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# Tribological and Corrosion Properties of Nickel Coatings on Carbon Steel

*Wear and corrosion are the main problems in mechanical elements in mechanical contact, and as a consequence there are economical losses. To enhance the tribological properties of the metallic materials, nickel coating has found a wide application in aerospace, automobile, chemical industries, and other. In this research, nickel coatings on carbon steel substrate were developed using nickel sulfamate bath and Watts nickel bath to obtain homogeneous electrodeposits, good adherence and non-porous material. The thickness of the nickel coatings obtained was 35.75 μm using the Watts nickel bath and 26.88 μm with the nickel sulfamate bath. In order to analyze the influence of the nickel coating, an experimental investigation of the sliding wear and corrosion properties of the coated specimens was carried out. The hardness of the nickel sulfamate bath coated surfaces was approximately 2.7 times higher than the surfaces without coating. The results suggest that the coated surfaces presented better properties including high hardness, good wear resistance, and good corrosion resistance.*

**Keywords:** *tribological properties, nickel electrodeposits, corrosion, wear, nickel coating.*

## 1. INTRODUCTION

Wear occurs during the operating between two contact surfaces. For wear resistance, coating [1-5] is a good alternative to protect the surfaces of the material when operating temperatures are very high, and when the operating time is long.

Electroless nickel coatings [5-8] based on the bath types have been progressively applied to a wider variety of applications in industry. Several researchers [4,6,8,9] have investigated the application of different electroless nickel coatings. They have observed that the nickel coating improved the tribological properties and protect the material surfaces in mechanical contact. In addition, the coating process can provide properties to reduce the stresses, to improve the adhesion and the corrosion resistance. The review about this coating technique suggests that the electroless coatings are mainly applied for wear and corrosion resistance applications. Due to the popularity of electroless nickel coatings, more advanced tribological applications have been investigated.

In this research, nickel coatings on 4140 carbon steel specimens were developed using nickel sulfamate bath and Watts nickel bath to obtain homogeneous electrodeposits, good adherence and non-porous material. In order to analyze the influence of the nickel coating, an experimental investigation of the tribological sliding wear and chemical properties of the coated specimens was carried out.

Received: April 2015, Accepted: July 2015
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**doi:10.5937/fmet1503206V**

## 2. COATING PROCEDURE

The coatings were prepared using two methods: Watts nickel bath and sulfamate nickel bath [10,11]. The main components for the Watts nickel bath are shown in Table 1.

**Table 1. Watts nickel bath components**

| Components | [g/l] |
|---|---|
| Nickel sulfate | 330 |
| Nickel chloride | 45 |
| Boric acid | 37 |

Table 2 shows the main components of the sulfamate nickel bath.

**Table 2. Sulfamate nickel bath components**

| Components | [g/l] |
|---|---|
| Nickel sulfamate | 800 |
| Nickel chloride | 30 |
| Boric acid | 30 |

The components were mixed with 250 ml deionized water using an agitator (80 rpm) in order to dissolve completely all the components. The dissolved components were filtered. The bath temperature was 40 °C and the pH value was 5. The cathode current density was 3 A/dm$^2$. After this process, the coating was ready to deposit on the surfaces of the specimens. The time of the deposition process was 60 minutes.

The material selected to fabricate the test specimens was 4140 carbon steel. The geometry and the dimensions of the specimens are shown in Figure 1. The specimen illustrated in Figure 3a was used for the corrosion tests and Figure 3b shows the specimen test pin used for the sliding wear tests.

