Design oriented simulation of the behavior of PAC consumables and experimental validation of results.

V Colombo[1], A Concetti[1], E Ghedini[1], S. Dallavalle[2]

[1]*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*

[2] *Cebora S.p.A., Via Andrea Costa 24, 40057 Cadriano di Granarolo, Italy*

Abstract: Hafnium cathode erosion phenomena are among the most critical issues in the development of plasma arc cutting technology, especially for high current level. In this work, the correlation between the distributions of different quantities inside the chamber of a plasma arc cutting (PAC) torch and the electrode and nozzle erosion has been investigated, by means of a 2-D FLUENT based numerical model. The model has been developed in the design phase of a new Cebora mono-gas plasma torch, in order to address critical issues, experimentally detected. Modelling and numerical simulation have allowed a better understanding of the physical phenomena experimentally observed during the prototype development and have suggested successful design solutions for consumables (in particular nozzle, electrode and primary gas diffusers). Direct correlation was found between modelling results and experimental evidences; numerical simulation has been used to predict electrode and nozzle expected life, proving useful to overcome the critical issues initially pointed out and to significantly improve the expected lifetime of consumables.

Keywords: plasma arc cutting torches, electrode erosion, numerical simulation

1. Introduction

In recent years, several experimental 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. In the meantime, modelling and numerical simulation have proven very useful tools for the investigation of the characteristics of the plasma discharge and for the optimization of industrial cutting torches [5-10]. The aim of this work is to investigate the correlation between some distributions of different quantities inside the plasma chamber and the erosion mechanisms of the hafnium emitter surface and of the nozzle inner surfaces by means of a 2-D axi-symmetric ANSYS FLUENT V12 - based numerical model [7-9].

2. Experimental set-up

Experimental tests have been accomplished through a prototype Cebora mono-gas plasma torch, able to operate in the current range 25-160 A both for manual and automated cutting. Experiments have been accomplished at 160 A under operative conditions typically used in cutting of MS plates thicker than 20 mm, with air as both plasma and shield gas. Electrodes have a press fit Hf insert with a 1.6 mm diameter flat emission surface, associated to a 1.8 mm diameter nozzle.

3. Results and discussion

The first experimental tests done with the torch prototypes during design process helped to identify some critical aspects dealing with both electrode and nozzle wear, in particular: too small values of the hafnium maximum depth “at death”, high average hafnium erosion rates, rapid wear of the nozzle orifice inlet.

Average hafnium erosion rate has been evaluated using the ratio between the total depth “at death” and the total number of Cutting Cycles (in the following

CCs); it has been measured in mm/20 CCs, as customarily in the plasma cutting experimental practice.

In this section, the influence of the plasma gas tangential and axial components on the electrode erosion and the evaluation of the real arc current density inside the nozzle orifice are showed.

The identified correlations allowed making suitable modifications to the consumables of the new torch prototypes, in particular electrode, nozzle and primary gas diffuser, overcoming the initially highlighted critical aspects.

Maximum value/intensity of the plasma swirl velocity at the nozzle orifice inlet

Erosion tests with a first version of the torch prototype showed that the electrode death would take place for about 0.8 mm Hf erosion depth (well before the 3.5 mm total axial length of the pellet) and with a quite high average Hf erosion rate (about 0.27 mm/20 CCs). The overall electrode service life in that case would be about 60 CCs (test1), unacceptable with respect to any market standard.

Simulative results (figure 4(a)) showed that the geometry of this first version prototype was characterized by reduced values of gas swirl velocity at the exit of the orifices of the primary gas diffuser and by a significant drop of the swirl velocity between the exit of the primary gas diffuser orifices and the nozzle orifice inlet; both phenomena led to very low values of the plasma swirl velocity in the region of the nozzle orifice

At first, the following torch design parameters were modified:

- number and diameter of the primary gas diffuser holes, together with the Ra size (figure 1);
- the distance between the exit of the primary gas diffuser orifices and the inlet of the nozzle orifice (Ha size, as shown in figure 1).

