

Simulation of the Damage Tolerance of Thermal Spray Aluminium Sacrificial Coating in Artificial Seawater

Adriana Castro Vargas
University of Leicester
University of Road
Leicester LE1 7RH
UK
NSIRC, TWI Ltd
Granta Park, Great Abington
Cambridge, CB21 6AL
UK
Technological University of Bolivar
Km 1 Vía Turbaco
Cartagena, 130011
Colombia

Shiladitya Paul
TWI Ltd
Granta Park, Great Abington
Cambridge CB21 6AL
UK
University of Leicester
University of Road
Leicester LE1 7RH
UK

ABSTRACT

Numerical simulations were conducted to understand the behaviour of sacrificial aluminium coatings obtained by arc spray with varying areas of damage and its capacity to polarise the steel under a simulated marine environment. The damage tolerance of a 300 μm thick coating of aluminium alloy AA 1050 (TSA) with 5%, 20%, 50% and 90% exposed steel surfaces was evaluated in a time-dependent model. Arbitrary Lagrangian Eulerian (ALE) was used in a moving mesh technique to simulate the consumption of the TSA coating surface. Cathode surface, in this case, exposed steel, is assumed non-deforming in the model. The simulations were compared with experimental measurements of open circuit potential (OCP) and corrosion rate (CR) from previous studies, where the electrochemical behaviour of TSA with exposed steel surface was evaluated over different periods of time in artificial seawater at 20°C. The corrosion rates obtained using the model are in broad agreement with those estimated from

laboratory experiments. In addition, the model predicted sacrificial protection offered by TSA coating as a function of the exposed steel.

Key words: Thermal spray coating, cathodic protection, marine environments, simulations and modelling.

INTRODUCTION

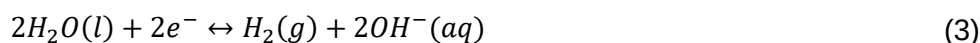
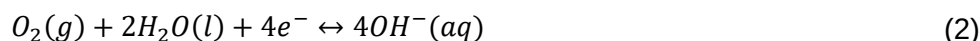
Thermal Spray Aluminium (TSA)

TSA is mainly used to protect offshore steel structures, including atmospheric, splash and immersed zones.^{1, 2} During installation or in service, the coating is likely to be damaged due to erosion, wear, scratch etc. TSA coatings protect by acting as a barrier and offering cathodic protection even if the substrate is exposed to seawater.³

The protection mechanism offered by TSA coatings with an exposed steel substrate in seawater is complex due to: (i) simultaneous anodic and cathodic reactions, (ii) passivation tendency of aluminium, (iii) formation of corrosion products, (iv) changes in local pH, (v) formation of calcareous layers to name a few.⁴ The primary protection mechanism offered by TSA is due to the potential difference between Al and steel. TSA acts as anode and the dissolution is produced according to Equation 1.



Oxygen reduction and hydrogen evolution (Equation 2 and 3) take place on cathode sites, in this case exposed steel.



As a result of these cathodic reactions, local pH increases by the production of ions OH^{-} and consequently, causes the precipitation of calcareous deposits on the steel. Depending on the temperature and constituents of the seawater, the deposits might provide some barrier properties.⁵⁻⁷ Over time, white corrosion products of Al oxides and hydroxides appear on the surface of TSA, reducing the self-corrosion of Al. Layers of white products have also been observed on the surface of the steel.⁸

However, while it is well established that TSA coating can provide protection when the defect surface is between 1% and 5%,^{9, 10} there are limited data of the damage tolerance in the presence of a large defect. On the other hand, several international standards such as ISO 2063⁽¹⁾, Norsok M501⁽²⁾, NACE No. 12/AWS C2.23M/SSPC CS 23⁽³⁾, AWS C2.18⁽⁴⁾ are used to specify, test, qualify and inspect coatings for offshore applications. Nevertheless, the damage tolerance generally is not included in these standards. Moving on now to consider numerical simulations, the following is a brief description of the recent findings in this aspect.

(1) ISO, International Organization for Standardization, CP 401 - 1214 Vernier, Geneva, Switzerland.

(2) NORSOK, Norwegian Standards Organization, Lilleakerveien 2a, NO-0283 Oslo.

(3) NACE International – SSPC, 15835 Park Ten Place Houston, Texas 77084, USA.

(4) AWS, The American Welding Society, 8669 NW 36 Street, #130, Miami, Florida.

