

ELECTRODEPOSITION OF NICKEL ON HEAT-TREATED LOW CARBON STEEL FOR YAM POUNDING BEATER

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This work focused on the mechanical and corrosion behaviors of electroplated nickel on heat-treated low carbon steel serving as an alternative to austenitic stainless steel for the yam beater in a yam pounding machine. Four standard samples were prepared for electrodeposition from the steel samples by heating to a temperature of 920°C with a 60-min holding time. One of the samples was air-cooled while the remaining three were quenched in H₂O and later tempered at 450°C, 550°C and 650°C for 60 min. After the heat treatment process, the ultimate tensile strength, toughness, and microhardness of the samples were obtained. Nickel electrodeposition was later carried out on the heat-treated mild steel using Watt standard bath concentration. Optical Microscopy (OM) and Scanning Electron Microscope equipped with energy dispersion spectroscopy (SEM/EDS) were used for the characterization of the heat-treated and nickel-electrodeposited samples. More so, the electrochemical behavior of the nickel-plated samples was studied in a yam fluid environment using the potentiodynamic polarization technique. X-ray fluorescence (XRF) was used to analyze the chemical and oxide composition of the samples. The results showed that among all the heat treatment operations, the sample heat-treated at 920°C and tempered at the highest tempering temperature of 650°C gave the highest toughness value (102 MJ/m³) when compared with stainless steel at 124 MJ/m³. The sample heat-treated at 920°C and tempered at 550°C displayed a corrosion rate of 0.022182 mm/yr as against the stainless steel sample with a value of 0.0031864 mm/yr. From the analysis, the nickel deposited on the heat-treated samples enhanced corrosion resistance in the yam fluid. XRF analysis of the yam before pounding, after processing with nickel electroplated, and stainless beaters shows the content of nickel as 0.0941%, 0.109%, and 0.1113%, respectively. It was concluded that the materials for the yam pounding beater, therefore, perform better if they were both heat-treated and nickel-plated. Invariably, stainless steel could be successfully replaced with heat-treated and nickel-plated mild steel for use as a yam pounding beater.

Keywords: Yam pounding beater; toughness; nickel plating; surface morphology; corrosion assessment.

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1. Introduction

Over the years, attention has always been drawn to the aesthetic and excellent performance of engineering materials which have a wide range of opportunities for surface modification as a method for combination of corrosion resistance along with high strength, hardness, and wear resistance.¹ One of the various methods of surface modification is electrodeposition. It is a process of modifying the surface properties of a metal part to impact corrosion resistance, hardness, and other mechanical properties.² However, the electrodeposition of nickel is a common surface finishing process that is commercially used to provide decorative, corrosion, and wear resistance. This is to ensure a better service life of most engineering components. According to Nigam *et al.*,³ nickel plating finds numerous applications mostly in the chemical and food processing industries. It is used as a coating agent since its properties can be controlled, varied over broad ranges as well as it prevents corrosion. For decades now, metallic materials have been given prominent consideration in designing and handling of agro-based machine, most especially for food processing. As a result, metallic materials have been used in the design of food processing and packaging machines such as pounded yam in Nigeria.⁴⁻⁷ However, the issue of corrosion has been a great challenge in the food processing industries, leading to the loss of production time and the risk of equipment failure.⁸⁻¹¹ There is also an additional risk of food contamination by corrosion products which certainly may result in food poisoning.¹¹ Foodstuffs are known to contain various chemicals that are mostly organic. However, when these chemicals are not prevented, they could become substrates, thus aiding corrosion due to microbial activities caused by the formation of chemical oxides or products that are aggressive to metallic material.¹¹

Stainless steels have been a standard for the fabrication of food processing equipment due to its corrosion resistance, mechanical strength, weldability, and formability.¹² However, the high cost of this material has been a setback in its consistent usage for food processing and packaging machines by local fabricating firms. In Nigeria, there has been an increase in the local fabrication of food processing equipment using materials that are not stainless steel to reduce cost and encourage the use of our

indigenous materials, thus making them attractive to the food processing needs. Low carbon steel (LCS) is an indigenous material, readily available, and cheaper compared to stainless steel. It can be modified to serve the same purpose the stainless steel had been known for. However, due to the relatively high corrosion rate of uncoated LCS, it is unsuitable for use in food processing, especially in a wet environment. Oluwole and Olorunfemi¹³ investigated the corrosion behavior of nickel-plated medium carbon steel in cocoa liquor and concluded that nickel-plated steel was found suitable for use in protecting steel equipment. The corrosion behavior of nickel-plated LCS in tomato fluid was also studied.¹⁴ The study reported that thick nickel coating was observed to offer protection in tomato fluid environment since corrosion was much less when nickel-coated steel was compared with the uncoated steel. However, little research has been recorded on the electrodeposition of nickel-plated steel for the yam beater application. A yam beater is a rotor that pounds the boiled yam into a smooth paste using a rotating part that results in the final product, pounded yam. Due to constant rotation, turning, and bending of the yam beater, the material is expected to be tough and corrosion-resistant.

Enhancing the corrosion resistance, aesthetic value, and high level of hygiene needed in the manufacturing of food processing equipment and storage are essential in the use of LCS. Therefore, carrying out an appropriate heat treatment and applying the process of electrodeposition of nickel on the steel is necessary. Hence, this research focuses on the surface modification of heat-treated LCS by nickel-plating to replace stainless steel in yam pounding beater. This study is an integral part of our research which seeks to examine morphology, oxide compositions, and corrosion resistance performance of electrodeposition of nickel on heat-treated LCS for yam pounding beater.

2. Experimental Set-Up

2.1. Materials

A flat bar of dimension 180 mm length, 25 mm width, and 6 mm thickness LCS and austenitic stainless steel (ASS) were sourced from dock yard, Ibadan, Oyo State, Nigeria. Tables 1 and 2 show the chemical

Table 1. Chemical composition of LCS sample.

Element	C	Si	Mn	P	S	Cr	Ni	Ti
Average content	0.182	0.185	0.572	0.041	0.032	0.106	0.107	0.0001
Element	Cu	Nb	Al	B	W	Mo	V	Fe
Average content	0.241	0.007	0.0001	0.002	0.027	0.002	0.0001	98.496

Table 2. Chemical composition of the stainless-steel sample.

