2 as a reference point to design the optimized spherical recess.

Experimental results showed that an initial planar emission surface gives rise to massive Hf ejections during first cutting cycles, inducing a preferred concave shape on the emitter, with consequent massive Hf deposition on the inner nozzle surfaces that negatively affect cut quality and nozzle service life. Moreover, the developed experimental procedure showed that the optimization of the initial recess shape of the Hf emitter surface not only minimizes the deposition of Hf oxides on the nozzle inner surfaces maintaining an electrode service life comparable to the one of electrodes with initially planar emission surface, as affirmed in [6], but also positively affects the subsequent trend of the Hf erosion rate, improving electrodes service life on the whole.
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