Experimental analysis of the behaviour of high current electrodes in plasma arc cutting during first cycles

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Abstract: The behaviour of hafnium cathodes at the beginning of their service life when operating at high current levels in the plasma arc cutting (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 the initial shape of the surface of the emissive insert exposed to plasma atmosphere.

Keywords: Plasma arc cutting, high current electrodes, electrode erosion.

1. Introduction
Cathode erosion phenomena put still a limit in the improvement of the performances of plasma arc cutting (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 Hf emitter, typically set for cutting mild steel (MS) plates thicker than 20 mm. Several studies [1-4] have been accomplished in order to understand phenomena that give rise to Hf erosion in different phases of the PAC operative cycle. It is well known that the cavity deepening rate of the Hf emitter at high current level is high during the first arc ignitions, to successively decrease and become approximately constant [3, 5-6]. The Hf-based products emitted from the cathode at the beginning of its service life deposit both on the cathode and on the nozzle, so leading to a loss of axial symmetry and to a local reduction of the boundary layer thickness, with important drawbacks both on cut quality and consumable service life. Moreover, due to their relatively low work function, double arcing phenomena, both destructive and non destructive [7], take place easier [1]. To avoid the negative effects induced by a natural deepening of the concave pit induced in the Hf insert with initially flat surface, this one can be initially shaped with a concave recess [5-6], so neatly removing a volume of emissive material that would anyhow be removed during the first few starts in a random or massively disordered way, also badly conditioning the subsequent erosion process. Hafnium erosion mechanisms on the emitter surface and modifications of the Hf insert morphological structure have been studied in realistic operative conditions for cutting MS plates with oxygen as plasma gas and air as shield gas at high current level (250 A). Results are discussed with the aim of setting up an experimental procedure to optimize the shape of the initial recess of the Hf insert fit to improve consumables service life.

2. Experimental set-up
The erosion tests on the electrodes have been accomplished through Cebora Plasma Prof 264 HQC plasma cutting system, equipped with the Gas Console PGC1-2, with the multi-gas plasma torch CP251G on a CNC cutting table. The system can operate in the current range 20-250A. Operative conditions are the ones typically used in cutting of MS plates 20 mm thick, with O\(_2\) plasma gas and air as shield gas at 250 A. For every cycle, piercing is followed by a 20 s linear cutting (both at optimum stand-off) and at reduced velocity (0.3 m/min vs the optimum of 2.1 m/min) which doesn’t affect badly erosion rate behaviour. The standard electrodes tested with an arc current of 250 A use a press fit Hf insert with a 2 mm diameter associated to a nozzle with 1.9 mm orifice diameter. Morphological modifications of the tested electrodes at different cutting cycles were measured by means of a Hommelwerke T2000 contact profilometer. Moreover, mean profiles of each electrode at subsequent erosion stages were calculated by interpolating six radial profiles from every 3D topography. Both the Hf volume which has been eroded from the initially plane emissive insert, and the Hf oxide (HfO\(_2\)) volume which deposited on the cathode surface, were detected. Scanning electron microscopy (SEM) of the tested electrodes was performed to validate the topographies reconstruction. Qualitative evaluation of the Hf deposition on the inner nozzle surface was carried out by stereo-microscopy using a new nozzle at each cutting cycle.

3. Behaviour and analysis of electrodes with no initial recess

3.1 Erosion tests
At a first stage, 3 series of test were carried out. For each series, 5 tests have been accomplished, each characterized by an increasing number of cutting cycles (CCs) to
which one electrode is subjected; each test has been started with a new electrode, associated to a new nozzle for each CC, in order to later investigate on the quantity of Hf-based particles being ejected during every arcing process and then deposited on the nozzle. On the whole, 15 electrodes and 45 nozzles have been used. The complexity of the phenomena involved in cathode erosion [1-4] during first cycles is characterized by a partial repeatability of the effects related to concave recess generation and morphological modifications in the Hf pellet. Fig. 1 shows the erosion cavity depth for each electrode of the abovementioned test series.

These first results highlighted how the erosion morphology and cavity depth that each emissive insert underwent after a certain number of CCs were strongly affected from the morphology of the cathode surface at the end of the previous CC. Thus, in order to better understand the ejection and erosion mechanisms that each electrode underwent during first cycles, 4 more 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.