Element	C	Si	Mn	P	S	Cr	Ni	Ti
Average content	0.08	0.617	2.237	0.1	0.075	12.141	7.809	0.058
Element	Cu	Nb	Al	B	W	Mo	V	Fe
Average content	0.953	0.074	0.025	0.006	0.144	0.527	0.197	74.957

compositions carried out at Universal Steel Limited, Lagos, Nigeria.

2.2. Heat-treatment operations (quenching, normalizing, and tempering)

The LCS and the ASSs were machined to standard following ASTM E36 specifications on standard tensile sample dimensions. Four flat tensile test pieces were heated to 920°C and held for 60 min in a muffle furnace. One of the samples was air-cooled while the remaining three were quenched in water, then they were tempered at 450°C, 550°C, and 650°C, respectively. Tensile test and micro-hardness test were carried out on the heat-treated samples using Instron universal tensile testing machine (Model: 3369) and micro-hardness tester (Model: LM-700AT), respectively. The entire tests were carried out on the samples for each heat-treatment process. This was done to establish the process that gives the best toughness.

2.3. Fabrication of the yam pounding beater

The yam pounding beater, which is the rotor that churns the yam into a smooth paste, is made up of blades and complementary shafts, which allow free rotation. The locally sourced LCS (flat bars) were marked out with a scribe and cut to size (70 mm length, 25 mm width, and 6 mm thickness) using a hacksaw to form two sets of beaters. An LCS electrode was used to weld the parts together to form the

beater. A thread of 2-mm pitch was made inside the bored shaft using a tapping tool. The beaters fabricated were later welded to the complementary shaft that had been machined to size using an electric arc welding machine to form the yam beater assembly.

2.4. Heat treatment of the yam pounding beater (quenching and tempering)

The yam beater produced was heated to 920°C and held for 60 min in a muffle furnace after which it was quenched in water. It was later re-heated to 650°C and held for another 60 min and cooled in air to improve the toughness.

2.5. Mechanical properties tests

A universal testing machine (Model No.: Instron 3369) was used to perform the tensile test. Each specimen was mounted on the testing machine and pulled monotonically at a strain rate of 10^{-3} s^{-1} until failure/fracture based on the ASTM E8/E8M-16ae1 (2016) standard. The test was conducted in triplicates for data reliability. The modulus of elasticity was determined using the stress-strain graph obtained from the tensile test. The hardness value of the samples was determined using a Vickers hardness tester with an indenter diameter of 5 mm. An applied load of 5 kN was used with a dwelling time of 30 s on each specimen. Six indentations were made on each sample, and the average was used in the determination of the hardness value by dividing the load applied by the surface area of the average value of

indentations. The Izod test was carried out by a pendulum-type testing machine which employs a standard square impact test sample measuring $75 \times 10 \times 10$ mm with a notch angle of 45° and a notch depth of 2 mm.

2.6. Sample preparation for electrodeposition (grinding and polishing)

For good and proper adhesion of nickel deposit on the yam beater, it was ground and polished. Emery papers with grit sizes 60, 120, 400, and 1200 were plastered onto the surface of an angle grinder for easy grinding of the beater. This was done one after the other to grind the surface consecutively. A polishing cloth was also plastered on the surface of the angle grinder to polish the beater. Alongside, six other samples with 20 mm length, 20 mm width, and 5 mm thickness being representatives of various tempering temperatures (450°C , 550°C , and 650°C), normalized and control samples were ground and polished. Both the SBT Model 900 grinder polisher and Metaserv 2000 grinder polisher were used with emery papers of grits 60, 120, 320, 400, 800, 1200 and polishing cloth consecutively. These six samples were prepared alongside with the yam beater for nickel electrodeposition to study the morphology of the deposit and the corrosion assessment.

2.7. Microstructural and chemical analysis

All samples were polished to have a smooth and uniform surface before the commencement of metallographic analysis. The samples were cut and prepared for metallographic examination with strict adherence to standard procedures as stipulated in ASTM ES +1. The morphology of the coatings was studied using a Scanning Electron Microscope (Phenom pro X Model No: 800-07334) equipped with an energy dispersion spectroscopy (SEM/EDS) detector. More so, chemical analysis of the yam before and after pounding with a nickel-plated beater was carried out using X-ray fluorescence (XRF). Significantly, this was done to investigate the probable effect of nickel injection in the yam after pounding, thus to ascertain the safety content of the food.

2.8. Pre-plating operation and electro-deposition of nickel on the yam beater (nickel plating)

The yam beater and the six test pieces were hung with copper wire. They were pickled in hydrochloric acid (HCl) for 2 min before rinsing in water. After this, anodic cleaning in a solution of hot (90°C) concentrated sodium carbonate — 8 g/L, sodium hydroxide — 10 g/L, and Trisodium phosphate — 12.5 g/L was done for 10 min. All the samples were later rinsed in water before undergoing the plating process. Nickel was then deposited on the heat-treated LCS substrates by a constant current electrodeposition technique. The LCS substrate served as the cathode while the anode was nickel. The beater and the test pieces were weighed with a digital weighing machine to note the initial weight (m_1) of each sample before plating. All the samples were later dipped in the main nickel tank solution for 35 min and then rinsed in water before drying in the air. The final weight (m_2) was then taken for each sample. Table 3 shows the nickel solution composition utilized.

2.9. Electrochemical behavior of the nickel plating

After the specimens were ground to smooth surface finish with various grit SiC papers and polished, the specimens were ultrasonically cleaned in yam fluid (pH = 5.5) at 80°C temperature with the aid of an EG & G Potentiostat Galvanostat Instrument for corrosion test. The electrochemical behavior of the produced nickel-coated LCS specimens was

Table 3. Nickel solution composition.

Composition	Concentration
Nickel sulfate	250–300 g/L
Nickel chloride	40–60 g/L
Nickel anode	Pure 99.99%
Boric acid	30–60 g/L
Nickel brightener	0.1–0.5 ml/L
pH	3.80–5.5
Plating time	20–45 min
DC rectifier	20–500 amps
Voltage	0.5–12 V
Temperature	35–60°C
Filtration	Constant filtration

investigated using an Autolab Potentiostat (PGSTAT302), which is computer-controlled. The experiments were conducted using the three-electrode corrosion cell setup with a saturated silver/silver chloride electrode (Ag/AgCl) (3 M KCl) as a reference electrode. A graphite rod served as a counter electrode and the sample as the working electrode. The corrosion potential (E_{corr}), corrosion current density (I_{corr}), polarization resistance (R_p), and corrosion rate were calculated using the Tafel extrapolation method. A scan rate of 0.2 mV/s was initiated at a potential range between -1.0 V and 2.0 V.