Simulative results showed that, changes in the primary gas diffuser geometry gave rise to a significant increase in the maximum value of the plasma swirl velocity at the nozzle orifice inlet (figure 4(b)); while the reduction of the Ha size gave rise to a significant reduction of the plasma swirl velocity drop and consequently to an increase of the maximum value of the plasma swirl velocity at the nozzle orifice inlet (figure 4(c)). Erosion tests accomplished under these same torch geometries and operating conditions (test 2 and test 3) showed that the increase in the maximum value of the plasma swirl velocity at the nozzle orifice inlet corresponds to an increase in the Hf erosion depth “at death”, without obtaining significant reduction of the Hf erosion rate. As a consequence, a significant increase of the electrode service life has been evidenced: form 60 CCs to 120 CCs (figure 2).

Swirl velocity field near the emission surface

In order to further increase the electrode service life, the swirl velocity field near the cathode emission surface has been analyzed, taking into account the swirl velocity radial profile at the axial level corresponding to a distance of 0.5 mm (line 1) from the emitter surface. By linking simulation and experimental results hitherto obtained, a direct correlation has been found between the Hf erosion rate and what has been called “Hf erosion rate predictor”, that’s to say the ratio between the plasma swirl velocity values on line 1 and the ones at the nozzle orifice inlet. In order to reduce the “Hf erosion rate predictor”, the distance between the Hf emitter surface and the nozzle orifice inlet (Hb size, as shown in figure 1) has been increased. Simulative results showed that the maximum value of the swirl velocity at the nozzle orifice inlet remained almost unaffected, while its extension was slightly reduced (figures 4(d) and 4(e)); the “Hf erosion rate predictor” values were significantly reduced (figure 3). At the same time, erosion tests results showed a significant reduction of the Hf erosion rate, even if the electrode service life remained almost constant, due to a slight reduction of the Hf erosion depth at death (figure 2).

The axial component of the plasma gas inlet velocity

To further increase the electrode performances, the design of the primary gas diffuser geometry has been changed, to introduce an axial component in the velocity of the plasma gas entering the plasma chamber, while maintaining unaffected its tangential component.

Simulative results showed that this modification gave rise to an increase of the maximum value of the plasma gas swirl velocity at the nozzle orifice inlet, with a slight increase of the plasma swirl velocity values on line 1 (figure 4(f)). The combination of these two changes in the plasma swirl velocity field gave rise to a quite similar “Hf erosion rate predictor” for the test 3 and test 6 cases (figure 3), confirmed by a quite similar experimental value of the Hf erosion rate too (about 0.26 mm/20 CCs).

In order to reduce the “Hf erosion rate predictor”, while maintaining the maximum value of the plasma gas swirl velocity at the nozzle orifice of 83 m/s, an increase of the Hb size from 2.9 mm to 3.6 mm has been introduced (test 7). Simulative results showed that the maximum value of the swirl velocity at the nozzle orifice inlet remained almost unaffected (figure 4(g)), while the “Hf erosion rate predictor” values were significantly reduced (figure 3).

On the side of experiment, erosion test results evidenced both a reduction of the Hf erosion rate to and an increase in the maximum erosion depth “at death” up to 1.7 mm, with a final significant increase in the electrode service life of 140 CCs (figure 2).

Evaluation of the real arc current density

The “real” arc current density in the orifice region, taking into account the effective radial extension of the central hot region in which the current flows, as ideally separate from the cold boundary region near the nozzle wall, has been evaluated. For this purpose, the temperature radial profile inside the nozzle orifice at different axial levels has been studied, for the torch geometry of test case 7. Figure 5 shows the radial behaviour of temperature and current density at the nozzle orifice inlet. The matching of the two curves shows that the current density is significantly different from zero in the region where plasma temperature is above 7500 K. Around this temperature nitrogen dissociation occurs and electrical conductivity increases significantly due to ionization. Therefore, the temperature value of 7500 K has been ideally taken as the transition between hot and cold regions in the plasma jet and its radial location as representative of the arc radius. This type of analysis can allow the study of the temperature field of the cold region along the nozzle orifice and it could be useful to predict nozzle wear phenomena.

References

[1] Nemchinsky V A and Severance W S 2006 What we know and what we know not about plasma arc cutting *J. Phys. D, Appl. Phys.* **39** R423-R438.

