Nigerian Journal of Technology (NIJOTECH)
Vol. 41, No. 4 July, 2022, pp.693 –699
www.nijotech.com

Print ISSN: 0331-8443
Electronic ISSN: 2467-8821
http://dx.doi.org/10.4314/njt.v41i4.7

Effects of Ferro-Silicon Addition, Heat-treatment and Plastic deformation on Corrosion Resistance of 6063 Aluminum Alloy

J. B. Agboola[1, *], O. A. Olawale[2]

[1,2] *Department of Metallurgical and Materials Engineering, University of Lagos, Akoka, Lagos State, NIGERIA*

Article history: Received 13 June 2022; Revised form 12 July 2022; Accepted 14 July 2022; Available online 10 September 2022

Abstract

6063 aluminium alloy is widely used in architectural applications such as window and door frames because of its nice appearance and acceptable strength. Its major alloying elements are magnesium and silicon. Not many studies focused on the influence of plastic deformation and the alloy content on post-processing quality and corrosion resistance of the alloy have been published. Considering the influence that variation in chemical composition could have on the properties of the alloy, this work aims to investigate the effects of Ferro-Silicon addition, heat-treatment and cold rolling on post-processing quality and corrosion resistance of 6063 Aluminium Alloy. 5000 g of Aluminium 6063 alloyed with 500 g of ferrosilicon was produced. Cast samples from the alloy were homogenized at 350 ºC before cold rolling in the range of 10%, 15%, 20%, 25%, and 30% reduction. The corrosion behaviour of the produced alloy was evaluated using a potentiodynamic test in a 3.5wt % sodium chloride solution. The results show that the addition of FeSi and cold- rolling results in improved mechanical properties but has little effect on corrosion resistance. Heat-treatment has not caused significant impact in corrosion resistance and mechanical properties of the alloy.

Keywords: Aluminium; Ferro-silicon; Cold rolling; heat treatment; Corrosion.

1.0 INTRODUCTION

Aluminum has found wide application in many manufacturing sectors such as chemical plant, architectural design, and marine industries. Although it is easy to fabricate aluminium into any form, its application for engineering purposes is restricted due to its softness. Hence the need to strengthen the metal to improve its usefulness. [1] has stated that cold rolling and heat treatment can be used to improve mechanical properties of materials and enhance their performance on application, but an important side effect of these techniques is that they may cause deterioration of the corrosion resistance of the material.

It has also been observed by [2] that aluminium can withstand corrosion by appropriate alloying and heat-treatment. [3] has reported that Intermetallic such as Al-Fe-Si-Mn and Al-Fe-Si, have a significant effect on mechanical properties of 6XXX aluminium if properly controlled. [4] has established that the low density of silicon helps to solubility of silicon in aluminium increases the abrasion resistance. [5] has observed that the majority of alloys are susceptible to intergranular corrosion when exposed to specific environment because grain boundaries serve as site for precipitation and segregation

[6] in their study of the effect of silicon on mechanical properties of aluminium alloys varied the silicon content from 5, 7, 9, 12.5 and 14% in five different aluminum alloys. It was observed that ultimate tensile strength (UTS) increased to the maximum value of 175 MPa at 14 wt% silicon.

[7] in their study, varied magnesium and silicon content in different proportions to produce different alloys of Al–Mg–Si. They homogenized the alloy at 560 ºC after which it was cold-rolled to 1mm thick sheet. The rolled samples were solutionized at 560ºC, cooled rapidly and aged for three days. It was observed that excess silicon enhanced the precipitation kinetics of the alloy and improved the hardness until the ratio of Mg/Si was close to 0.4. However, they did not study the corrosion behaviour of the alloy and the mechanical test was limited to hardness test.

*Corresponding author **(Tel:** +234 (0) 8035600524**)**

Email addresses: *joeagboola@gmail.com* (J. B. Agboola), *dmy4lag@yahoo.com* (O. A. Olawale)

[8] studied the influence of annealing and plastic deformation on corrosion behaviour and mechanical properties of Cu-12Al-2Ni-5Fe alloy. The alloy was rolled to 5%, 10%, 15% and 20% reductions and annealed at 350ºC, 400ºC, 450ºC and 500ºC. It was simulated in seawater underflow condition using open circuit potential and potentiodynamic polarization. It was observed that, as the degree of cold rolling and heat treatments of the alloy increased there was higher impact strength and a reduction in corrosion rate.

[9] investigated the effect of plastic deformation on the microstructure and corrosion resistance of the NBR ISO 5832-1 stainless steel. The alloy was subjected to deformation of 30%, 50% and 70% reduction by cold rolling. It was observed that 30% and 50% reduction caused voids at the matrix-inclusion interface. However higher level of reduction of 70% improved localized corrosion resistance. The study did not consider the mechanical properties of the samples.

