Journal of Metals, Materials and Minerals, 36(1), e2334, 2026

Effects of gum additives on nickel electroplating for enhancing steel corrosion resistance

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Received date:
24 February 2025
Revised date:
17 November 2025
Accepted date:
17 December 2025

Keywords:
Electroplating;
Nickel coating;
Gum additives;
Corrosion resistance;
Steel

Abstract

Low-carbon steels are widely used across various industries but have limited corrosion resistance, leading to safety hazards and a shortened service life. Nickel plating is a common method for enhancing steel corrosion resistance. The plating bath solution can be modified by adding additives to improve the properties of the coating. In this research, gum arabic, guar gum and gelatin were used as additives in a nickel electroplating bath. SS400 low-carbon steel, as a substrate, was plated with nickel from these different baths at 5 V for 25 min. Nickel coated with green additives showed higher hardness compared to those without additives, with the hardness of the coating using gum arabic measured at approximately 357 ± 6 HV. The morphology of the surface coating was characterized using SEM, which revealed that coating with gum arabic had a smooth surface, while those with gelatin and guar gum exhibited in an uneven or cracking surface, resulting in low hardness. The corrosion resistance was evaluated by immersing samples in a 3.5% NaCl solution. Nickel coatings with gum additives exhibited lower corrosion rates than those without. Among the additives, gum arabic demonstrated the best performance, producing the smoothest coating, the highest hardness, and the lowest corrosion rate.

1. Introduction

Low-carbon steel is widely used in industries due to its affordability, desirable mechanical properties and cost-effectiveness. However, it has low corrosion resistance particularly in aggressive environments [1]. This corrosion raises safety and environmental concerns, reduces service life, and increases the cost of replacing parts. Applying corrosion protection is essential to extend its service life, enhance performance, and ensure cost-effectiveness. Various methods have recently been developed to protect carbon steel from corrosion, including alloying, coating, cathodic protection, corrosion inhibitors and surface treatments [2]. Among all types of coatings, electroplating is the most economical. Moreover, it is a simple and effective technique with easily controlled process parameters to achieve desired surface properties. It is versatile and suitable for most types of surface coating [3]. Nickel electroplating is one of the most common coating used to improve both corrosion and wear resistance on carbon steel [4]. Among the industrial methods for nickel electrodeposition, Watts-type solutions are the most widely used baths. A previous study reported that nickel electroplating on carbon steel using a Watts bath improved hardness when applying a current density in the range of 10 $mA\cdot cm^{-2}$ to 50 $mA\cdot cm^{-2}$ at ambient temperature. The highest hardness value of 293 HV was achieved at a current density of 30 $mA\cdot cm^{-2}$ [5]. The primary components of a Watts bath include nickel sulfate, nickel chloride, and boric acid, with the option to incorporate various types of additives such as saccharin, benzene-sulphonic acid, allylsulphonic acid, coumarin and sodium lauryl sulfate. These additives are employed to enhance the morphology, mechanical properties, and appearance of the nickel coating [6,7]. For instance, the addition of saccharin to a nickel electroplating bath reduces the nickel grain size. These smaller grain sizes lead to smoother and more uniform coating layers [8]. Furthermore, organic additives such as glue, gelatin and gum have been widely used in electroplating baths due to their availability, affordability, and eco-friendly characteristics compared to other organic additives. Gelatin and gum have been studied as additives in electroplating process, enhancing coating quality by improving grain structure, surface morphology, and resistance to corrosion. Gelatin is a versatile organic additive in electroplating, enhancing grain refinement, improving surface smoothness, modifying morphology, and increasing corrosion resistance across various metal coatings including copper, tin, zinc electrodeposition [9-11]. Its effectiveness varies depending on the type of metal and specific operating conditions. The co-electrodeposition of nickel-based alloys have been investigated. Gelatin is shown to modify crystal size, enhances corrosion resistance, and significantly impacts the morphology of Ni–Co deposits [12]. On the other hand, gelatin slows the deposition rate of Re-Ni alloys by reducing internal stresses and preventing nuclei growth. It affects the morphology by causing grain coarsening, increasing surface roughness, and reducing crack size, with a small carbon presence attributed to gelatin absorption [13]. Additionally, gum arabic improves the catalytic properties of Ni–Mo coatings, enhancing their efficiency in hydrogen evolution reactions. Its application in oil pipelines contributes to longer reactor lifespans [14]. With increasing environmental concerns, eco-friendly electroplating processes have gained significant attention. Conventional nickel electroplating baths contain various chemical reagents that may cause environmental issues. Therefore, in this research aims to simplify the process and improve cost-effectiveness through an environmentally friendly approach while maintaining good coating performance particularly corrosion resistance on low-carbon steel. Gums including gum arabic and guar gum were employed as additives in a self-prepared nickel electroplating bath and compared with gelatin. The morphology of the coating, as well as physical, mechanical properties, and corrosion behaviors, were examined.

