Surface modification of carbon steel by electrodeposition composite coating for improving erosion-corrosion resistance: a review

Dr. Ekbal M. S. Salih¹ Dr. Haydar A.H. Al–juboori² Nadheer R. A. Al-Hamdani³

University of Babylon - College of Materials Engineering 1.2.3.

ekbaseed@gmail.com Drhayderalgibory@yahoo.com alinadheer9@gmail.com

Abstract. This paper included an explanation of one of the methods of protection from corrosion, as it dealt with the use of electroplating technology by using solid ceramic particles embedded in chromium on carbon steel as a base material as an effective way to increase the service life of fluid-carrying tubes, considering that they are exposed to a joint effect of chemical and physical action. The formation of composite coatings on carbon steel and the factors affecting the success of these coatings in addition to a group of studies that dealt with these factors and their impact on increasing the resistance to conditions surrounding the metal represented by resistance to chemical corrosion in the presence of erosion (such as the concentration of solid particles in the paint solution, the temperature of the paint solution, the effect of The current density on the quality of the coatings and the effect of the thermal treatment on the coatings). The current density, the concentration of solid particles and the temperature have the greatest influence in determining the efficiency of the composite coatings.

Key words: Cr-SiC composite coating; electrodeposition; Erosion-corrosion resistance

1- Introduction

Erosion and corrosion of engineering materials are major variables that might lead to component failure or diminish their operational readiness. One approach to avoid these problems is to use a good coating system on the surface to protect the material from degradation and corrosion. Electrodeposition, plasma thermal spray, and physical vapor deposition are some of the techniques used to generate protective coatings. [1] In order to improve wear and corrosion resistance, nanoparticles are now being employed to reinforce composite materials used in coating systems. The electrocodeposition of inert ceramic nanoparticles such as SiC in a metal matrix is a good approach to make a hard plated coating on a metal surface. A pore-free metallic coating with the fewest micro
fissures may easily separate the metal surfaces, save in the most corrosive environments. It's possible to utilize a coating with a lower friction coefficient but a higher micro-hardness. [2].

2-The mechanism of composite plating and types of inclusions

A range of particles, ranging in size from tens of nanometers to hundreds of microns in diameter and formed spheroidal, tubular, fibrous, or lamellar, may be integrated into a metal deposit to form a composite coating. as shown in figure (1) [3].

![Figure 1](image1)

**Figure (1)** Scale of composite materials in dependence on the size of the built-in particles [3]

Particles are incorporated into metallic coatings by convection into the cathode surface, mechanical entrapment of particles in the expanding metal matrix, and/or electrophoretic migration of particles to the growing metal deposit.

The measures are: (a) production of charged particles, e.g. as a result of ions and surfactants adsorbed on particle surfaces, (b) physical particle movement via a convection layer, (c) particle mass transit through a concentration boundary (diffusion) layer, (d) migration driven by the potential gradient through an electrical double layer, and (e) physical embedding of particles in an electrical double layer. as shown in figure (2) [4, 5, 6, 7].

![Figure 2](image2)

**Figure (2)** Mechanisms of particle co-deposition into a metal deposit [8]
3-Factors effect on co-deposition of particles into metal deposit

The efficient co-deposition of particles into metal deposits is influenced by a number of process parameters, including particle properties (e.g. concentration, surface charge, type, shape, size), electrolyte composition (e.g. electrolyte concentration, additives, temperature, pH, surfactant type and concentration), applied current density (e.g. direct current, pulsed current, pulse time, duty cycle), and electrolyte composition (e.g. electrolyte concentration, additives, temperature, pH, surfactant type and concentration). (for example, laminar, mixed, and turbulent regimes), as well as the shape and size of the electroplating tank and electrode geometries (rotating disk electrode, rotating cylinder electrode, plate-in-tanks, parallel plate electrodes and many variations of electroplating tanks). [4, 5, 6, 7].

The general factors affecting composite electroplated deposits are shown in Figure (3), in the form of input variables to a model and the output results required.