[10] investigated corrosion susceptibility of cold deformed 5052 Aluminium alloy in seawater. They concluded that a highly deformed sample is more prone to corrosion than fairly deformed and undeformed samples. [11] have established that rolling and heat-treatment of Al-Ti alloy enhanced tensile strength by 24.7% and har**dness** by 20.5%.

[12] investigated the influence of thermal treatment on corrosion behaviour of 6061 Aluminium alloy using 3.5% NaCl solution. It was established that the solution-treated 6061 aluminium alloys had a higher hardness and lower corrosion resistance. However, the work did not examine the influence of plastic deformation on corrosion resistance.

[13] studied the effect of heat treatment on corrosion behaviour of the 6063 alloy containingAl_3Ti using 30gr/l NaCl + 10ml/l HCl solution at a temperature of 20 to 23 ºC. It was observed that heat treatment improved corrosion resistance. [14] have also established that post mechanical working such as drawing and straightening impaired corrosion resistance of the metal.

[15] in their study, compared the effects of heat-treatment on strength and ductility of rolled and forged 606 Aluminium alloy. It was established that strength and ductility were significantly improved in rolled sample compared to forged samples when heat-treated after deformation. [3] has also established that the cold working of 6063 Aluminium alloy increased its hardness.

It is known from the literature source that intermetallic such as Al-Fe-Si has a significant effect on the mechanical properties of 6XXX aluminium alloy. However, the effect of the alloy content, plastic deformation and heat-treatment on post-processing quality and corrosion resistance of the alloy is rarely studied. Hence, considering the importance of chemical composition changes on the resultant properties, it is of special interest to investigate the effects of Ferro-Silicon addition, heat-treatment and plastic deformation on post-processing quality and corrosion behaviour of 6063 Aluminium Alloy.

2.0 MATERIALS AND METHODS

Al-Si alloys were prepared by melting 5000 grams of 6063 aluminium with 500 grams of ferrosilicon in a crucible furnace. The melted 6063 aluminium alloy and the ground ferrosilicon were stirred thoroughly to obtain a homogenous mixture and held at 720 ºC. The molten metal was poured into cylindrical metal dies of diameter 16 mm and length/height of 140 mm. Five samples were cast at a time.

Cast samples from the alloy were homogenized at 350 ºC before cold-rolling in the range of 10%, 15%, 20%, 25%, and 30% reduction using a laboratory rolling mill. One of the samples not cold- rolled served as control. The machined samples for each of the reductions were heat-treated using Carbolite electric arc furnace. The samples were heated to 500 °C and held for one hour and finally quenched in tap water.

The hardness test was done by using a test load of 490.3N and a dwell time of 10s. The test was done at 3 different points on each of the samples and the average hardness was determined and recorded. The impact test was carried out using the Charpy impact testing machine, made in England, Serial no: 3915. The tensile test was carried out using a Universal Instron Machine, model 3369.

The corrosion test was carried out using electrochemical process. An electrochemical measurements tests were performed using Gamry's three-electrode cell system (model PC14/750), in 0.6M NaCI solution of pH 5.5 according to ASTM G69-1. 6063 aluminium alloy served as a working electrode (WE). A saturated calomel electrode was used as a reference (RE) and a graphite rod was used as an auxiliary electrode (AE). Polarization curves were recorded in a single sweep starting from -0.5 V versus OCP and going as high as 0.5 V versus OCP. The scan rate was 0.20 mV/s. The Icorr and Ecorr values were measured using the Tafel plot.

Specimens for microstructural analysis were prepared by grinding with silicon carbide emery paper and thereafter polishing the samples with Grinding and Polishing Machine QPOL 250 M2 followed by etching with diluted hydrofluoric acid while the microstructural analysis was performed using a scanning electron microscope.

3.0 RESULTS AND DISCUSSION

3.1 Chemical Composition of the 6063 Aluminium Alloy

The chemical composition of the alloy under investigation in wt %, before and after alloying with ferrosilicon is given in table 1.

Table 1: Chemical composition of 6063 aluminium alloy

Elements	Composition (wt %)	
	6063 aluminium	**6063 aluminum alloyed with ferrosilicon**
Si	**0.45**	**2.34**
Fe	**0.22**	**0.65**
Mn	0.01	0.01
Mg	0.54	0.48
Zn	0.01	0.01
Na	0.03	0.02
Ti	0.01	0.02
Others	0.22	0.01
Al	98.70	96.14

3.2 XRD pattern of Al 6063 alloyed with ferrosilicon

Figures 1 and 2 show the XRD Results of the as-received and alloyed Al 6063 respectively.