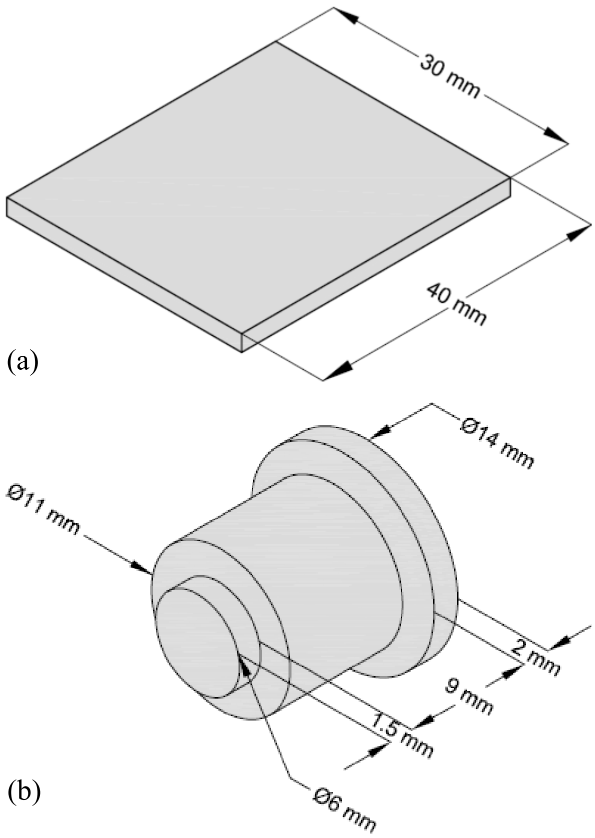


**Figure 1. Specimens for: (a) corrosion tests and (b) sliding wear tests**

Before the coating process the specimen surfaces were cleaned, dried and polished. Then the specimens were weighted.

## 3. EXPERIMENTAL TESTS

The characterisation of the hardness of the coated surfaces of the specimens was carried out according to the ASTM E140 [12], using a micro durometer Buehler Lake Bluff, Illinois, USA. The applied loads for this test were 100, 200 and 300 gf and the testing time was 15 s.

The equipment used to evaluate the adhesion of the coating on the 4140 carbon steel specimen was an electometer 105, which used araldite AV-100. The evaluation was carried out according to the standard ASTM D4541 [13].

Corrosion resistance of the coated specimens was evaluated using the anodic polarization method [14-16]. The equipment used for the corrosion tests was ACM Instruments Gill AC instrument 654, which was connected to electrochemical cell. The corrosive solution selected was phosphoric acid (70 % $H_3PO_4$), the pH value was 1.5 at ambient temperature.

Tribological test was carried out according to ASTM G99 standard [17]. The pin-on-disk wear tester, used in this research, is illustrated in Figure 2, which consists of (1) revolution counter, (2) selector of speed, (3) disk holder and lever arm (4), loads (5), (6) load cell, (7) counter weight, (8) data base computer, (9) interface and (10) pin specimen. This equipment was designed by the tribological group of SEPI ESIME ZAC of the Nacional Institute Polytechnic of Mexico.

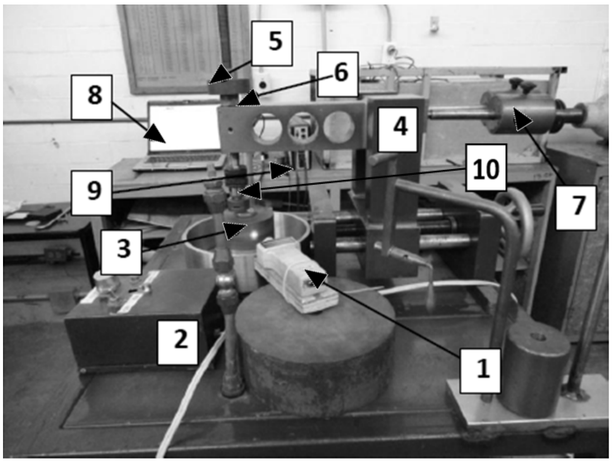


**Figure 2. Pin-on-disk tester**

This tester was used to investigate the wear process under sliding conditions. The test was performed on: (a) 4140 carbon steel pin without coating, (b) coated pin with Watts nickel bath, and (c) coated pin with nickel sulfamate bath.

This investigation was carried out with a normal force of 5 N (≈ 0.2 MPa), which was applied against the surface of the stainless steel 304 rotary disk. Circular wear scar was generated on the disk. Table 3 shows the wear test conditions in dry condition at ambient temperature between 22 to 24 °C.