3. Results and Discussion

3.1. Effect of heat treatment on ultimate tensile strength of LCS

Figure 1 shows that the ultimate tensile strength (UTS) varies from one heat-treatment process to the other. The air-cooled sample gives the least UTS value of 305.5 MPa. The samples heat-treated at 920°C and tempered at different temperatures of 450°C, 550°C, and 650°C give the UTS values of 622.0 MPa, 561.1 MPa, and 642.2 MPa, respectively. The UTS value (642.2 MPa) of the sample heat-treated at 920°C and tempered at 650°C was observed to be the highest. The UTS value of the stainless steel (621.9 MPa) was more compared with the as-received sample (control) of 367.8 MPa but lower than the UTS value for the heat-treated and tempered sample. The increase in the UTS resulted

from high tempering temperature, which reverts the original martensitic structure (got from quenching) to ferrite cementite mixture. Hence, this improves the toughness property, which is usually the combination of strength and ductility.

3.2. Effect of heat treatment on Young's modulus of elasticity of low steel

The Young's modulus of elasticity of the samples, as shown in Fig. 2, revealed that the sample heat-treated at 920°C and tempered at 450°C gives the maximum value of 4873.9 N/mm². However, the value reduced drastically to 2873.9 N/mm² as the tempering temperature increased to 550°C but later rose to 4468.8 N/mm² following the increase in the tempering temperature to 650°C. This shows that the tempering temperature affects the stiffness of the sample. Also, the close range between the modulus values of tempered samples (450°C and 650°C) and stainless steel with modulus value of 5087.7 N/mm² indicates that tempering operation, especially at high tempering temperature, improves the ductility, toughness, and stiffness of the sample.

3.3. Effect of heat treatment on toughness of LCS

Toughness values of heat-treated LCS as against various heat treatment operations show that the sample heat-treated at 920°C and tempered at the

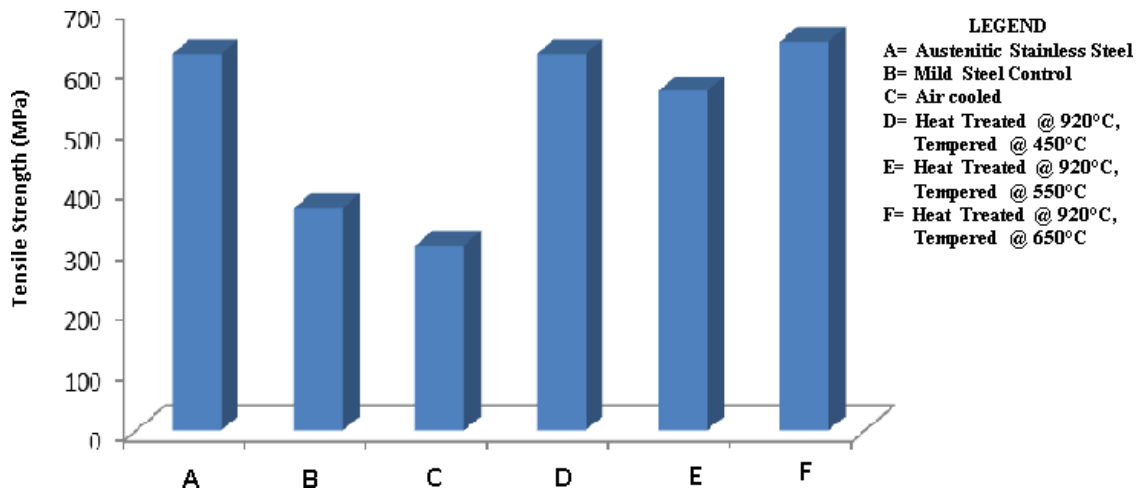


Fig. 1. (Color online) UTS values against different heat treatment operations.

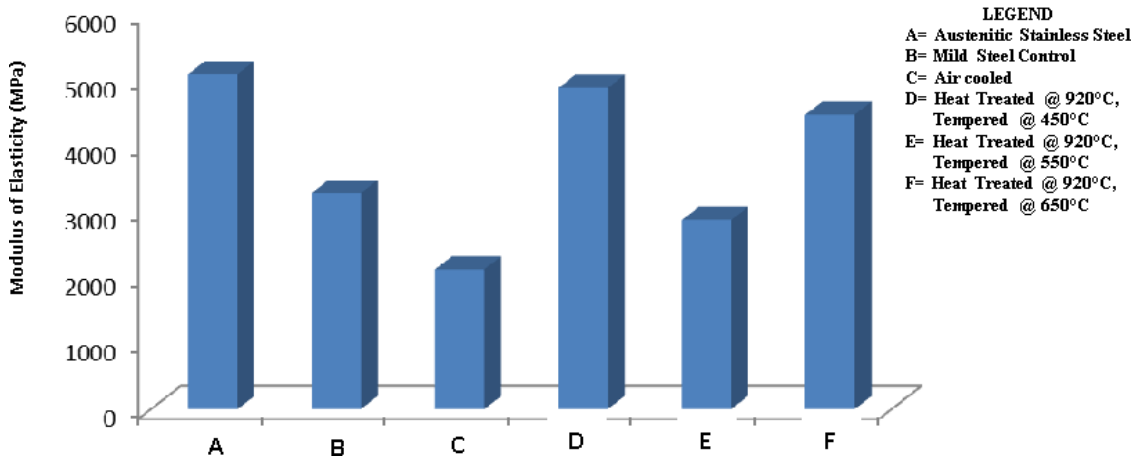


Fig. 2. (Color online) Modulus values against different heat treatment.

highest tempering temperature (650°C) gave the highest toughness values (102 MJ/m³). However, in general, the stainless steel gave the highest toughness value of 124 MJ/m³ (Fig. 3). Sample tempered at 550°C has the lowest toughness value (56.1 MJ/m³) while the sample tempered at 450°C and air-cooled sample gave 72.4 MJ/m³ and 59.5 MJ/m³, respectively. It is significant from the results that high tempering temperature has an effect on the toughness of the sample.¹⁵ When the specimens are tempered at temperature 650°, the phase transformation takes place from unstable martensite to a mixture of ferrite and cementite. At this temperature, cementite (Fe₃C) agglomerates and coalesces. The structure becomes an aggregate with ferrite and cementite in quite fine spheres, referred to as tempered martensite and tempered bainite.