3.2 Morphological analysis

After the first arc ignition, all the tested electrodes evidenced the presence of a concave recess in the Hf emissive insert and a toroidal Hf deposit surrounding its boundaries on the cathode surface (Fig.s 2-3). Moreover, SEM macrograph of Fig. 3a exhibits the presence of a fine dispersion of Hf oxide surrounding the massive Hf deposit. Finally, part of the Hf eroded volume is deposited on the inner nozzle surface, as shown in Fig. 4a. Fig. 3b highlights the correspondence between the 3-D topography reconstruction and the real electrode morphology. Fig.s 7 and 8 report the detailed evolution of the cross sectional mean profiles and volume measurements, eroded from the Hf plane insert and deposited on the cathode surface, of all the tested electrodes as a function of the number of CCs. For E3, after 2 CCs and E4, after 1 CCs, the deposited volumes exceed the erosion ones; this result could be explained by taking into account the higher density of the pure Hf (13.09 g/dm³) with respect to the one of HfO₂ (9.7 g/dm³). Moreover, the oxide layer could be strongly irregular and affected from cracking and porosity (Fig. 6). This could affect both the amount of HfO₂ deposited on the cathode surface, leading to an increase in the measured values of the deposited volume, and the superficial layer of the emissive insert, so decreasing the measured erosion volume.
Cracking and porosity of the HfO$_2$ layer on the emissive insert (optical microscopy).

For 3 out to 4 electrodes (E1, E2, E4), the deepening of the erosion cavity is approximately linear up to 2 cutting cycles; between 2 and 3 CCs the maximum erosion depth tends to slightly decrease as well as the erosion volume. Thereafter, erosion depth for electrodes E1 and E2 slightly increases up to 5 CCs achieving depth values similar to those measured after 2 CCs (about 500 µm, Fig.9). On the contrary, electrode E4 cavity depth passes from 290 µm to 660 µm between 3 and 4 CCs, whilst the recess depth tends to remain almost constant thereafter. Electrode E3 behaves differently, as the recess depth decreases from 1 to 2 CCs, then undergoes to a deepening after 3 CCs, whereas it remains almost constant at about 500 µm between 3 and 5 CCs. Eroded volume measurements as a function of the number of CCs are in excellent agreement with the maximum value of the recess depth, showing similar trends (Fig. 9).

Correspondence was also found between the amount of Hf detected on the nozzles inner surfaces and the deepening rate of the erosion cavity: massive HfO$_2$ deposits were found when the cavity depth increased significantly, while nozzle inner surfaces were found to be almost clean when the erosion volume and the recess depth decreased or remained almost constant. Only for electrode E3 a limited amount of Hf was detected on the nozzle inner surface after 2 CCs (Fig.2), irregular and less dense after 2 CCs (Fig. 5), thus explaining the abovementioned disagreement.
The evolution of the recess shape, together with the erosion volume and nozzle inner surface analysis induce some considerations about the optimal initial shape that an emissive insert should be given when operating at high currents in PAC [5, 6]. The shape of the emissive surfaces which characterized electrodes E1 and E2 between 2 and 5 CCs can be considered as a reference point to start an experimental procedure for the optimization of the recess shape. Indeed, during this phase both cathodes maintained their cavity depth and erosion volume almost constant, while no or extremely limited Hf emission was detected, proving how the Hf volumes eroded during first 2 CCs could be removed from an optimized emissive insert. The design of the emissive surface could be deduced from the analysis of the 3-D topographies (Fig. 10) and mean profiles carried out for the considered phases.

Conclusions and future developments
The behaviour of high current electrodes in plasma arc cutting were investigated by means of morphological analysis during first cycles. The process of cathode erosion at this stage was found to be only partially deterministic. Thus, 3-D morphology of a set of electrodes was reconstructed after each of 5 cutting cycles. The amount of Hf emitted from the cathode insert increased linearly with the number of cutting cycles upon reaching a phase of lower erosion rate. Mean eroded Hf volume and insert geometry that 3 out to 4 electrodes assumed at the beginning of this phase could be considered to determine an optimized insert shape for high current cathodes. Future developments will be aimed at the optimization of a first guess for the initial recess shape as defined on the basis of presented results, in order to minimize massive Hf ejections during first starts with important benefits on arc stability, cut quality and consumable service life.

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