**Table 3. Wear test conditions**

| Parameters | Value |
|---|---|
| Velocity | 0.95 m/s |
| Rotational speed | 200 rpm |
| Load | 5 N |
| Time | 600 s |

The friction coefficient was predicted by the ratio of the frictional force to the load on the pin specimens. Wear was quantified by measuring the amount of the material removed.

## 4. RESULTS

### 4.1 Specimens obtained by coating nickel bath types on 4140 carbon steel

**Watts nickel bath**

The specimens coated by nickel bath types are shown in Figure 3.


**Figure 3. Specimens coated for: (a) corrosion tests and (b) tribology tests**

Tables 4 and 5 show the weights of the specimens before and after the coating process by using the Watts nickel bath.

**Table 4. Weights of the specimen pin uncoated and coated with Watts nickel bath for tribology tests**

| Specimen | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | Weights [g] | | | | |
| Uncoated | 9.02 | 8.88 | 8.94 | 8.96 | 8.74 |
| Coated | 9.23 | 9.07 | 9.14 | 9.17 | 8.94 |

**Table 5. Weights of the specimen pin uncoated and coated with Watts nickel bath for corrosion tests**

| Specimen | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | Weights [g] | | | | |
| Uncoated | 5.50 | 5.60 | 5.50 | 5.64 | 5.35 |
| Coated | 5.75 | 5.85 | 5.73 | 5.87 | 5.60 |

**Nickel sulfamate bath**

The weights of the specimens before and after the coating process by using the nickel sulfamate bath are illustrated in Tables 6 and 7.

**Table 6. Weights of the specimen pin uncoated and coated with nickel sulfamate bath for tribology test**

| Specimen | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | Weights [g] | | | | |
| Uncoated | 9.11 | 8.94 | 8.95 | 8.80 | 8.93 |
| Coated | 9.31 | 9.14 | 9.15 | 9.01 | 9.14 |

**Table 7. Weights of the specimen uncoated and coated with nickel sulfamate bath for corrosion test**

| Specimen | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | Weights [g] | | | | |
| Uncoated | 5.53 | 5.66 | 5.35 | 6.58 | 5.50 |
| Coated | 5.78 | 5.90 | 5.59 | 6.79 | 5.75 |

From the results it can be observed that the coated specimens, with Watts nickel bath and nickel sulfamate bath, for tribology tests have been increased approximately 0.2 g and the specimens for corrosion tests have been increased 0.24 g.

### 4.2 Coating thickness

The thickness of the coating was measured according to ASTM B689 Standard, which were between 35.25 and 35.75 μm for the Watts nickel bath and from 25.15 to 26.88 μm for the nickel sulfamate bath.

### 4.3 Hardness tests

Table 8 shows the comparison of the hardness obtained from the Vickers technique. For this comparison 4140 carbon steel pin specimen uncoated, 4140 carbon steel pin specimen coated with Watts nickel bath, and 4140 carbon steel pin specimen coated with nickel sulfamate bath were used.

**Table 8. Results of the hardness**

| | Hardness HV | | |
|---|---|---|---|
| Load [gf] | 4140 carbon steel pin specimen uncoated | Pin specimen coated (Watts nickel bath) | Pin specimen coated (Nickel sulfamate bath) |
| 100 | 247 | 254 | 745 |
| 200 | 166 | 171 | 421 |
| 300 | 166 | 187 | 387 |

The comparison showed that pin specimen coated with nickel sulfamate bath had the highest hardness between 34 % and 48 % higher than the pin specimen coated with Watts nickel bath, and from 33 % to 42 % higher than pin specimen uncoated.

### 4.4 Adhesion

The results suggest that the coating bath type has shown good adhesion to the 4140 carbon steel pin specimen up to 15 $kg/cm^2$ with the Watts nickel bath and 12 $kg/cm^2$ with nickel sulfamate bath. After those loads the coating started to be detached from the carbon steel pin specimen.

### 4.5 Tribological tests

The sliding wear properties have been analysed for 4140 carbon steel pin specimens uncoated, 4140 carbon steel pin specimens coated with Watt nickel bath, and 4140 carbon steel pin specimens coated with nickel sulfamate bath, using a pin-on-disk tester at constant load of 5 N (≈ 0.2 MPa), the test time was 600 s, the velocity was 0.95 m/s, the rotational speed was 200 rpm, and the wear track radius was 0.047 m.