Sacrificial Coatings Modelling

The electrode potential and electrolyte potential may change in space and time, thus a corrosion model must be able to describe the potential distribution in the metal and electrolyte. Recently, there have been advances in computational tools and corrosion simulations. Software-based on finite element methods to solve physical problems employing differential equations, incorporate parameters as electrolyte conductivity, current density, dissolving – depositing species, change in electrode size, film resistance due to corrosion products, etc. In addition, the electrochemical reactions are introduced at the metal surface as a boundary condition. However, the simulation of these parameters have been computed in separated models.¹¹

When aluminium and steel are exposed to seawater, a galvanic couple is established between those metals. TSA coating provides cathodic protection to the substrate by acting as sacrificial anode. Therefore, this work will use the galvanic corrosion model approach. This model is based on the transport of dissolved species in an electrolyte according to Nernst – Planck equation. Transport by convection and diffusion are neglected and the solution takes form of Laplace equation. This equation is well known to calculate the distribution of potential in a region of space not occupied by electrically charged bodies.¹² When contributions by convection and diffusion are significant, the Laplace equation will not capture a realistic situation in a particular physical process.¹¹ Several studies of galvanic corrosion simulation of sacrificial coatings have been found in the literature, some of which are described below.

The mechanism of corrosion protection of steel by a damaged zinc coating in 3.5 wt. % NaCl solution was simulated by Saeedikhani et al.¹³ The model predicted the period of sacrificial protection offered by a 96% zinc primer. In addition, changes in the geometry of the zinc electrode were in good agreement with experiments. Similarly, the corrosion of zinc and aluminium coatings coupled to a mild steel, using deaerated 0.01M H₂SO₄ as electrolyte was simulated by Cross S et al.¹⁴ The remarkable finding was the rapid consumption of zinc while aluminium did not dissolve enough to provide effective cathodic protection. The results showed reasonable quantitative agreement with experimental measurements.

Huang et al.¹⁵ simulated the cathodic protection and potential distribution on cold spray Al-Zn coating with damage using Q235 steel as substrate and natural seawater as electrolyte. In contrast with the previous findings, this work concluded that Al-Zn coating is not able to provide cathodic protection when the defect size is greater than 1 mm in width. A three-dimensional geometry was built in the model and the insulation boundary condition was applied to the external domain to match with experiments; however, the electrolyte domain, electrode and electrolyte distribution potential in the whole geometry are not reported thoroughly.

Despite this progress in modelling of sacrificial coatings, no simulations of TSA damage tolerance have been found in the literature. Therefore, this work seeks to provide information on the ability of the damaged TSA coating to polarise steel through numerical simulations, varying the size of the exposed substrate. In addition, it will serve as a reference to compare the effect of corrosion products and deposits in future investigations.

EXPERIMENTAL PROCEDURE

Experiments

In order to compare the results of the simulations, experimental measurements of open circuit potential (OCP) and corrosion rate (CR) from two previous studies were taken into account: a) Prediction of Thermal Spray Coatings Performance in Marine Environments by Combination of Laboratory and Field Tests⁹ and b) Cathodic Protection of Offshore Structures by Extreme Damage Tolerant Sacrificial Coatings.⁸ For this work, part of the results will be used and referred to as experiments A and B,

respectively. The experiments evaluated specimens of TSA – coated steel with simulated damage (exposed steel). Application and sample preparation details can be found in the studies mentioned above. The configurations of the experiments A and B are listed in Table 1.

Table 1
Configurations of the experiments

Parameter	Experiment A ⁹	Experiment B ⁸
Substrate dimension	40 mm x 40 mm x 6 mm. Figure 1 (a)	500 mm x 45 mm x 6 mm. Figure 2 (a)
Total area	1600 mm ²	22500 mm ²
Coating area	1520 mm ² (95%)	2250 mm ² (10%)
Exposed steel area	80 mm ² (5%)	20250 mm ² (90%)
Coating alloy	AA 1050 obtained by arc spray (TSA)	
Coating thickness	300 μm	
Electrolyte	Artificial seawater following ASTM D1141 ^{(5), 16}	

Model

Geometry of Experiment A

A 2D axisymmetric space dimension component was designed to match with the experimental system with the surface area maintained as in the physical specimen. The damage was built varying the defect radius with 5 mm, 10 mm, 16 mm and 21.4 mm, with values representing 5%, 20%, 50% and 90% of exposed steel surfaces, respectively. The resulting geometry is shown in Figure 1 (b).