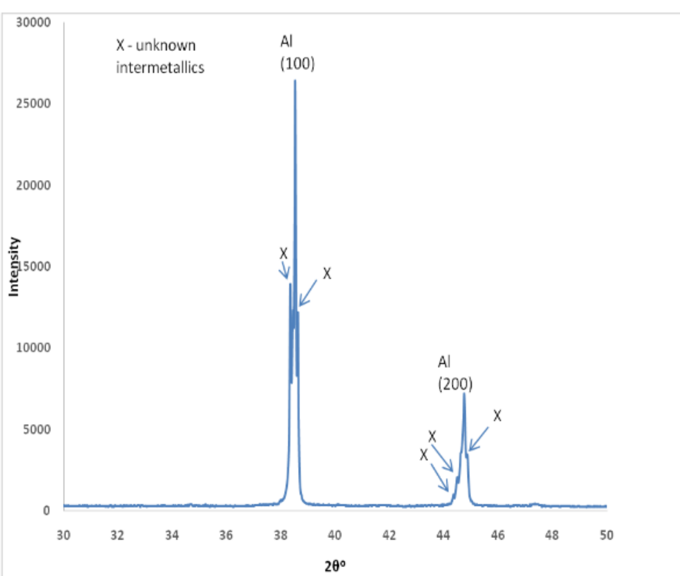

Figure 1: XRD pattern of as received Al 6063

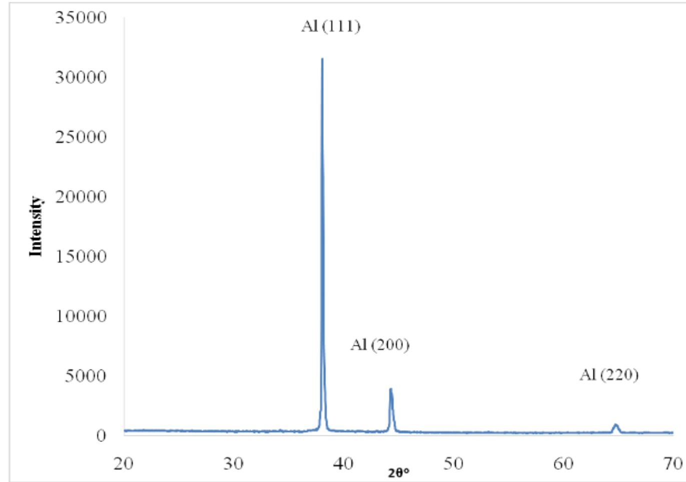

Figure 2: XRD pattern of Al 6063 alloyed with ferrosilicon

From Figures 1 and 2, the Al-Si-Fe phase present at about an angle 38° is in consonant with that reported by (Birol 2012, and kumar *et al*., 2012). It would be observed that the concentration of Si and Fe increased indicating that alloying with ferrosilicon was successful. The presence of tin and copper may indicate the presence of impurity from the ferrosilicon. There was also reduction in the magnesium which may be due to loss of some element during homogenous mixing

3.3 Mechanical Characterization

3.3.1 Impact Strength

Figure 3 show the result of the impact test of the rolled, heat-treated and non-heat-treated samples. The figure reveal that the rolled-heat-treated samples exhibit higher strength for all degrees of plastic deformation when compared to the as received samples.

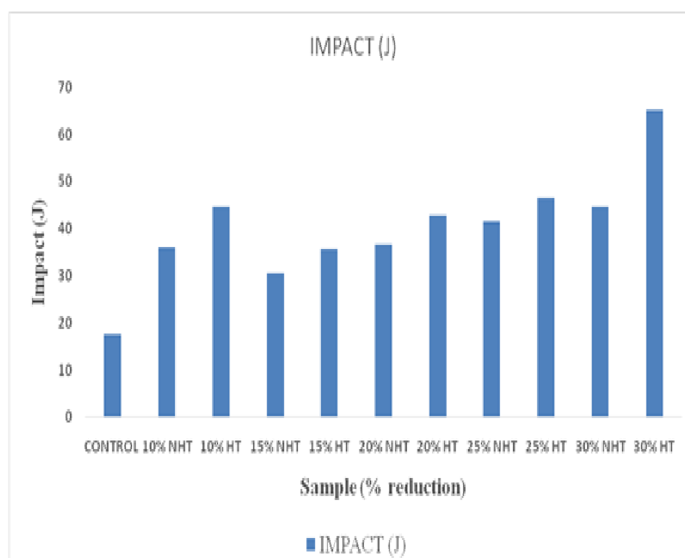

Figure 3: Impact Stress of Heat treated and non-heat treated cold rolled samples

3.3.2 Hardness

Results of the hardness tests are shown in Figure 4. Maximum hardness is observed in the rolled-non-heat-treated samples while minimum value is observed in the as received samples. The heat-treated samples show lower hardness value due to small number of precipitates formed with large distance from one another. This allows free dislocation movement and hence less hardness value. The high hardness value observed in the non-heat-treated sample is attributed to the refining influence of FeSi.