3.4. Effect of heat treatment on hardness of LCS

Figure 4 displays the variation of heat-treatment processes on the hardness property of the LCS. It was observed that the hardness value sample of the air-cooled was 224.2 HV. The samples tempered at different temperatures of 450°C, 550°C, and 650°C gave the hardness values 242.5 HV, 246.6 HV, and 238.6 HV, respectively. These values were obtained before plating with nickel. However, the hardness values of the samples increased after nickel-plating on the tempered LCS. This indicates that the nickel-plating on the samples increased the hardness property. Aside from the control sample, the air-cooled sample has the least hardness value of 224.2 HV followed by that of the sample tempered at 650°C.

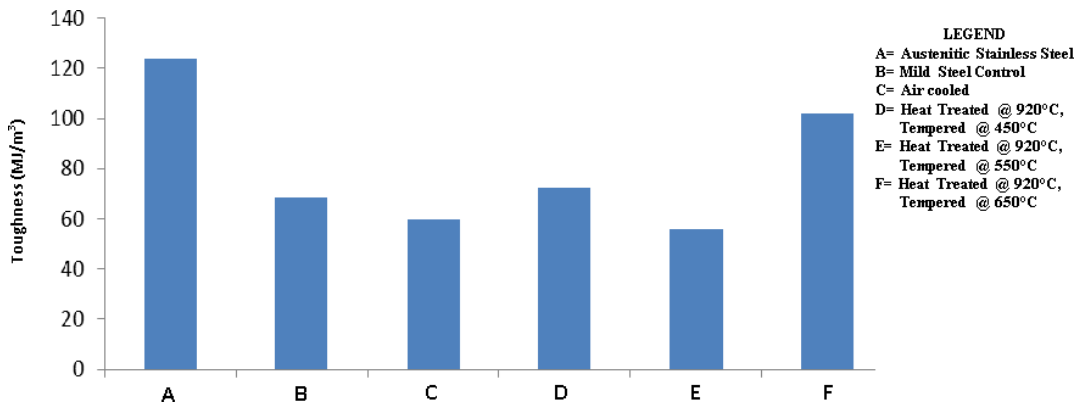


Fig. 3. (Color online) Toughness values against different heat treatment.

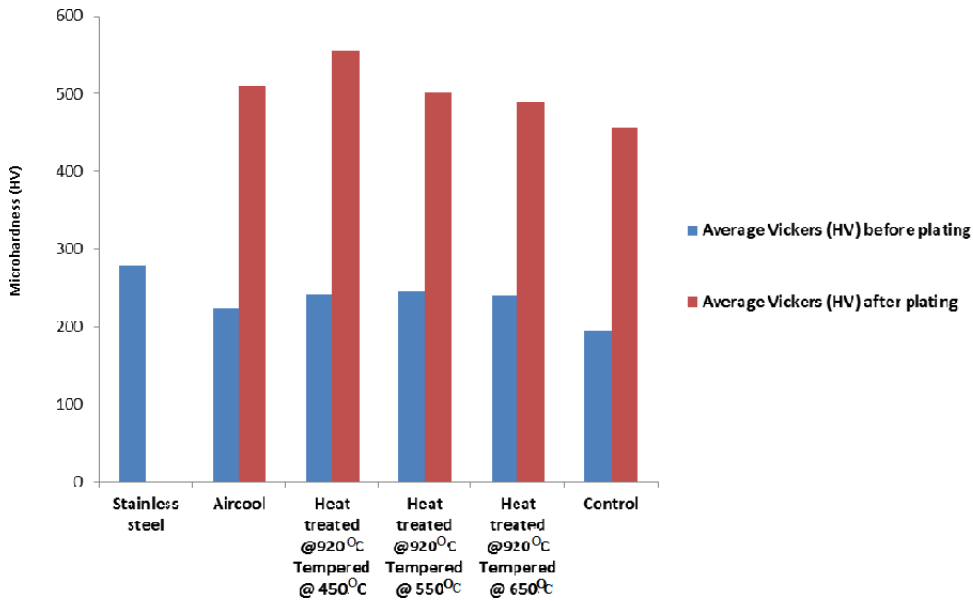
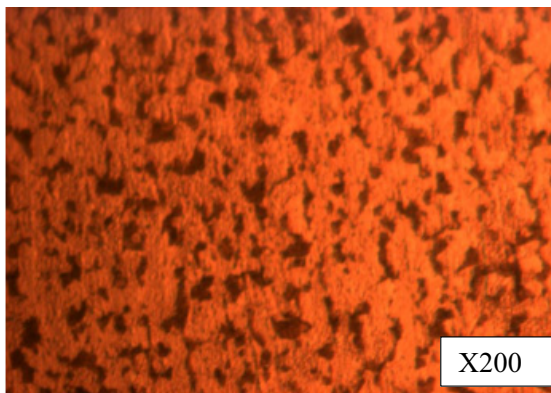


Fig. 4. (Color online) Hardness values before and after nickel plating against different heat treatment.

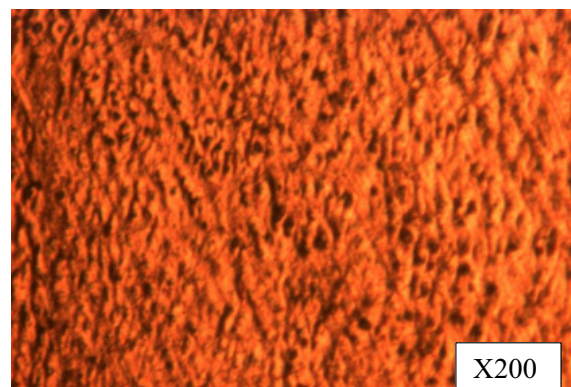
This implies that the higher the tempering temperature, the more closely will the original martensitic structure revert to ferrite cementite mixture. As a result, strength and hardness fall progressively such that toughness and ductility increase.¹⁶ This indicates that proper tempering operations will optimize the mechanical properties of steel such as hardness property. The hardness value of the stainless was higher than any of the tempered LCS samples before plating. However, after plating the tempered LCS, the hardness of the LCS was the lowest.