[2] Nemchinsky V A and Showalter M S 2003 Cathode erosion in high-current high-pressure arc *J. Phys. D, Appl. Phys.* **36** 704-712

[3] Nemchinsky V A 2003 Cyclic erosion of a cathode in high-pressure arcs *J. Phys. D, Appl. Phys.* **36** 1573-1576

[4] Peters J, Yin F, Borges C F M, Heberlein J and Hackett C 2005 Erosion mechanism of hafnium cathodes at high current *J. Phys. D, Appl. Phys.* **38** 1781-1794

[5] V. A. Nemchinsky, “Plasma flow in a nozzle during plasma arc cutting” J. Phys. D, Appl. Phys. **31,** 3102–3107 (1998)

[6] Freton P, Gonzalez J J, Gleizes A, Peyret F C, Caillibotte G and Delzenne M, “Numerical and experimental study of a plasma cutting torch” J. Phys. D, Appl. Phys. **35**, 115–131 (2002)

[7] Colombo V, Dallavalle S, Ghedini E, Masini G, Russo D and Vancini M., “2-D and 3-D fluidynamic and plasma characterization of DC transferred arc plasma torches for metal cutting” J. High Temp. Mater. Process. **10,** 379–392 (2006)

[8] Colombo V, Concetti A, Dallavalle S, Ghedini E and Vancini M “Understanding plasma fluid dynamics inside plasma torches through advanced modeling” IEEE Transactions on Plasma Science **36,** 389-402 (2008)

[9] V Colombo, A Concetti, E Ghedini “Design oriented simulation of consumables in PAC and experimental validation of results”, Plasma Sources Sci. Technol., **20** 035010 (2011)

[10] Murphy A B, “Transport coefficients of air, argon-air, nitrogen-air, and oxygen-air plasmas” Plasma Chem. Plasma Process. **15**, 279-307 (1995)

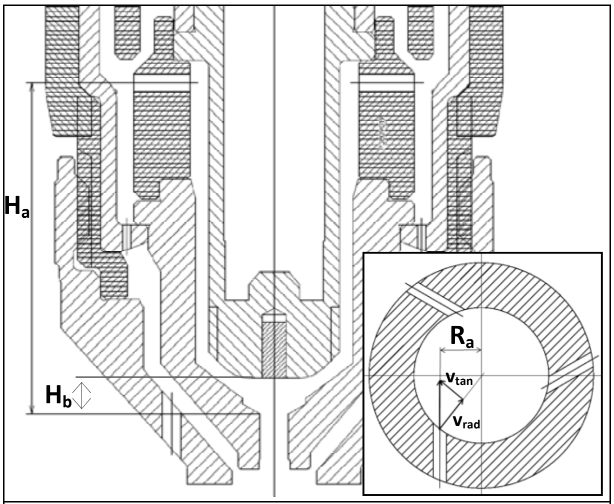

Figure 1. 2-D schemes of the torch and of the primary gas diffuser of the *first version* prototype (test 1).

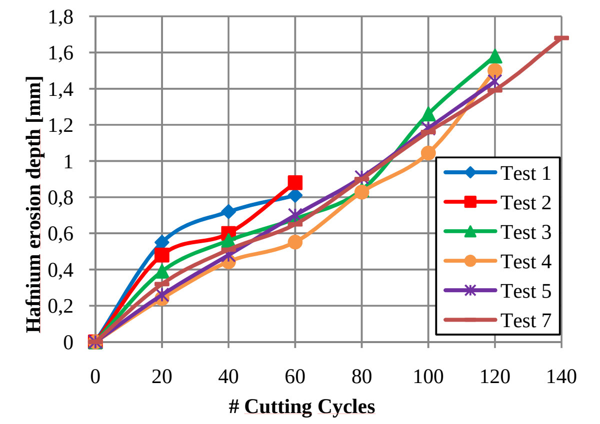

Figure 2. Radial dependence of the ratio between the swirl velocity profile at the axial level of LINE 1 and the maximum swirl velocity at the nozzle orifice inlet for the test cases from 1 to 7; taken from [9].