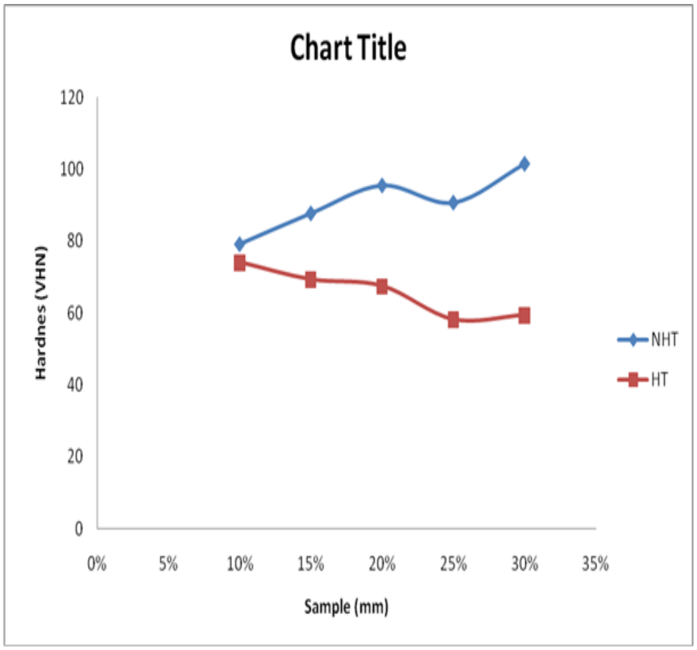

Figure 4: Hardness of heat-treated and non-heat-treated cold rolled Samples

3.3.3 Tensile Strength

Figure 5 show the maximum tensile strength of the alloy under consideration. It can be seen that the cold-rolled, non-heat-treated samples have higher maximum strength compared to the heat-treated samples. During plastic deformation, dislocations are generated and they move. As the number of dislocations in the crystal increases, their movement become impaired. This strengthens the alloy. Although the presence of precipitates was observed in the heat-treated samples, the effect was not remarkable in the overall mechanical properties of the alloy. This is probably due to a decrease in the matrix coherency. The degree of precipitation after stable equilibrium is reached is less than can be induced by heat – treating. Consequently, the full-strength capability of the alloy is not attained. Additions of the dispersoid FeSi content results in improved mechanical properties for all degrees of plastic deformation and heat treatment.

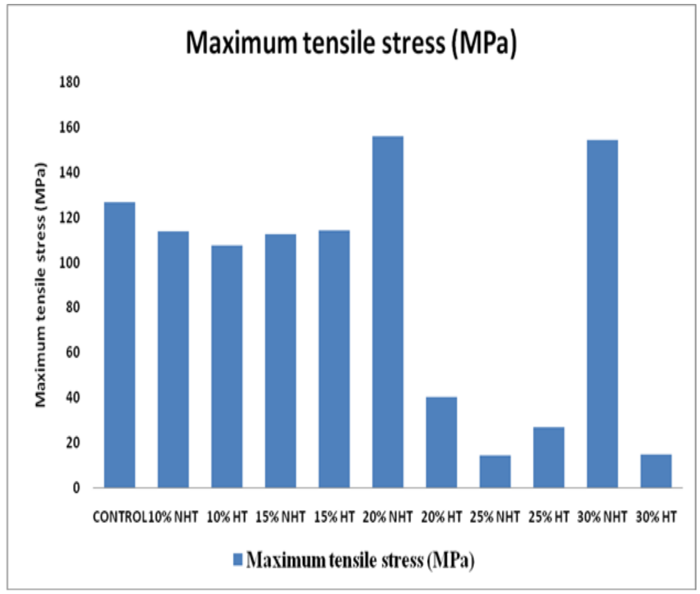

Figure 5: Maximum Tensile Strength of Cold Rolled and Heat-treated samples

3.4 Corrosion Characterization

Figure 6 present the results of TAFEL polarization curves of Aluminium alloy cold rolled at 10%, 20%, and 30% reductions in 3.5 wt % NaCl (synthetic saline environment) while Figure 7 shows the polarization curves of cold rolled and heat-treated aluminium alloys. Table 2 shows a summary of data obtained from potentiodynamic corrosion tests.