The tests were carried out at ambient temperature from 22 to 24 °C in dry condition. The material of the disk was stainless steel 304. Table 9 shows the results of sliding length ($L$), wear volume loss ($V_w$), wear rate ($Q$), wear factor ($K$), friction force, ($F_f$) and friction coefficient (μ).

Figures 4, 5 and 6 show the friction force as a function of the time. From figure 4 it can been seen that there are large and irregular fluctuations of the friction force during the sliding test. In addition, it is observed that the friction coefficient of 0.96 is found under the values reported by the literature.

The results shown in Figures 5 and 6 suggest that the coating with Watts nickel bath protected for a short time, approximately 20 seconds, the 4140 carbon steel pin specimen surfaces. While the coating nickel sulfamate bath presented more sliding wear resistance, which resists up to 250 seconds. Therefore, the friction force and friction coefficient were smaller than the coated pin specimen with the Watts nickel bath and the pin specimen uncoated, as it can be seen in Table 9.

**Table 9. Results of the sliding tests [18]**

| Pin specimen | $L$ [m] | $V_w$ [$mm^3$] | $Q$ [$mm^3/m$] | $K$ [$mm^3/Nm$] | $F_f$ [N] | μ |
|---|---|---|---|---|---|---|
| Specimen uncoated | 579.42 | 0.95 | 0.00160 | $3.2 \times 10^{-4}$ | 4.79 | 0.96 |
| Specimen coated (NSB) | 579.42 | 0.20 | 0.00034 | $6.8 \times 10^{-5}$ | 4.22 | 0.84 |
| Specimen coated (WNB) | 579.42 | 0.30 | 0.00051 | $1.0 \times 10^{-4}$ | 4.39 | 0.87 |

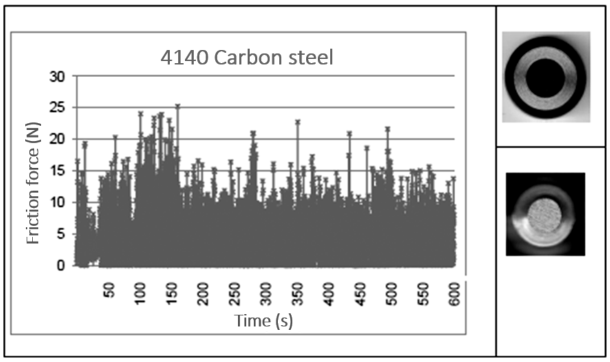


**Figure 4. Friction force of the 4140 carbon steel pin specimen uncoated as function of the time [18]**

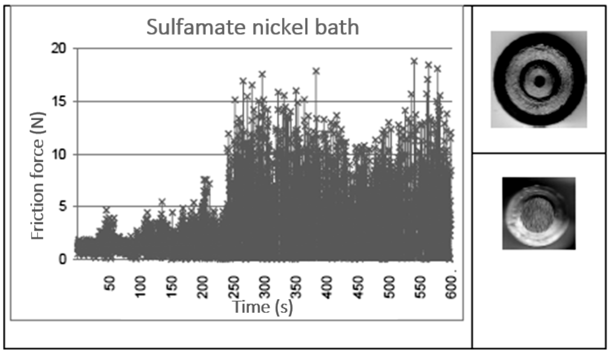


**Figure 5. Friction force of the 4140 carbon steel pin specimen coated with sulfamate nickel bath as function of the time [18]**

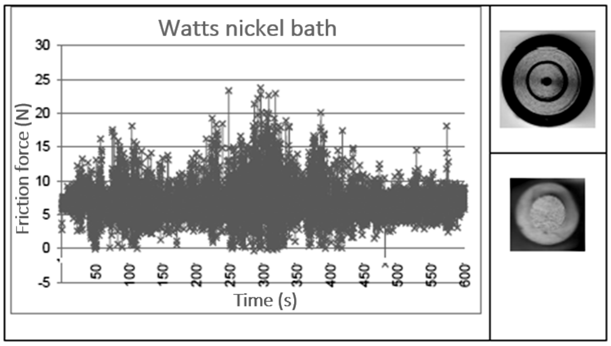


**Figure 6. Friction force of the 4140 carbon steel pin specimen coated with Watts nickel bath as function of the time [18]**