2. Experimental

2.1 Sample preparation

Low-carbon steel grade SS400 (composition : C ≤ 0.05 wt%, Mn ≤ 0.5 wt%, P ≤ 0.035 wt%, S ≤ 0.035 wt%, with the remainder being Fe) was used as the substrate material. Samples were prepared with dimensions of 20 mm in width, 40 mm in length, and 2.5 mm in thickness. A hole with a diameter of 3 mm was drilled into each sample to facilitate the attachment of copper wire. Each sample was ground sequentially with abrasive papers with grits sizes of 180, 320, 600 and 1200. Subsequently, the samples were polished with alumina powder of 1 µm and 0.3 µm, respectively, using a polishing cloth for finishing. The samples were then cleaned with acetone, followed by detergent cleaning in an ultrasonic cleaner at 50°C for 15 min. Next, the samples were immersed in hydrochloric acid for 5 s to activate the surface. Between each cleaning stage, the samples were rinsed with distilled water.

2.2 Electroplating process for nickel coating

The nickel electrolyte of the Watts bath type, with composition shown in Table 1 was prepared. A basic composition of the Watts electrolytic solution, consisting of nickel sulfate, nickel chloride and boric acid, was dissolved in distilled water with the pH maintained at 3.5. The nickel electrolyte solution was added to the bath, setting up the nickel electroplating system. The nickel anode severs as the positive electrode (anode), while the sample serves as the negative electrode (cathode), and both connected to a DC power supply. The distance between the nickel plate and the carbon steel was 3 cm apart. This certain distance can reduce voltage loss in the bath. The real potential of carbon steel is close to the power supply voltage, resulting in more uniform current distribution. Initially, an experiment was conducted on nickel electroplating without adding any additives to determine the optimal conditions. The study examined different parameters, including voltages of 2 V, 5 V, and 8 V, and plating times of 15 min, 20 min, and 25 min. The entire electroplating process was carried out at 40°C. Once the optimal nickel plating conditions are identified, 1 $g \cdot L^{-1}$ of each additive was added to the plating solution. The comparison of the nickel electroplating baths used in this research is shown in Figure 1.

2.3 Characterization

The hardness of the coatings was measured using a vickers micro-hardness tester. Microhardness was measured under a load of 980.7 mN or 100 gf for 15 s which is suitable for thick coating (~ 50 µm). The color of the coatings was examined using a colorimeter. The morphology of the coatings was inspected using an optical microscope (OM), a scanning electron microscope (SEM) and energy dispersive X-ray (EDX) analysis.

Immersion corrosion testing was conducted according to ASTM G31-72, following these procedures. The samples were first cleaned with acetone, rinsed twice with distilled water, dried and weighed. The samples were then immersed in a 3.5% sodium chloride solution at room temperature for 24 days in a closed system. With extremely caution while using 10% sulfuric acid (H_2SO_4) in an ultrasonic cleaner for rust removal, all specimens were dipped only for a very short period and then rinsed thoroughly to remove alkaline/acidic residues, dried and weighed again, with the weight recorded. The surface after corrosion was observed and recorded with stereo microscopes with camera every 3 days on each condition.

3. Results and discussion

3.1 Optimal nickel plating conditions

To establish the optimal conditions for the self-made nickel electrolytic solution, an initial experiment was conducted on nickel electroplating without the use of additives. Various parameters were tested, including voltages of 2 V, 5 V, and 8 V, as well as plating times of 15 min, 20 min, and 25 min.

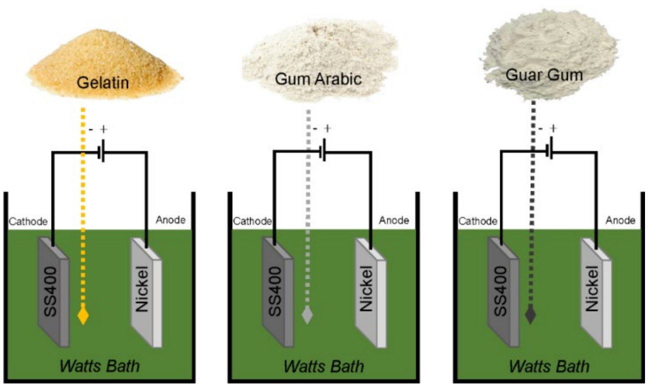


Figure 1. The nickel electroplating baths with different additives.