3.5. Effect of heat treatment on microstructural transformation

Figure 5(a) shows the micrographs of as-received LCS before plating. As conventionally established, the untreated steel microstructure in Fig. 5 shows a pearlite (dark portion) structure in a matrix of ferrite, while Fig. 5(b) shows the photomicrographs of LCS heat-treated at 920°C and air-cooled. It could be observed that the ferrite/cementite lamellae in pearlite are much finer. For this reason, the



(a)



(b)

Fig. 5. (Color online) Microstructures of the heat-treated LCS before nickel plating showing (a) as-received LCS; (b) LCS heat-treated at 920°C and air cooled; (c) LCS heat-treated at 920°C and tempered at 450°C; (d) LCS heat-treated at 920°C and tempered at 550°C; (e) LCS heat-treated at 920°C and tempered at 650°C; and (f) austenitic stainless steel (X200).

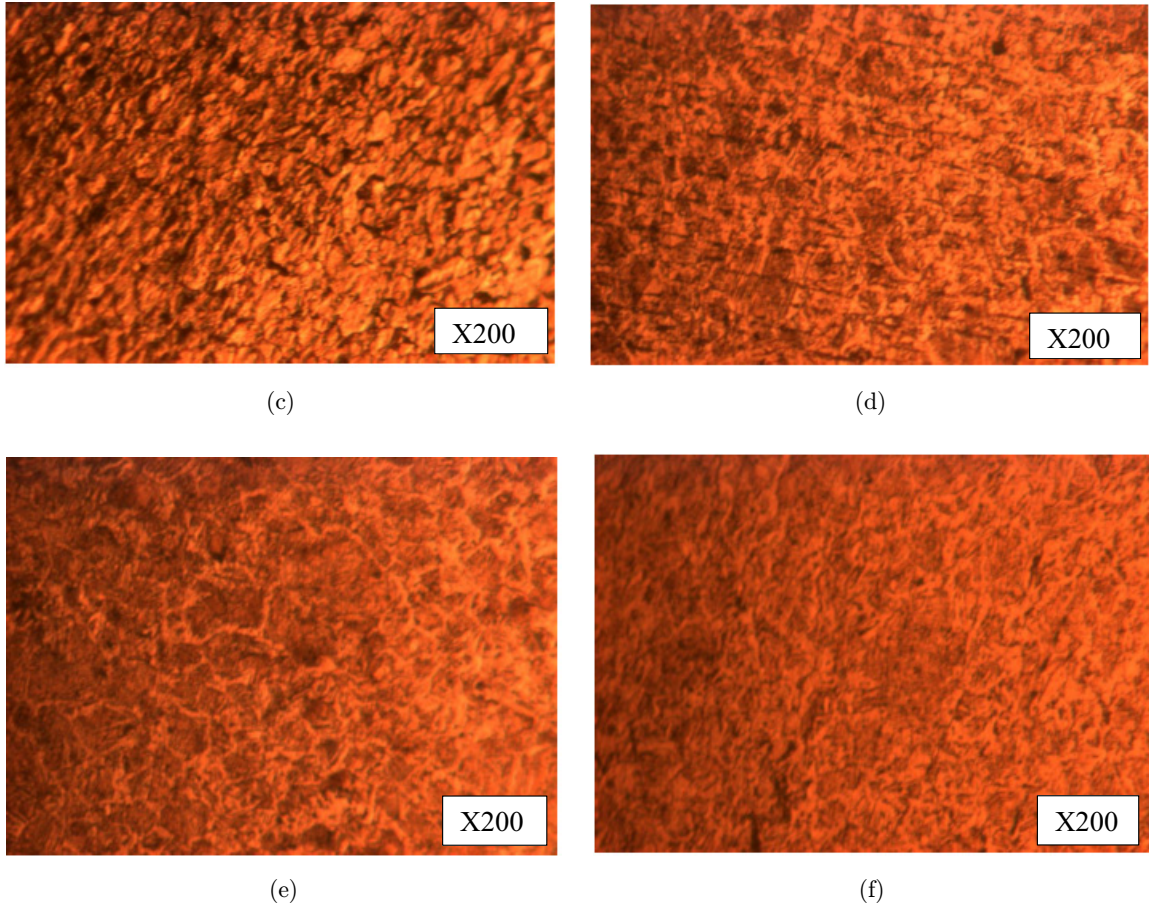


Fig. 5. (Continued)

mechanical properties are somewhat better than that of the control sample.^{16,17} Figures 5(c)–5(e) show the micrograph of LCS heated at 920°C, tempered at 450°C, 550°C, and 650°C, respectively. The tempering aided the microstructure to proceed in some measure toward equilibrium, with the precipitation of microscopical particles of cementite in varying amounts from the original martensitic structure.¹⁷ It could be observed that all the tempering temperatures resulted in tempered martensite, while the sample tempered at the highest tempering temperature (650°C) revealed more equiaxed grain of ferrite and small rod-shaped carbides dispersed within the ferrite matrix. Also, it was revealed that the higher the tempering temperature, the more closely the original martensitic structure reverts to this ferrite cementite mixture. Hence, the strength and hardness fall progressively while toughness and ductility increase.¹⁵ Figure 5(f) shows the micrographs of

stainless steel. No difference could be observed as no treatment has been given to it, and thus, it serves as the control sample for this experiment.

3.6. Effect of heat treatment on electrodeposition of nickel on the LCS

The amount per unit area of nickel deposited on various heat-treated LCS revealed that the highest quantity of 0.013 g/cm² was deposited on LCS heat-treated at 920°C and tempered at 650°C while the least quantity of 0.0020 g/cm² was deposited on LCS heat-treated at 920°C and tempered at 550°C (Table 4). According to Oloruntoba,¹⁸ the microstructure is related to the amount deposited in a way that ferrite phase or single-phase structure promotes metal deposition than dual or carbide phase structure. The amount deposited on the sample

Table 4. Electrodeposition parameters and results for the nickel-plated LCS.

Sample	Coating thickness (μm)	Weight gain (g)	Coating per unit area (g/cm^2)
Air cool	0.00048	0.3	0.0043
HT @ 920°C Tempered @ 450°C	0.00042	0.4	0.0038
HT @ 920°C Tempered @ 550°C	0.00022	0.3	0.0020
HT @ 920°C Tempered @ 650°C	0.00140	0.2	0.0130
Control	0.00023	0.2	0.0021

Note: HT, heat-treated.

heat-treated at 920°C and air-cooled was 0.0043 g/cm^2 while the sample heat-treated at 920°C and tempered at 450°C was 0.0038 g/cm^2 . The obtained values corroborate the observed effect on the microstructure.

