

**COMPARATIVE CORROSION STUDIES OF THERMAL  
PLASMA NITRIDING CONDITIONS AGAINST  
GALVANIZING OF CARBON STEEL EXPOSED TO  
CHLORIDE CONTAINING SOLUTIONS**

Oliveira, M.A.S.<sup>a\*</sup>, Ferreira, B.C.<sup>a</sup>, Thim, G.P.<sup>a</sup> and Scheid, V.H.B.<sup>b</sup>

<sup>a</sup>Chemistry Department, Instituto Tecnológico de Aeronáutica (ITA),<sup>b</sup>  
Instituto de Estudos Avançados – CTA, Pça Mal Eduardo Gomes, 50 –  
CTA, São José dos Campos, SP, Brazil, CEP 12228-900

\*e-mail: [dora@iefita.br](mailto:dora@iefita.br)

Thermal plasma nitriding of AISI1010 carbon steel was carried out in an industrial plasma nitriding furnace (Metal Plasma S/C Ltda) under the different plasma nitriding conditions showed in Table 1.

Samples treated under each different thermal plasma nitriding conditions were identified by the codes showed in Table 2.

Salt spray, mass loss and electrochemical corrosion measurements were performed for bare, galvanized and thermal plasma nitrided carbon steel surfaces.

The electrochemical corrosion measurements were performed utilizing a conventional three-electrode cell containing a platinum wire as counter electrode, a saturated silver/silver chloride as reference electrode and a working electrode. The working electrode was samples of the bare, galvanized and thermal plasma nitrided carbon steel with a 1.0 cm<sup>2</sup> exposed area. The electrolyte solution was a 0.5 mol L<sup>-1</sup> NaCl aqueous solution, pH 5.8. All potentials were measured at room temperature (≈ 25 °C) and were controlled with an MQPG-01 potentiostat. The working electrode potentials were varied from -1.80 to +1.50 V at a scanning rate of 10.0 mV s<sup>-1</sup>. These tests were performed in triplicate and the averaged results are shown in Table 3.

The salt spray test was performed following the American Society for Testing and Materials (ASTM B117-97). In order to determine the time to observe pit formation, two panels of each different surface were taken out from the salt spray chamber and assessed through an optical microscope (LEICA Reichert Polyvar 2) after every 24 hours. All differently treated surfaces presented pit formation after 24 hours of exposition to the sodium chloride spray. However, it was observed visually that the rusting degree decreased in the following sequence: bare > Cf55 > Cf56 > Cf62 > Gal.

The mass loss tests were performed following the American Society for Testing and Materials (ASTM C694-90a). Utilizing the mass variation average ( $\Delta m$ ) of ten panels of surfaces submitted to each different treatment, the corrosion rate ( $V_{cor}$ ) was determined using the Equation 1:

$$V_{cor} = \Delta m S^{-1} t^{-1} \quad \text{Eq. 1}$$

where

$\Delta m$  = mass variation average (g),  $S$  = exposed area (cm<sup>2</sup>) and  $t$  = exposition time (h) to a sulfuric acid aqueous solution. The results of these tests, for some surface treatments, are shown in Table 4.

Table 3 presents the corrosion parameters (polarization resistance ( $R_p$ ), corrosion potential ( $E_{cor}$ ) and corrosion current density ( $j_{cor}$ )) obtained from the electrochemical tests for the bare, galvanized and some of the thermal plasma nitrided carbon steel surfaces. The results in Table 1 show that the corrosion potentials ( $E_{cor}$ ) presented by galvanized surfaces are more negative than those presented by the bare surfaces. The results in Table 1 also showed that the  $E_{cor}$  of the nitrided surfaces shift to more positive values than those of the bare and galvanized surfaces. The corrosion current densities ( $j_{cor}$ ) presented by nitrided surfaces decreased with the temperature, nitriding time and nitrogen concentration in the gas flux inside the nitriding furnace. This tendency was also confirmed by the results of salt spray and mass loss (some of them showed in Table 4). The results showed in Tables 3 and 4 indicate that, among the different nitriding conditions used in this work, there is an optimal nitriding condition which is: nitrogen/hydrogen flux ratio equal to 3/1, nitriding temperature equal to 600 °C and nitriding time equal to 30 min. Nitrided surfaces under this optimal condition presented a corrosion resistance seven times higher than that presented by galvanized surfaces.

**ACKNOWLEDGEMENTS**

The authors thanks the FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO (FAPESP) for the funds granted to Bruna Carolina Ferreira Research Grant No 00/13448-0.

Table 1. Parameters of the thermal plasma nitriding treatments.

Parameter	
Gas composition	H <sub>2</sub> : 50–52%, N <sub>2</sub> : 50–75%
Temperature	400–600 °C
Time	10–60 min

Table 2. Identification code for samples submitted to each different thermal plasma nitriding conditions.

Code	Plasma nitriding parameters
Sf	Bare carbon steel
Gal	Galvanized
Cf42	400 °C, 10 min, N <sub>2</sub> /H <sub>2</sub> =1/1
Cf52	500 °C, 10 min, N <sub>2</sub> /H <sub>2</sub> =1/1
Cf55	500 °C, 30 min, N <sub>2</sub> /H <sub>2</sub> =3/1
Cf56	500 °C, 60 min, N <sub>2</sub> /H <sub>2</sub> =3/1
Cf62	600 °C, 30 min, N <sub>2</sub> /H <sub>2</sub> =3/1

Table 3. Corrosion parameters for the bare, galvanized and some of the thermal plasma nitrided carbon steel surfaces exposed to 0.5 mol L<sup>-1</sup> NaCl aqueous solution, pH 5.8, at room temperature (≈ 25 °C).

Treatment	R <sub>p</sub> (10 <sup>4</sup> Ω cm <sup>2</sup> )	E <sub>corr</sub> V(Ag/AgCl)	j <sub>corr</sub> (10 <sup>6</sup> A cm <sup>-2</sup> )
Sf	(2.3 ± 0.9)	(-0.69 ± 0.06)	(2.0 ± 0.9)
Gal	(3.5 ± 1.8)	(-0.77 ± 0.04)	(1.7 ± 0.7)
Cf42	(5.5 ± 2.7)	(-0.50 ± 0.11)	(0.54 ± 0.22)
Cf52	(11.8 ± 3.3)	(-0.36 ± 0.05)	(0.36 ± 0.08)
Cf55	(6.4 ± 5)	(-0.16 ± 0.02)	(0.050 ± 0.005)
Cf56	(27 ± 9)	(-0.09 ± 0.02)	(0.095 ± 0.021)
Cf62	(1050 ± 600)	(-0.35 ± 0.07)	(0.00379 ± 0.0009)

Table 4. Mass loss and corrosion rate results.

Treatment	$\Delta m$ (g)	$V_{cor}$ [10 <sup>3</sup> (g cm <sup>-2</sup> h <sup>-1</sup> )]
Sf	(0.197 ± 0.004)	(6.59 ± 0.15)
Gal	(0.520 ± 0.014)	(173.0 ± 0.5)
Cf55	(0.0415 ± 0.0009)	(1.38 ± 0.03)
Cf62	(0.0111 ± 0.0005)	(0.37 ± 0.02)