Table 1. The chemical composition of the Watts electrolyte for nickel electroplating.

Chemical composition	**Chemical formula**	**Composition [$g \cdot L^{-1}$]**
Nickel sulfate	$NiSO_4 \cdot 6H_2O$	250
Nickel chloride	$NiCl_2 \cdot 6H2O$	40
Boric acid	H_3BO_3	40
Additive	gum arabic, guar gum or gelatin	1

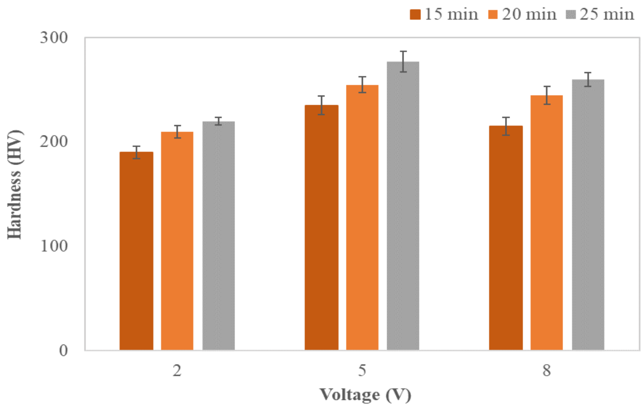


Figure 2. Hardness of nickel coatings at different voltages and plating times.

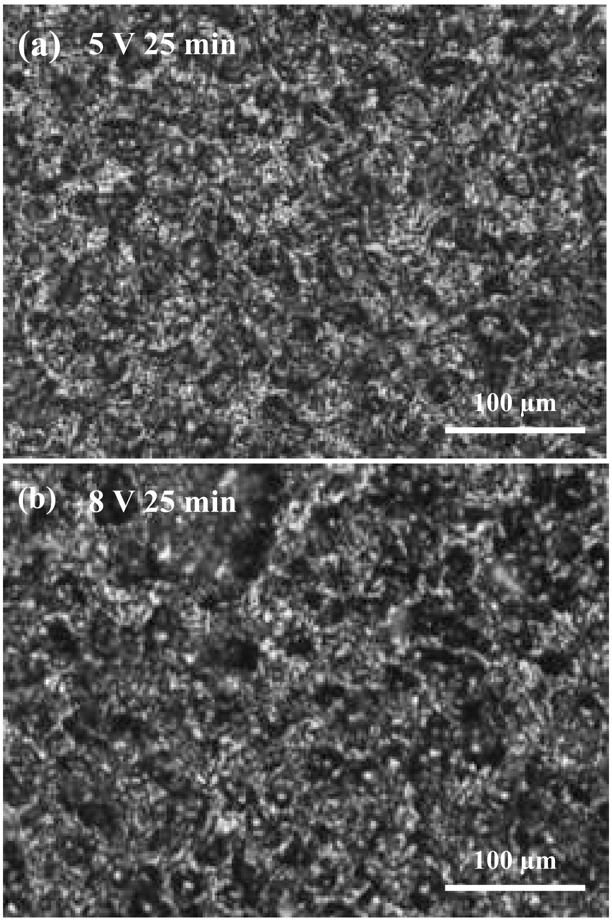


Figure 3. Surface morphology of nickel coating observed using an optical microscope at different voltages for 25 min (a) 5 V, and (b) 8 V.

The properties of the surface coating were evaluated through hardness testing. The hardness of nickel coatings under different voltages and plating times is shown in Figure 2. The results indicate that applying a voltage at 5 V produced the highest hardness values. Hardness tended to increase with longer plating times. The optimal condition was achieved at 5 V for 25 min, resulting in the highest hardness value of 277 ± 10 HV. However, at 8 V, the hardness decreased compared to that at 5 V. Observations using an optical microscope revealed that nickel coatings at 8 V exhibited increased porosity, as shown in Figure 3, which likely contributed to the reduced hardness. This finding is consistent with the work of Fan *et al.* [15], who reported that hardness decreased at higher voltages due to irregular morphology and increased porosity, the highest hardness was observed at lower voltages where porosity was minimal.

3.2 Effect of additives on nickel coating

After determining the optimal conditions for nickel plating, which were a voltage of 5 V for 25 min, the nickel plating process was carried out by adding various additives, including gelatin, arabic gum, and guar gum. The addition of additives resulted in higher hardness compare to the no-additive condition. The highest hardness was observed with gum arabic, yielding a value of 357 ± 6 HV, while gelatin and guar gum produced hardness values of 343 ± 4 HV and 335 ± 7 HV, respectively, as shown in Figure 4. According to previous studies, gum or gelatin inhibits nucleus growth, leading to grain refinement and higher hardness [9,11-14].