![Figure (3) Input variables to a model of composite plating and the output results sought](image)

![Figure (4) images of electrodeposited nickel coatings with inclusions a and b; examples of composite nickel-particle deposits Images of a composite nickel containing nanosized silicon carbide particles in](image)
cross-section (darker). The coatings were electrodeposited with 1.5 mol dm$^{-3}$ nickel sulfate, 5 g dm$^{-3}$ boric acid, 5 mL dm$^{-3}$ anti-pitter wetter, 4 mL dm$^{-3}$ hardener from, and 1 g dm$^{-3}$. Nickel composites were electrodeposited at 50 mA cm$^{-2}$ for 2 hours at 60 C° with a rotation speed of 300 rpm [9] and c surface morphology of a nickel composite coating containing Nano tubular titanates. A Watts nickel electrolyte containing 20 g dm$^{-3}$ of nanotubular titanates was used for electrodeposition. At 60C° for 2 hours at 50 mA cm$^{-2}$ [10]

4. The consistency of composite plating is influenced by a number of factors.

These can be categorized into Figure (5) based on the bath structure, plating conditions, and electrode/bath geometry for ease of use.

![Figure 5 Factors influencing the quality of composite plating, grouped according to the bath composition, plating conditions and electrode/bath geometry](image)

5. Examples of research on the topic

Surviliene and colleagues at Vilnius University investigated the impact of silicon carbide on chromium coatings on carbon steels used as a base material. The effect of SiC particles on the corrosion activity of the chromium coating in relation to the substrate can be seen in Fig. (6), which shows the electrochemical impedance spectra (EIS) obtained at Ecorr for both the Cr and Cr–SiC coatings. As shown in fig. (6)
Figure (6) after 30 minutes of immersion in 0.01 M H2SO4 + 0.5 M Na2SO4 solution, impedance spectra of Cr–SiC and Cr coatings and substrate were reported at Ecorr. The coatings were 10 mm thick.

Since the surface of SiC particles is covered with a film of SiO2 as a result of oxidation of SiC in the Cr (VI) bath, analysis of coatings deposited in Cr (VI) baths containing 10–50 g dm⁻³ of SiC particles has shown that, despite a very limited inclusion of the particles in the deposit, they have a major effect on the morphology of the Cr coating as shown in image below [11]. The deposit’s surface, which was formed in a bath containing 50 g dm⁻³ SiC, may be described as a spherolite with a ball-like crystal structure, which was most likely generated by the presence of foreign particles embedded in the deposit (Fig(7d).

![Figure 6](image1.png)

**Figure (6)** Impedance spectra of Cr–SiC and Cr coatings and substrate after 30 minutes of immersion in 0.01 M H2SO4 + 0.5 M Na2SO4 solution.

![Figure 7](image2.png)

**Figure (7)** Micrographs of the Cr (VI) bath-deposited coatings [11]

![a](image3.png)  a: no SiC particles; b: 10 g dm⁻³ SiC particles; c: 30 g dm⁻³ SiC particles; d: 50 g dm⁻³ SiC particles

To improve the coating’s mechanical properties, direct current (DC) and pulse electro deposition (PED) techniques with different pulse frequency and duty cycles were used to produce Cr-ZrO2 composite coatings on a low carbon steel substrate. Pulsing and higher pulse frequencies were
discovered to refine the matrix and increase the ZrO2 content in the coating. Crystallographic orientation of the Cr matrix has an impact on hardness and wear properties in addition to fine structure and dispersion. In the case of DC deposition, the wear mechanism was found to be primarily abrasive, with no adhesive tendency as shown in figure (8) [12].

Figure (8) SEM image of Cr-ZrO2 coatings obtained with (a) no pulse; (b) 4 kHz; (c) 8 kHz; and (d) 12 kHz with 10% duty cycle.[12]

The structure of the electrodeposited composite coatings prepared using the pulsing and DC techniques is shown in Figure (8). Near inspection of the DC coating (Fig. 8(a)) reveals a very fine crack indicating that coatings obtained by pulsed depositions are crack-free. Cracks in Cr coatings are fairly common, and their removal is critical for service applications. The main causes of crack formation are stress and hydrogen evolution at the cathode during coating. No crack was found in the majority of the pulsing conditions in this sample, which may be due to stress relaxation or a lack of hydrogen. Despite the evolution of hydrogen, the coating can be crack-free due to the formation of chromium hydride. In the event that only a portion of the hydrogen is consumed, in the case of Cr-hydride formation, the pressure produced by the remaining amount of evolved hydrogen may be insufficient to cause the crack to form.
Fig. (9) (a) Wear depth versus sliding distance plots of Cr-ZrO2 coatings deposited with different pulsing conditions; wear track of Cr–ZrO2 coating deposited (b) in DC mode and (c) with 4 kHz frequency and 30% duty cycle.[12]

By electroplating, Cr-C coatings and Cr-C/Si3N4 composite coatings were deposited on a low carbon steel (0.2 percent carbon) substrate using direct current plating. The effects of plating parameters such as the concentration of Si3N4 in the plating bath and current density on the coating composition, deposition intensity, morphology, surface roughness, micro-hardness, and wear conduct of electrodeposited Cr-C/S have been investigated.