3.7. Surface morphology of nickel electrodeposition

Figure 6(a) reveals the surface morphology and EDX of the nickel electrodeposited on the LCS heat-treated

at 920°C and air-cooled. Uneven deposition of nickel film was observed on the plate resulting in a poor reflection of the LCS. The EDX spectrum revealed a high concentration of 97.9% of nickel and 2.1% of carbon at a selected portion of the sample. This could be a result of the fine structure of ferrite and pearlite obtained from the air-cooled substrate, which most probably allows more metal diffusion as a result of more grain boundaries in fine structure than coarse structure.¹⁸ Figures 6(b)–6(d) show the surface

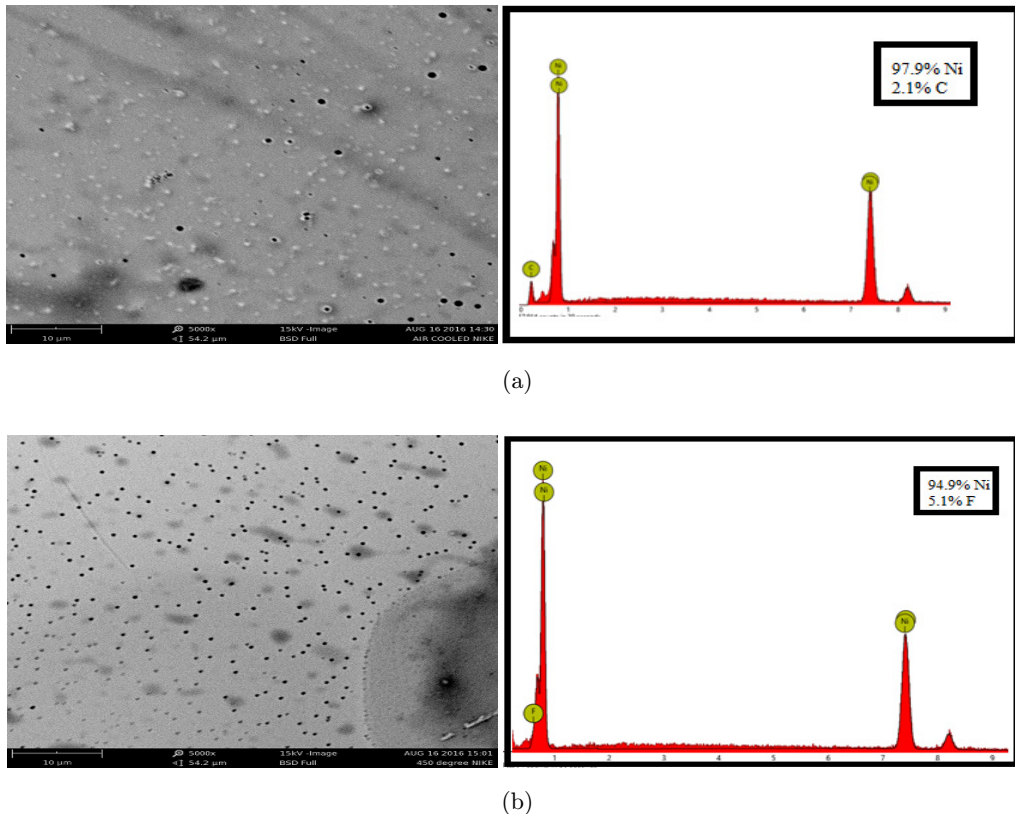
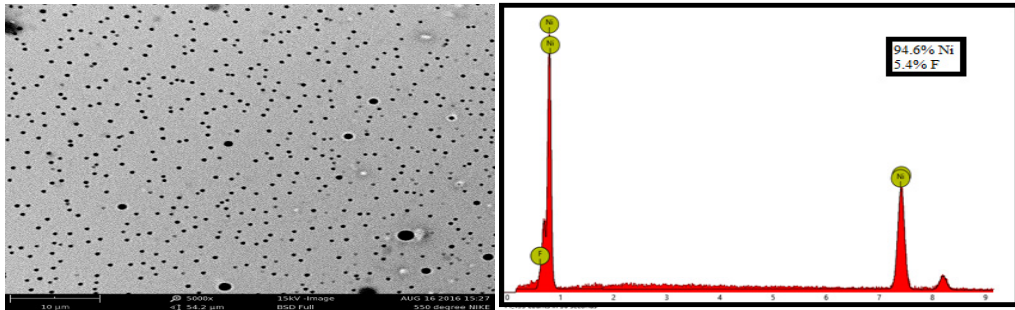
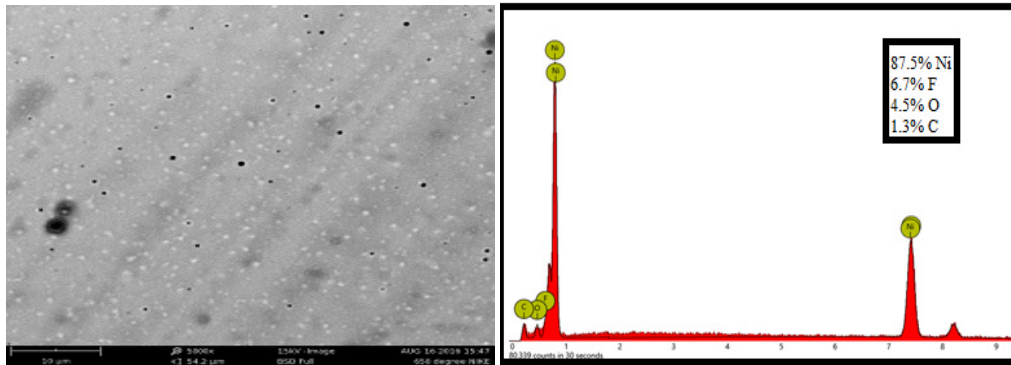


Fig. 6. (Color online) (a) SEM micrograph of LCS heat-treated at 920°C, air cooled, and nickel-plated. (b) SEM micrograph of LCS heat-treated at 920°C, tempered at 450°C, and nickel-plated. (c) SEM micrograph of LCS heat-treated at 920°C, tempered at 550°C, and nickel-plated. (d) SEM micrograph of LCS heat-treated at 920°C, tempered at 650°C, and nickel-plated.