The surface characteristics of specimens were visually observed for nickel-coated samples with different additives, compared to samples without additives and without surface coating, using a voltage of 5 V for 25 min. It was found that the nickel-coated surface exhibited a bright, satin finish. When gelatin was used as an additive, the specimen had an uneven coating surface, and the color was inconsistent, possibly due to the yellowish color of the gelatin. With gum arabic as the additive, the specimen had a smooth coating surface. However, when guar gum was used, the coating surface appeared rough and cracked. As a result, as shown in Table 2. The addition of additives affected the color of the coatings, as shown in Table 3.

The morphological analysis of the surface of the nickel-plated steel with different additives, compared the no-additive condition, as shown in Figure 5. It was revealed that the addition of additives resulted in a more uniform surface compared to the no-additive condition. The nickel coating without additives had a rough surface with numerous pores. In contrast, the coating with gum arabic as additive exhibited the smoothest and most uniform surface. The coating with gelatin as additive showed a smooth surface, but when observed at 2000x magnification, slight roughness and small pores were present. The coating with guar gum had an uneven surface with cracks.

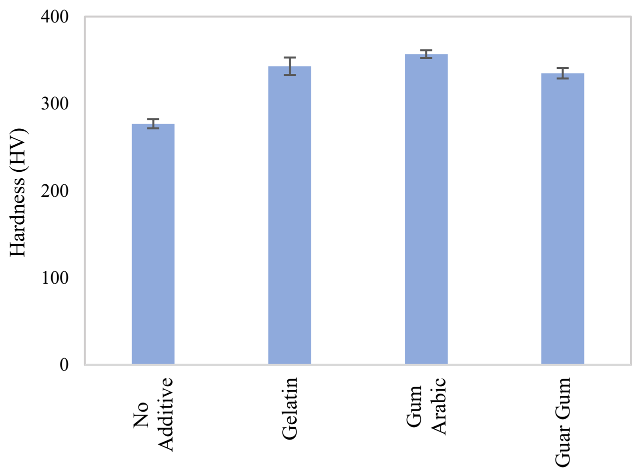


Figure 4. Hardness of nickel coatings with different additives, compared to no additive (plated at 5 V for 25 min).

Table 2. Surface characteristics of nickel-coated samples with different additives, compare to samples without additives and without surface coating (plated at 5 V for 25 min).

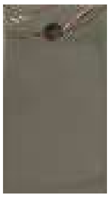
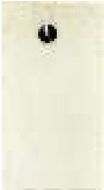
Without surface coating	Without additives	Different additives		
		Gelatin	Gum arabic	Guar gum
				

Table 3. The CIE Lab color values of the nickel coatings with different additives, compare to samples without additives (plated at 5 V for 25 min).

Conditions	CIE Lab		
	L*	a*	b*
Without additives	77.43 ± 2.59	2.76 ± 0.55	9.63 ± 0.87
Gelatin	40.13 ± 9.78	4.03 ± 3.35	3.53 ± 0.98
Gum arabic	19.33 ± 3.76	0.769 ± 0.55	0.90 ± 0.43
Guar gum	35.23 ± 4.95	1.24 ± 1.85	1.80 ± 0.45

Table 4. Chemical composition analysis of the surface coating with different additives.

	Element [wt%]		
	C	O	Ni
Gelatin	7.40	7.23	88.37
Gum arabic	7.97	4.74	87.29
Guar gum	7.35	7.30	85.35

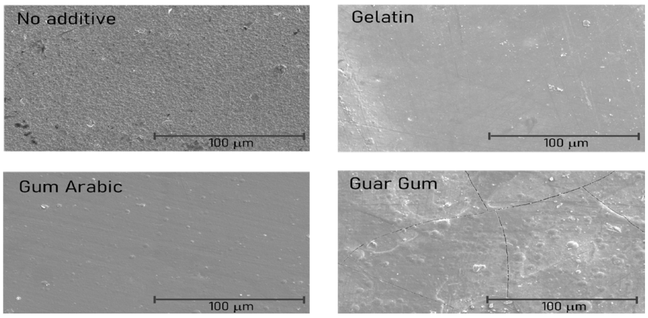


Figure 5. SEM images of the surface of the nickel-plated steel with different additives compared to without additives.