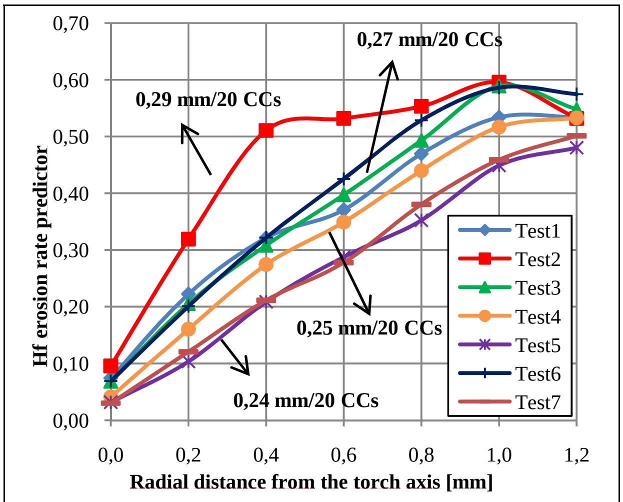

Figure 3. Hafnium erosion depth [mm] at different CCs for the test cases from 1 to 7; taken from [9].

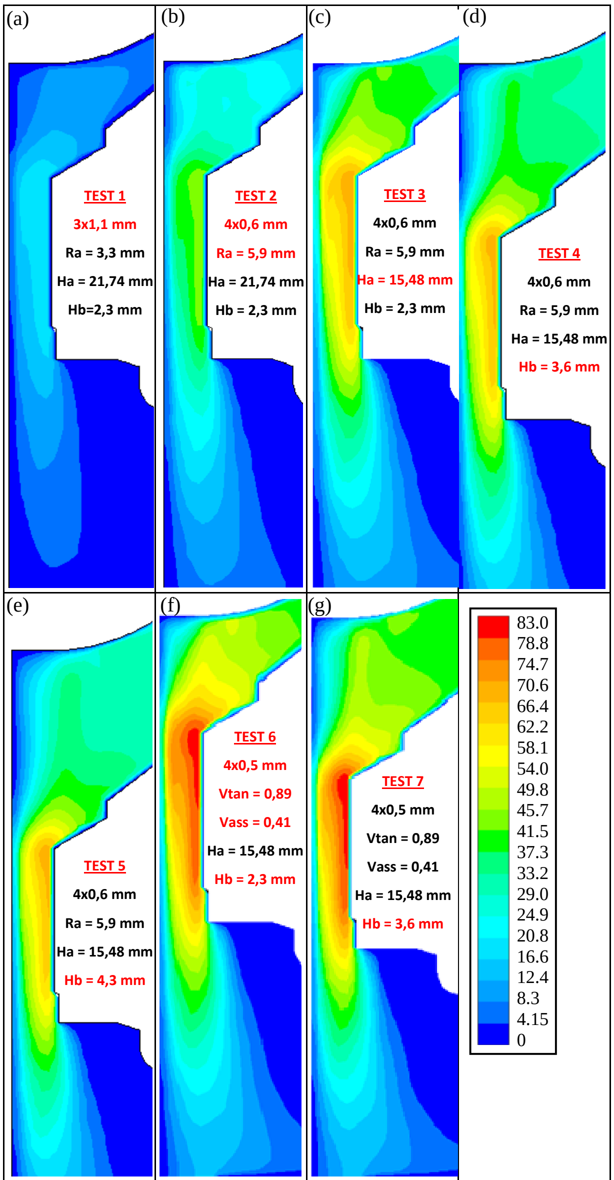

Figure 4. Comparison of the plasma swirl velocity field [m/s] from the simulations of the torch geometry for the test cases from *(a)* 1 to *(g)* 7; taken from [9].

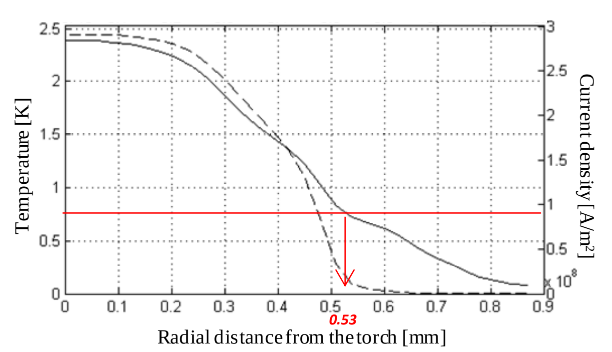

Figure 5. Radial dependence of the temperature [K] and of the current density [A/m^2] at the nozzle orifice inlet, from the simulation of the torch geometry of test case 7; taken from [9].