(c)



(d)

Fig. 6. (Continued)

morphology of the nickel electrodeposited on LCS heat-treated at 920°C and tempered at 450°C, 550°C, and 650°C, respectively. It was observed that the deposition was more uniform as revealed in the micrograph. This could be a result of high tempering temperature which tends toward a single lath structure without the acicular. The single phase of the lath structure without the acicular shape of martensite enhances adhesion.¹⁸ Also, by carefully controlled tempering treatment, the quenching stresses can be relieved, and some of the carbon can precipitate from the supersaturated solid solution to form a finely dispersed carbide phase.¹⁹ Some blisters and stardust were also observed, which could be a result of dirt or dust in the nickel bath. A selected portion of the sample in Figs. 6(b)–6(d) shows the EDX spectrum of nickel concentration of 94.9%, 94.6%, and 87.5% nickel, respectively. Nickel counts were recorded as the maximum among all the other elements, small quantities of other elements may be considered as impurities that were subsumed under the nickel

salt; and thus, it shows uneven deposition of nickel on this sample.

3.8. Effect of corrosion on electrodeposition of nickel on the heat-treated LCS in yam fluid environment

Figure 7 displayed the potentiodynamic polarization curves for the various test specimens exposed to yam fluid. It could be observed that the stainless steel and the thermally treated samples especially the one heat-treated at 920°C and tempered at 550°C showed the highest corrosion potentials when compared with those heat-treated at 920°C and tempered at 450°C and 650°C, air-cooled, and control. This means that it displayed the highest corrosion resistance in the tested environment. However, these samples displayed the lowest corrosion rate and recorded the highest polarization resistance compared with others. The severeness of corrosion attack on LCS was

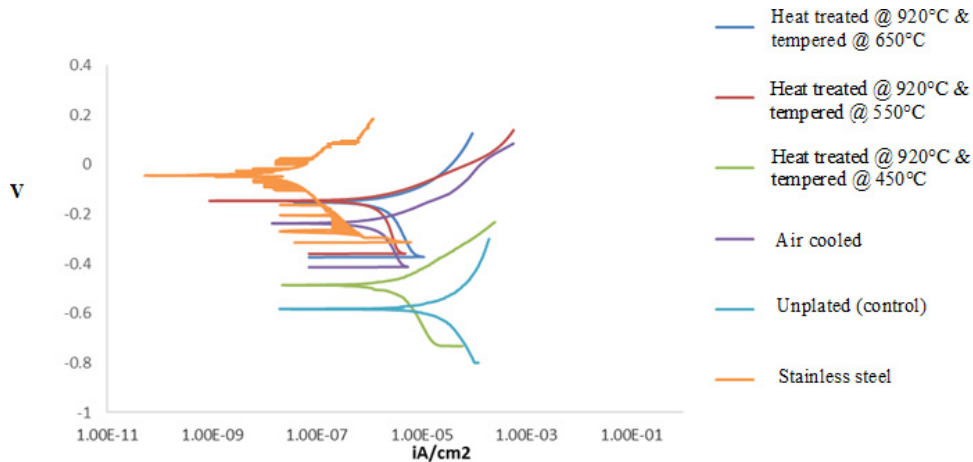


Fig. 7. (Color online) Potentiodynamic polarization curves for the various test specimens exposed to yam fluid.

lessened by the heat treatment and nickel-plating operation.¹⁸ The protective films formed by nickel and chromium present in the stainless and the nickel-plated samples prevent metal dissolution. No tarnishing or result was gotten from 100% yam fluid because yam is more of a hydroxide. There was no migration of electron until the surface was later activated with a pinch of salt. A general look at all the corrosion parameters shows clearly that this sample (heat-treated at 920°C and tempered at 550°C) exhibited the highest corrosion resistance out of all the treated samples. It has a lower corrosion rate, current density, high corrosion potential, and polarization resistance. Compared with the unplated sample (control), polarization resistance was also significantly increased. Besides, the E_{corr} value

increase relative to that of the control. According to Fayomi *et al.*,²⁰ the combination of heat treatment and plating has positive effects. Materials for the yam pounding beater, therefore, perform better when both heat-treated and nickel electroplated, especially for high temperature and corrosion-resistant applications in the yam fluid environment. Figure 8(a) revealed the surface morphology of LCS heat-treated at 920°C and tempered at 550°C, while Fig. 8(b) revealed the surface morphology of unplated LCS. It was observed that the corrosive attack on the unplated steel was more severe than that of heat-treated and nickel-plated LCS. This is a result of a higher concentration of nickel on the surface of the plated sample, which resists the corrosive attack of the yam fluid as compared to that of the unplated LCS.

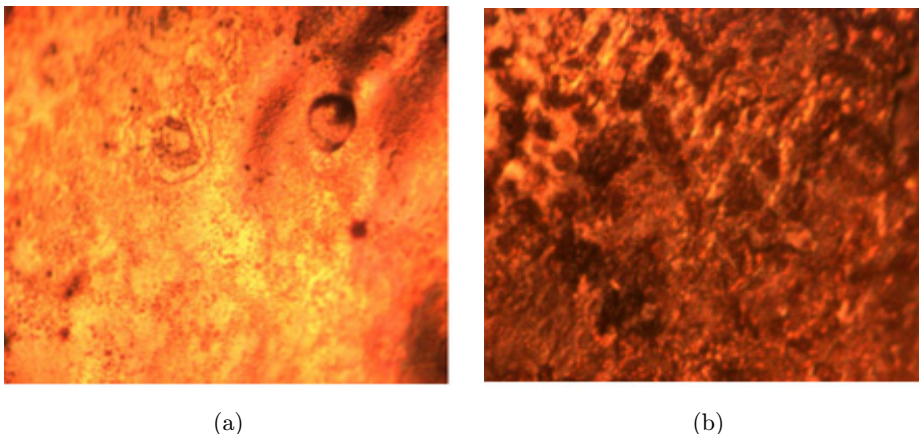


Fig. 8. (Color online) (a) The surface morphology of LCS heat-treated at 920°C and tempered at 550°C, while Fig. 8(b) reveals the surface morphology of unplated LCS.