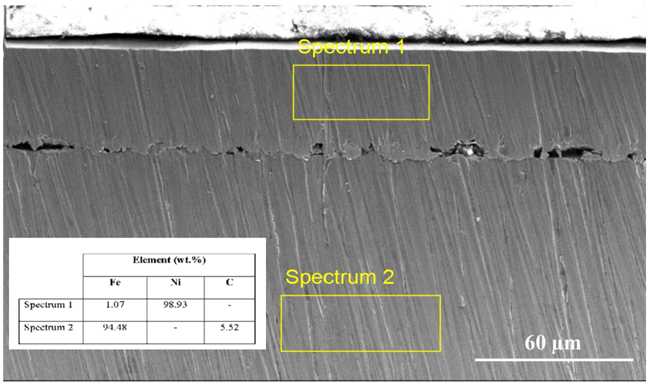


Figure 6. Cross-sectional area of the nickel-plated steel analyzed using the EDX technique for chemical composition.

The chemical composition analysis using the EDX technique on the cross-sectional area of the nickel-plated steel revealed that spectrum 1 mainly consisted of nickel, while spectrum 2 indicated the presence of iron and carbon. This confirms that the coating on the low-carbon steel is primarily composed of nickel, as shown in Figure 6. The coating thickness, measured using the ImageJ, was found to average 45.791 ± 2.538 µm. The surface coating with different additives were also analyzed for chemical composition using the EDX technique, as shown in Table 4. The results showed that the coating mainly contained nickel, along with carbon and oxygen. This indicates that the coating contains additives as part of its composition. According to previous studies, gum and gelatin contain functional groups such as –OH, –COOH, $–NH_2$ and –C–O–C– which adsorb and partially decompose on the cathode surface. The resulting carbon and oxygen are incorporated into the nickel coating, leading to grain refinement, increased hardness and a smoother surface morphology [6,13].

The corrosion testing was conducted by immersing the uncoated specimens, the nickel-plated specimens, and the nickel-plated specimens with gum additives into a 3.5% sodium chloride solution for 24 days. Observations and test results were recorded every 3 days. Figure 7 illustrated the relationship between weight loss after immersion in a 3.5% sodium chloride solution. It was found that nickel coatings containing additives exhibited reduced corrosion rates compared to those without additives and the uncoated specimen, particularly after 24 days. Using gum arabic as an additive in the nickel coating resulted in the lowest weight loss.

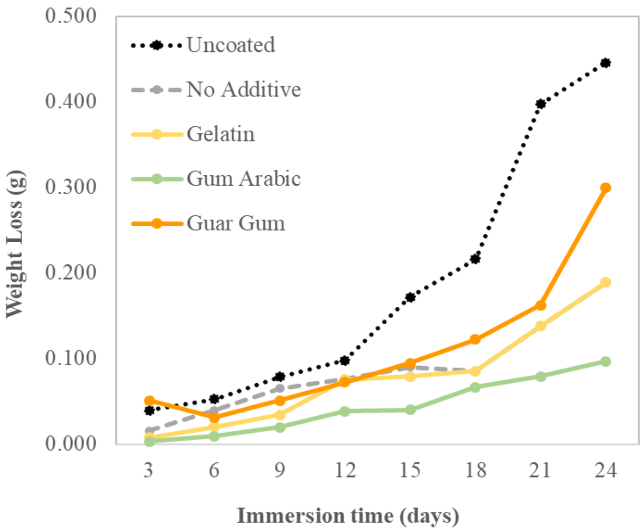


Figure 7. Weight loss of nickel coating with different additives compared to without additives and uncoated, after immersion in 3.5% NaCl solution.

4. Conclusions

A self-made nickel electrolytic solution was successfully prepared. The optimal condition for nickel plating, set at 5 V for a duration of 25 min. Nickel plating with additives significantly improved surface properties and morphology including hardness, smoothness, and uniformity compared to coatings without additives. Among the additives evaluated, gum arabic demonstrated the best performance, providing the highest hardness (357 ± 7 HV), the smoothest surface, and the lowest corrosion rate in a 3.5% sodium chloride solution after 24 days. These findings confirm the effectiveness of gum arabic as an additive for enhancing the quality and durability of nickel coatings. It is an economical and effective alternative for improving corrosion resistance in low-carbon steel.

Acknowledgements

The authors extend their heartfelt gratitude to the Department of Materials Science, Faculty of Science, Srinakharinwirot University, for their financial support. We also wish to express special thanks to Mr. Ghit Laungsopapun from the Thailand Institute of Scientific and Technological Research for his invaluable assistance with SEM.

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