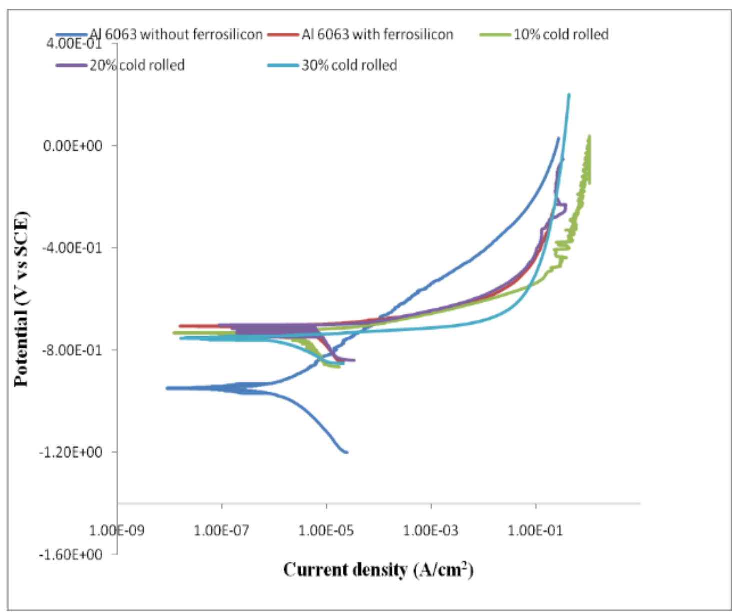

Figure 6: Tafel Polarization curves of cold rolled aluminium alloys in 3.5wt % NaCl solution

Table 2 show the values of Ecorr and Icorr obtained from Figures 3 and 4.

Table 2: Summary of the experimental data derived from the Tafel polarization curves

	Cold Rolled		Cold Rolled and Heat treated	
Samples	**Ecorr (v)**	**i_{corr} (A/cm^2)**	**Ecorr (v)**	**i_{corr} (A/cm^2)**
As received Al 6063	-0.951	1.6×10^{-6}	-0.951	1.6×10^{-6}
Al 6063 alloyed with ferrosilicon	-0.704	3.93×10^{-6}	-0.704	3.93×10^{-6}
10 % cold rolled	-0.731	6.43×10^{-6}	-0.703	2.56×10^{-6}
20 % cold rolled	-0.715	9.63×10^{-6}	-0.676	3.22×10^{-6}
30 % cold rolled	-0.753	4.87×10^{-6}	-0.742	2.94×10^{-6}

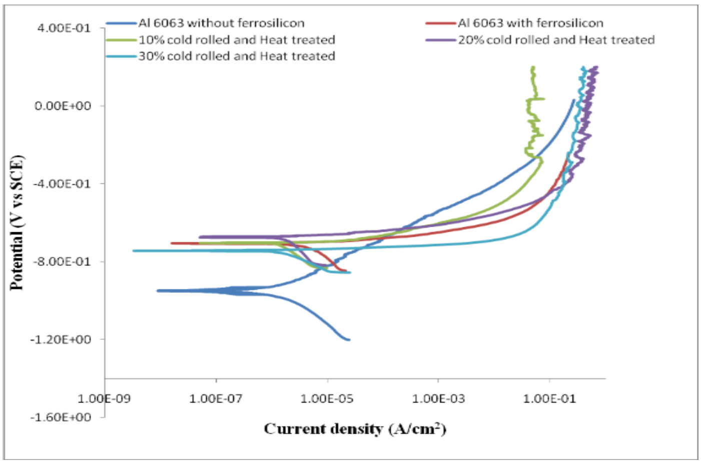

Figure 7: Tafel Polarization curves of Cold- rolled and heat-treated aluminium alloys in 3.5wt % NaCl solution

From table 2, it can be seen that the as-received aluminium 6063 sample displayed the highest resistance to corrosion compared with the alloyed and cold rolled sample. Among the cold rolled samples, the 20 % reduction samples exhibited the highest corrosion resistance. This conforms to Sekunowo *et al*., (2015) who concluded that deformed sample due to cold rolling is more prone to corrosion than undeformed sample and this is attributed to the initiation of corrosion sites at the grain boundaries. Heat- treatment slightly improved the corrosion resistance of the samples.

3.4 MICROSTRUCTURAL ANALYSIS

SEM micrographs of the cold rolled and heat-treated aluminium 6063 alloy are shown in Figure 8 (a-g). As can be seen in Figures 8 (a) and (c), the 10% and 20% cold-rolled samples exhibited broad grain size distribution, straight grains with uneven grain boundaries. The 20% cold-rolled sample exhibit relatively larger grains. Among the cold-rolled samples, the grains in the 30% cold-rolled samples are comparatively smaller. From figures 8 (a, d and f), it can be seen that the grain size variation is considerably reduced and more spherical after heat-treatment. The microstructure of the alloy contains constituents of type Al_xFeSi_y which are formed during solidification.