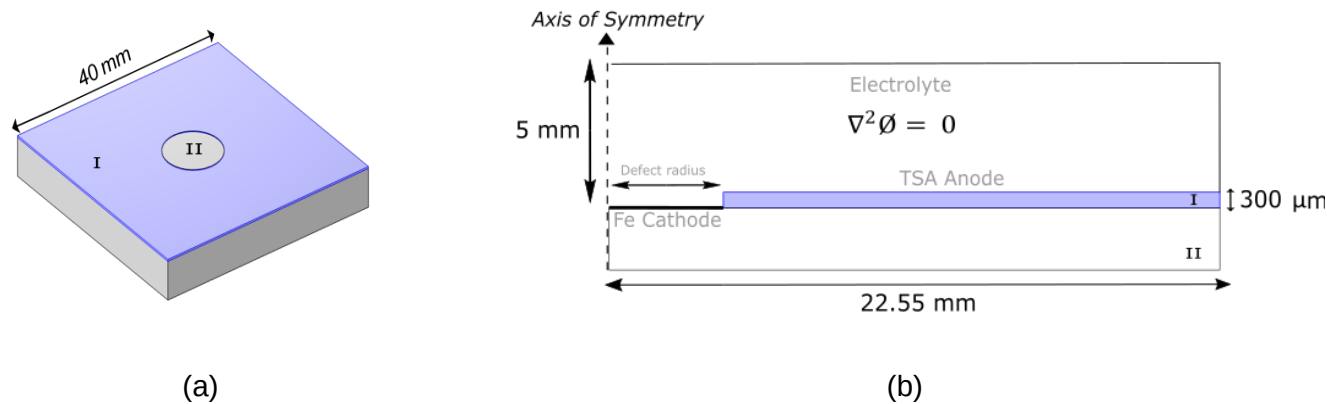


Figure 1: (a) Thermally sprayed coated sample with 5 % of surface area defect. (I) TSA coating, (II) Exposed steel. (b) Geometry of the model, 2D axi-symmetric space dimension.

Geometry of Experiment B

Corrosion simulations were performed in a 2D space dimension component, considering 10% of TSA as anode and 90% of exposed steel as cathode. The damage was built varying the length of TSA with 475 mm, 400 mm, 250 mm, and 50 mm, whose values represent 5%, 20%, 50% and 90% of exposed steel length, respectively. Figure 2 (b) shows a schematic of the geometry built in the model.

⁽⁵⁾ ASTM International, 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959.

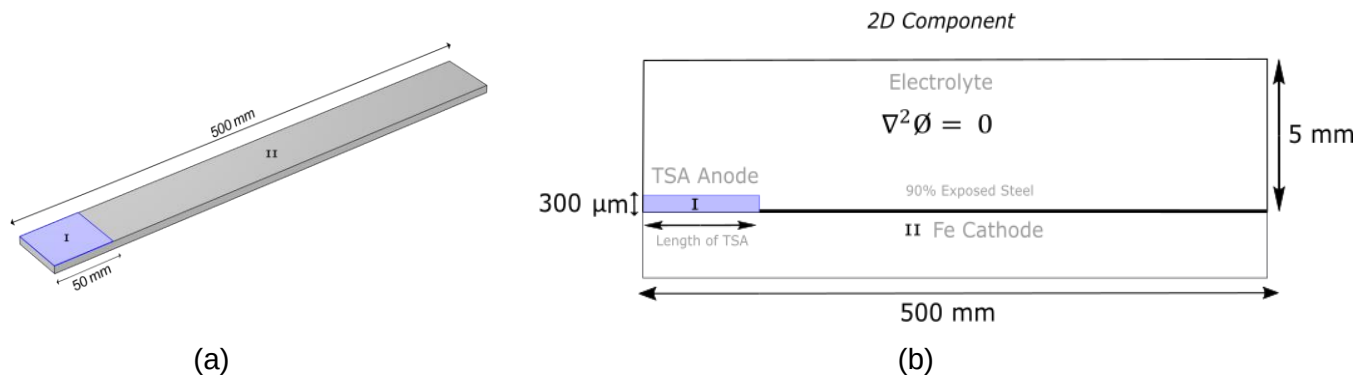


Figure 2: (a) Thermally sprayed coated sample with 90% of defect. (I) TSA coating, (II) Exposed steel. (b) Geometry of the model, 2D space dimension.

Governing Equations and Boundary Conditions

The Nernst – Planck equation describes the transport of dissolved species i in an electrolyte:

$$N_i = -D_i \nabla c_i - \frac{D_i z_i F}{RT} c_i \nabla \phi + c_i v \quad (4)$$

Where N_i is the flux of dissolved species i , D_i diffusion coefficient, c_i concentration of species i , z_i is the valence, F is the Faraday constant, R is the ideal gas constant, T is the temperature, ϕ is the electrical potential, and v is the solution velocity. The model takes the following assumptions:

Electrolyte is well mixed, it means that all concentration gradients are eliminated, thus no production or consumption reactions between dissolved species are expected. Since quiescent conditions are considering, the solution velocity v can be set to zero. The mass balance of the species is given by Equation 5.

$$\frac{\partial c_i}{\partial t} = -\nabla \cdot N_i = 0 \quad (5)$$

In the electrolyte domain is assumed electro- neutrality condition, represented by Equation 6:

$$\sum_i^n z_i c_i = 0 \quad (6)$$

Equation 4 takes form of Laplace equation, for the electrical potential as transport by convection and diffusion are neglected.

$$\nabla^2 \phi = 0 \quad (7)$$

According to Equation 8, Ohm's law is applied to calculate potential gradient at the anode and cathode boundaries.

$$\nabla \phi = -\frac{j_a}{\sigma} \quad (8)$$

Where, j_a is anodic current density, σ is electrical conductivity of electrolyte solution, this parameter will define how the current in the domain depends on the gradient of the potential. Similarly, the boundary