The study revealed that at a bath loading of 5 g L−1 and a current density of 20 A dm−2, the maximum degree of Si3N4 particle incorporation, around 17.22vol%, is obtained. The incorporation of Si3N4 particles increases the micro hardness of the coatings and significantly increases their wear resistance due to the enhanced dispersion strengthening effect as shown in fig(10) [13].

Figure (10) the effect of current density on the Si3N4 content and deposition rate in Cr-C/Si3N4 composite coatings [13]
Fig.(11) SEM micrograph (BSE mode) of the Cr-C/Si3N4 composite coatings formed in a plating bath containing 5 g L-1 Si3N4 nano-particulates at current densities of (a) 10 A dm-2, (b) 15 A dm-2, (c) 20 A dm-2, (d) 25 A dm-2, and (e) 30 A dm-2.[13]

To investigate electrochemical deposition of a Cr coating on low carbon steel, Shixian Zhang et al investigated the possibility of thermodynamic calculations of electrochemical reduction in a NaCl–KCl–NaF–Cr2O3 molten salt method. According to the findings, during electrochemical reduction, Cr (III) is reduced to Cr in two steps: Cr3+ + e = Cr2+ and Cr2+ + 2e = Cr. Controlling the rate of electroactive ion diffusion. Electrochemical deposition was used to create a lightweight, uniform Cr coating with a thickness of 250µm. Cr coated low-carbon steel has a much higher corrosion resistance than plain low-carbon steel. [14].

Figure (12) In a 3.5 percent NaCl solution, Nyquist graphs of Cr-coated low-carbon steel and low-carbon steel [14]
Because of this difference, the impedance radius of the Cr-coated low carbon steel is slightly greater than that of the low carbon steel. Low-carbon steel with a Cr coating has a far higher corrosion resistance than low-carbon steel.

**Figure (13)** SEM pictures of the Cr coating applied on a low-carbon steel substrate for 6 hours at 1073 K [14]

Hung-Hua Sheu et al investigated the corrosion resistance and mechanical properties of Cr-C/Al2O3 composite coatings electrodeposited from Cr (III) plating baths containing Al2O3 particles and wear resistance of Cr-C thin films. With an icorr of 2.84 10^{-7} A/dm2, the Cr-C/Al2O3 composite coating has the highest corrosion resistance. But, as the heating temperature rises, the corrosion resistance of Cr-C/Al2O3 composite coatings deteriorates as cracks form. According to the findings, heat treatment improved the hardness of Cr-C coatings and Cr-C/Al2O3 composite coatings due to the precipitation of chromium carbide and chromium oxide. The micro-hardness of the Cr-C/Al2O3 composite coating is significantly improved as Al2O3 particles are introduced into the Cr-C matrix as shown in figures (14),(15) [15].

**Figure (14)** Surface morphologies of Cr-C coatings heated at different temperatures as seen by SEM: (a) as-plated, (b) 200 °C, (c) 400 °C, and (d) 600 °C [15]
Morphologies of the surface The Cr–C/Al2O3 composite deposit was heated at different temperatures: as plated, 200°C, 400°C, and 600°C[15]

**Conclusion**

1. The technique of producing composite coatings from solid ceramic particles is one of the successful methods of achieving a longer service life of the part to be protected in harsh corrosive environments.
2. The composite coating technique is considered as a method with a standard low cost in terms of manufacturing and maintenance costs relative to other methods, but it has limitations when the parts to be protected are of large sizes.
3. This method is considered one of the methods of surface modification of the surface of carbon steel, which is considered a cheap material, so that when its surface is modified with composite coatings, it turns into an effective material for protection from corrosion compared to many types of stainless steel.
4. The current density, the concentration of solid particles and the temperature have the greatest influence in determining the efficiency of the composite coatings.

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