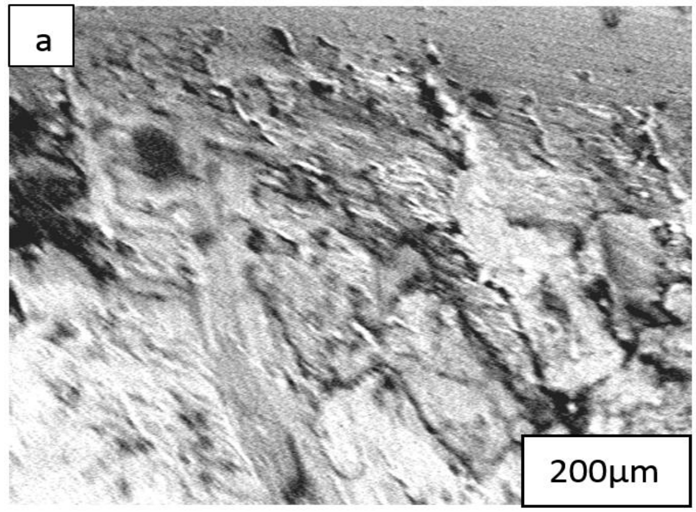

Figure 8 (a): 10 % cold rolled sample

From the Microstructure analysis presented in Figure 8 (a-f), grain refinement is maximum for the heat-treated samples and lowest for the as-received and rolled-samples. The grain refinement introduced more grain boundaries and this hinders dislocation movements, having to change its orientation to pass through a grain and also a larger grain area thereby resulting in high strength of the material.