3.9. Chemical analysis of the yam before and after pounding

Figures 9–11 showed the spectra of the XRF characterization carried out on the yam before pounding,

after pounding with the nickel-plated beater, and with stainless steel beater. The figures revealed the nickel content in the yam as 0.0941%, 0.109%, and 0.1113%, respectively. Analyses before and after

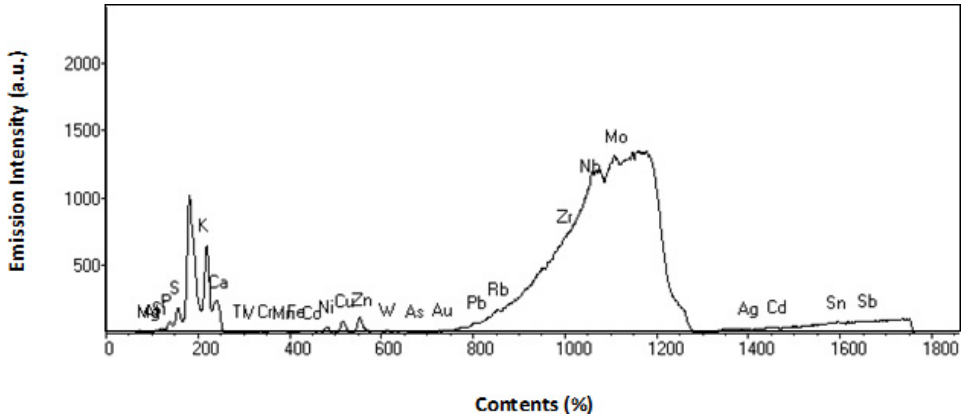


Fig. 9. XRF spectrum of yam before pounding.

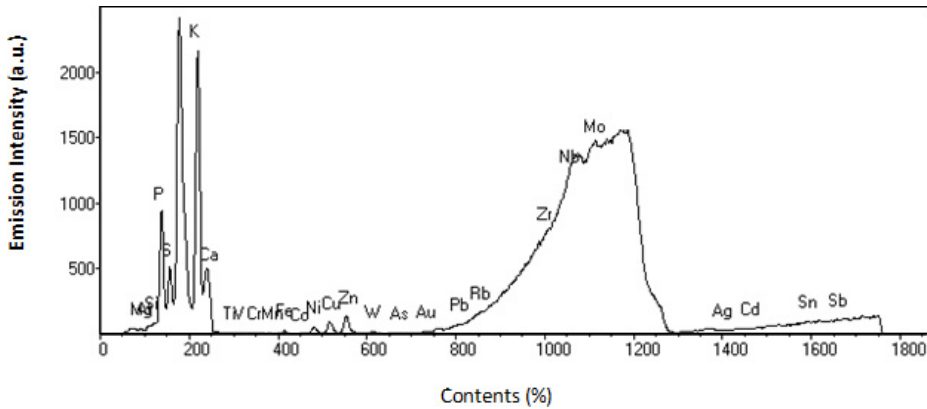


Fig. 10. XRF spectrum of the yam after pounding using nickel-plated beater.

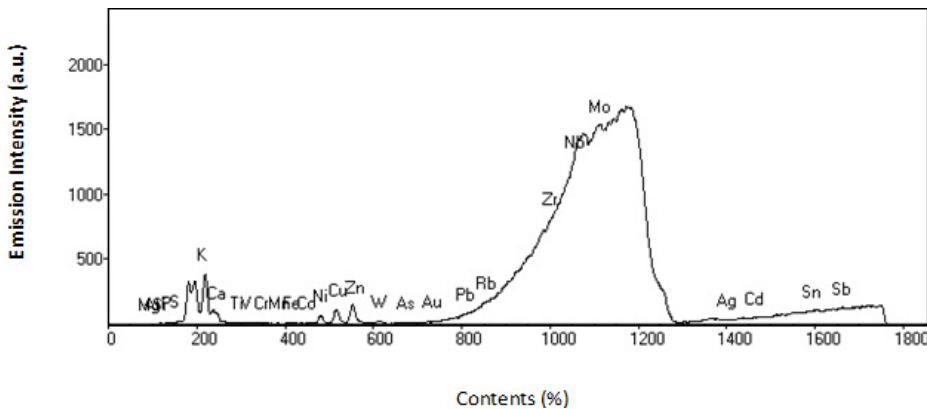


Fig. 11. XRF spectrum of the yam after pounding using stainless steel beater.

Table 5. Mechanical properties, corrosion rates, and remarks for the samples.

Samples	Tensile properties (MPa)	Toughness (MJ/m ³)	Hardness (HV)	Corrosionrate (mm/yr)	Remark
HT @ 920°C, Temp. @ 450°C	622	72.4	556.2	0.043526	No tarnishing
HT @ 920°C, Temp. @ 550°C	561.1	56.1	500.1	0.022182	No tarnishing
HT @ 920°C, Temp. @ 650°C	642.2	102	490.7	0.036482	No tarnishing
Control (unplated)	367.8	68.5	239	14.365	Corrosive attack
Austenitic stainless steel	621	124	279.8	0.0031864	No tarnishing

Note: HT, heat-treated; Temp., tempered.

pounding revealed that nickel content was present in the yam. However, the content was more when a stainless steel beater was used compared to when a nickel-plated beater was used for processing of the yam. It could be opined that the hardness of the yam in comparison with nickel-plated or stainless steel could be seen to be relatively smaller for it to cause any wear. More so, the operating temperature (less than 100°C) is below the activation temperature which could cause ionization or metal release. Consequently, nickel-plating can, therefore, be considered a viable means for preventing the corrosion problem of the yam beater.

3.10. Summary of the mechanical properties of the treated and coated LCS compared with stainless steel

A summary of the mechanical properties for the various specimens as captured in Table 5 shows that the LCS material heat-treated at 920°C and tempered at 650°C possesses superior mechanical and corrosion resistance properties when compared with other specimens.

4. Conclusion

In this work, the electrodeposition of nickel on heat-treated LCS for yam pounding beater was studied. Based on the analyses, the following conclusions can be drawn:

- (i) The mechanical properties of LCSs were found to be strongly influenced by all the heat treatment processes carried out. The optimum toughness of 102 MJ/m³ was achieved from the LCS heat-treated at 920°C and tempered at 650°C.

- (ii) The sample heat-treated at 920°C, tempered at 550°C, and nickel-plated gives the lowest corrosion rate of 0.022182 mm/yr compared with the unplated sample that gave 1.4364 mm/yr. Whereas, the ASS gave a corrosion rate of 0.0031864 mm/yr.
- (iii) From the analysis, the nickel deposited on the heat-treated samples enhanced corrosion resistance in the yam fluid. XRF analysis of the yam before pounding, after processing with nickel electroplated and stainless beater shows the content of nickel as 0.0941%, 0.109%, and 0.1113%, respectively. It was concluded that materials for the yam pounding beater, therefore, perform better if they were both heat-treated and nickel-plated. Invariably, stainless steel could be successfully replaced with heat-treated and nickel-plated LCS for use as yam pounding beater.

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