### 4.6 Corrosion tests

The comparison of the results obtained from the corrosion test of the 4149 carbon steel, the coated carbon steel with Watts nickel bath and coated carbon nickel sulfamate bath are shown in Table 10. From the results it can be observed a high polarization with coating nickel. The coated 4140 carbon steel with nickel sulfamate bath presented the highest resistance to the polarization and as a consequence the corrosion velocity was the lowest.

## 5. CONCLUSIONS

The main conclusions of this research are summarised below.

The thickness of the coating was between 35.25 and 35.75 μm for the Watts nickel bath and from 25.15 to 26.88 μm for the nickel sulfamate bath.

**Table 10. Tafel polarization to determine the corrosion velocity [18]**

| Specimen | $R$p [Ω/cm$^2$] | $B$a [mv] | $B$c [mv] | $I_{corr}$ [μA/cm$^2$] | $V$c [mm/y] |
|---|---|---|---|---|---|
| Uncoated | 10.95 | 233.11 | 238.75 | 4.68 | 40.21 |
| Coated (WNB) | 62.93 | 109.73 | 95.32 | 0.35 | 0.05 |
| Coated (NSB) | 1756.90 | 94.351 | 155.50 | 0.014 | 0.008 |

$R$p: polarization resistance; $I_{corr}$: corrosion rate; $V$c: corrosion velocity; $B$a: anodic Tafel slope; $B$c: cathodic Tafel slope.

The best results of the adhesion of the coating on the 4140 carbon steel pin specimen with the Watts nickel bath was up to 15 kg/cm$^2$ and 12 kg/cm$^2$ with nickel sulfamate bath. After those values the coating started to be detached from the carbon steel pin specimen.

The pin specimen coated with nickel sulfamate bath had the highest hardness between 34 % and 48 % higher than the pin specimen coated with Watts nickel bath, and from 33 % to 42 % higher than pin specimen uncoated.

The results suggest that the coating nickel bath type on a 4140 carbon steel pin specimen improved the hardness of the surfaces. Therefore, the wear and corrosion resistance is higher than the pin specimens uncoated.

From the results was observed that the wear resistance and the friction coefficient values increase when the hardness of the pin specimens is higher.

## ACKNOWLEDGMENT

The authors wish to thank the National Institute of Nuclear Investigations and the National Institute Polytechnic of Mexico, for the financial support to carry out this work through the project SIP No. 20150075.

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## ТРИБОЛОШКЕ И КОРОЗИОНЕ КАРАКТЕРИСТИКЕ ПРЕВЛАКА НИКЛА НАНЕТИХ НА НИСКОЛЕГИРАНИ ЧЕЛИК

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Хабање и корозија су главни проблеми који се јављају код машинских елемената који су у релативном кретању и контакту, што као последицу има економске губитке. Превлаке никла су, захваљујући побољшању триболошких карактеристика металних материјала основе, нашле широку примену у авио, аутомобилској, хемијској и другим индустријама. Превлаке никала, испитиване у овом раду, су електрохемијски нанете на основу од нисколегираног челика коришћењем Ватовог односно сулфаматног купатила. Добијене су непорозне превлаке са добром чврстоћом везе са основом. Дебљине добијених превлака никла су биле 35,75 μm (Ватово купатило) односно 26,88 μm (сулфаматно купатило). Тврдоћа узорка са превлаком нанетом из сулфаматног купатила је била око 2,7 пута већа од тврдоће основног материјала. Извршена су и експериментална испитивања триболошких и корозионих карактеристика добијених превлака. Триболошка испитивања су била у условима клизања. Резултати показују да се наношењем превлака углавном добијају боље триболошке карактеристике (мање трење и хабање), уз већу тврдоћу и бољу отпорност на корозију.