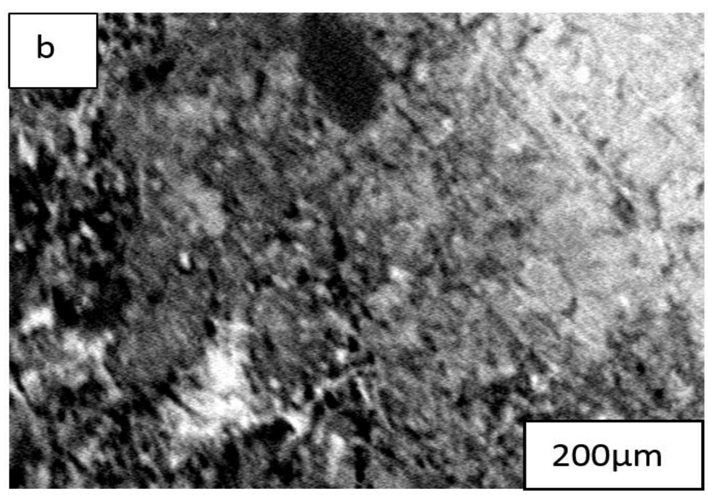

Figure 8(b): 10 % cold rolled and heat-treated sample

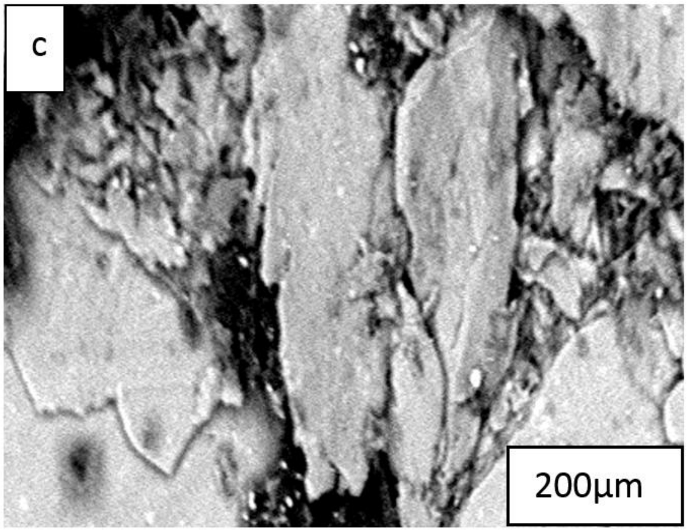

Figure 8(c): 20 % cold rolled sample

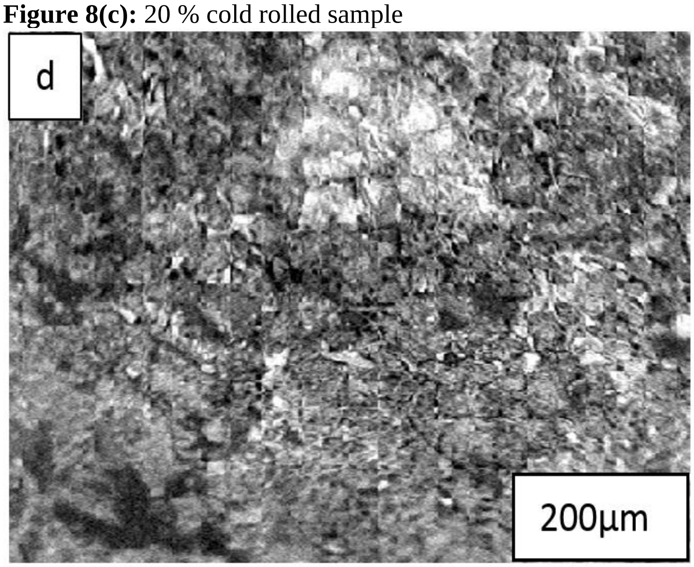

Figure 8(d): 20 % cold rolled and heat treated

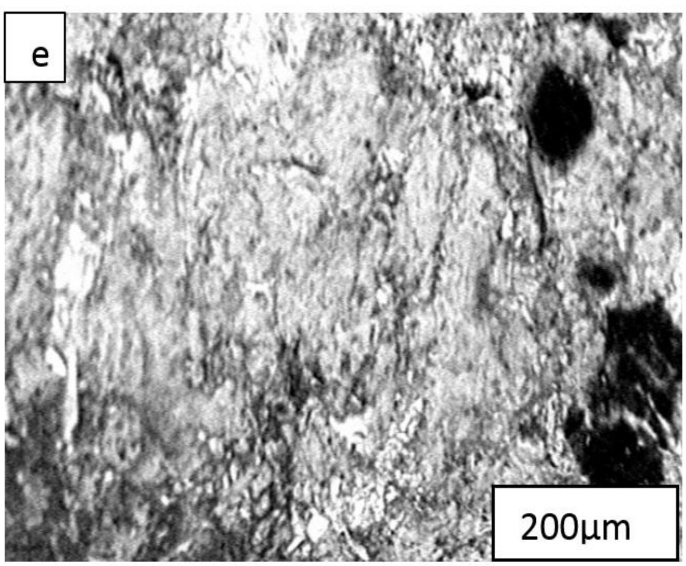

Figure 8 (e): 30 % cold rolled sample

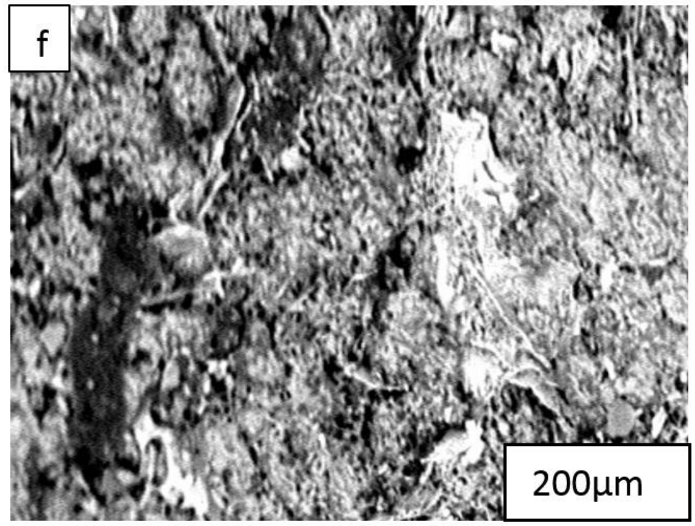

Figure 8(f): 30% cold rolled and heat treated

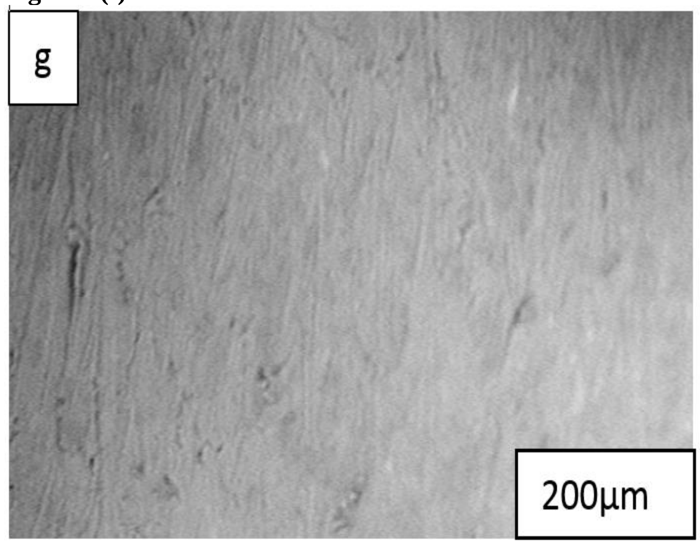

Figure 8(a-g): SEM micrographs of cold- rolled and heat- treated, cold- rolled samples

The coarse grains observed in the cold -rolled samples on the other hand have larger grain boundaries than the fine grains and hence due to sliding of the grain boundaries, ductility is more in case of these grains.

4.0 CONCLUSION

The effects of Ferro-Silicon addition, plastic deformation and heat-treatment on Corrosion resistance of 6063 aluminium alloy has been presented. SEM images and XRD results shows the presence of constituents of type Al_xFeSi_y. Microhardness tests have corroborated that samples with FeSi addition present better mechanical properties with a higher hardness and tensile Strength value which is attributed to the FeSi precipitates formed at the grain boundaries. As the degree of plastic deformation of the alloy increased, hardness and impact strength value increased while corrosion resistance reduced. Heat-treatment has not caused any significant impact on corrosion resistance and mechanical properties of the alloy.

REFERENCES

[1] Adeosun S. O., Balogun S.A., Sekunowo O.I. and Usman M.A. "Effects of Heat Treatment on Strength and Ductility of Rolled and Forged Aluminum 6063 Alloy", *Journal of Minerals & Materials Characterization & Engineering*, 9 (8), 2010, pp 763-773.

[2] Adeosun S.O., Sekunowo O. I. and Talabi S.I. "Combined effect of cold rolling and heat treatment on the mechanical properties of Al-Ti alloy", *World Academy of Science, Engineering and Technology International Journal of Materials and Metallurgical Engineering,* 8 (3),2014, pp 235-240.

[3] Adeosun S.O., Sekunowo O.I., Balogun S.R. Osoba L.O. "Effect of deformation on the mechanical properties of Aluminium- Magnesium Alloy", *Journals of minerals and materials characterization and engineering,* 10 (6), 2011, pp553-560.

[4] Davis J.R., "Aluminium and Aluminium alloys", ASM, Metals Handbook Vol 13, 2001 Corrosion Fundamentals and protection.

[5] Nowotnik G.M., "Influence of chemical composition variation and heat treatment on microstructure and mechanical properties of 6xxx alloys", *Archives of Materials Science and Engineering*, 46 (2),2010, pp98–107.

[6] Milind G.K., Pradeep M.D., "Impact of Silicon Content on Mechanical Properties of Aluminum Alloys*" International Journal of Science and Research,* Vol 4 (6), 2015, pp2319-7064.

[7] Stephen D.C and Bernard S.C., "Corosion: Fundamentals, Testing, and Protection, *ASM International,* Vol (13A),2003, pp 1783.

[8] Gundu D.T., Tile J.M. Folrunsho D.O. "Effect of cold rolling and annealing treatments on microstructure, impact, toughness and corrosion resistance of Cu-12 Al-2Ni-5Fe NaB alloy", *America journal of engineering research*, 5 (10), 2016, pp307-310.

[9] Alexander H.R., Cristiaann H.R., Isolda C. "Cold rolling effect on the microstructure and pitting resistance of the NBR ISO 5832-1 Austenitic Stainless steel", *International Journal of Electrochemical Science,* Vol 8, 2013, pp 12810-12815

[10] Sekunowo O.I., Durowaye S.I. and Anozie E. C. "Corrosion Propensity of Cold Deformed 5052 Aluminium Alloy in Seawater", *British Journal of Applied Science & Technology,* 8(1), 2015, pp46-52.

[11] Phull B., "Evaluating Intergranular Corrosion, Corrosion: Fundamentals, Testing, and Protection", ASM Handbook, ASM International, Vol 13A,2003, pp568-571

[12] Chuan-bo Z., Xi C., Chun-ling L., Xiao-lan S., Ke C. "International Journal of Electrochemical Science "Vol 11, 2016, pp7254 –7261, doi: 10.20964/2016.08.35.

[13] Isadare D.A., Adeoye M.O., Adetunji A.R., Oluwasegun K.M., Akinluwade K.J. "The influence of homogenization treatment on aging response of 6063 aluminium alloy", *Advance in research international,* Vol 5 (3),2015, pp 1-11.

[14] Cevik E., Sun Y., Ahlatei H. "Effect of peak-aged heat treatment on corrosion behavior of the 6063-alloy containing Al_3Ti", *Archives of metallurgy and materials* Vol 57, 2012, pp 469-477.

[15] Rana R.S., Rajesh P. and Das S. "Review on the Influence of alloying element on the microstructure and mechanical properties of Aluminium Alloys", *International Journal of Scientific and research Publication* 2 (6), 2012, Pp2250-3153