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Research Article

The Study on Characteristics of Heat Treatment of The AA2024 Aluminum Alloys

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Abstract

This study examined the behavior of AA2024 aluminum alloys, which received different heat treatments, i.e., homogenization, quenching, artificial aging, and recrystallization. The homogenization temperature is set at 495 °C for 5 hours and followed by slow cooling in the furnace. Then a quenching treatment was done with cold water. Artificially aged alloys were heated to 495 °C for 5 hours, followed by rapid water cooling, then heating to 140 °C for 2 hours, and followed by slow cooling in the furnace. The recrystallization treatment was also studied by heating the solution to 495 °C for 5 hours, followed by rapid cooling with cold water and heating to 310 °C for 3 hours in the furnace. In this study, we used an optical microscope and a scanning electron microscope to analyze the microstructures of the samples. X-ray fluorescence analysis was used to determine the proportion of each element on the surface of each alloy. Phase and structural analyses were performed by X-ray diffraction while the mass loss was calculated after 60 hours of exposure for all samples in a climate chamber. Our work revealed that the rate of mass loss could decrease with heat treatment of the alloy due to the emergence of additional phases and dispersoids. The result showed that the surface fraction of each element was changed due to heat treatment in an aggressive environment, in which the Al_2Cu and Al_2CuMg phases disappeared after the solution treatment as revealed from the XRD data.

Keywords: AA2024, SEM, heat treatment, weight loss, XRD, aluminum alloys

1. INTRODUCTION

High-strength aluminum alloys have a prominent role in the aviation industry. Currently, these alloys account for approximately 80% of the weight of the empty frame of a civil transport aircraft. Improvements in the alloys and the development of high strength, high toughness, and superior corrosion resistance grades have enabled them to maintain their leading position. The Zn, Cu and Si elements were added to pure aluminum to enhance its physical qualities, however, these elements were corrosive.

Due to their high strength-to-weight ratio, simplicity of processing, and affordability, aluminum and its alloys are considered essential engineering materials [1]-[3]. They are widely used in the aerospace and construction sectors [4][5]. However, unlike other metal alloys, aluminum and its alloys exhibit a wide range of microstructures due to alloying components and impurities [6]. The high-strength and heat-treatable aluminum alloys of the 2xxx and 7xxx families are mainly used in heavy vehicles, buildings, and the aerospace industry. Magnesium and copper are added as alloying components in the 2xxx series to improve their mechanical properties [7][8].

Metal joining is an essential part of the manufacturing process for massive structures [9][10]. The primary strengthening method for high-strength 2xxx aluminum alloys is artificial precipitation aging which is frequently used to increase the strength of the alloy. Due to their exceptional resistance to stress corrosion cracking, these aluminum alloys are widely used in the automotive and aerospace industries [11]. Alcoa first proposed this alloy as an "alclad" sheet with a T3 temper in 1931. Al2024 is said to have better formability with slight variations in composition, such as HF-2024 created by Pechiney [12]-[14].

Heat treatment techniques are effective to improve the mechanical properties of 2xxx series aluminum alloy welds [15][16]. Mechanical properties are frequently enhanced by solutions and aging processes. Recently, heat treatment techniques have been used to improve the characteristics of 2xxx series WAAM aluminum alloy components. Gu et al. [17] processed WAAM 2219 aluminum alloy using solution processing and artificial aging and discovered the immense potential of its strongest qualities. To treat the

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deposits of 2219 aluminum alloy, Bai et al. [18] performed unique heat treatment, reporting that the final strength was increased. To treat WAAM 2024 aluminum alloy, Qi et al. [19] used solution and natural aging (with varying solution treatment temperatures). The property development trend was also examined, and it was found that the properties showed an increasing trend with increasing solution processing temperatures, however, the research results are not thorough enough. Thus, more organized research is needed [20].

Since the heat treatment procedure considerably impacts the alloy's microstructure, mechanical properties, and corrosion resistance, it is crucial to study the heat treatment to prevent corrosion of 2024 aluminum alloy. In particular, heat treatment can increase the corrosion resistance of aluminum alloy 2024 by precipitating small particles of reinforcing phases, such as Al_2CuMg and Al_2Cu, which can increase the alloy's resistance to localized corrosion. In addition, the distribution and shape of intermetallic particles can be affected by the heat treatment procedure, which can substantially impact the corrosion resistance of the alloy [21]-[25]. In general, understanding how heat treatment affects corrosion resistance is essential to construct and optimizing the heat treatment procedure of 2024 aluminum alloy and improving its performance in aerospace and other industries. The study aims to test the impact of heat treatment on 2024 aluminum alloy. The microstructural results, mass loss, X-ray fluorescence and X-ray diffraction were discussed in detail.

2. MATERIALS AND METHODS

2.1 Material

The studied alloy is AL 2024 T3 of dimension (1 mm × 2,5cm × 2,5cm) is shown in Figure 1 while the chemical composition is shown in Table 1.

2.2 Methods

2.2.1 Heat Treatment

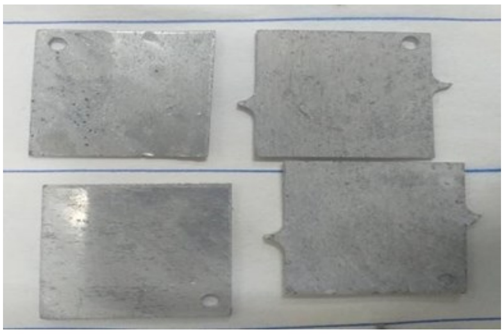

Figure 1. Aluminium alloy 2024 T3

The alloy underwent various heat treatments using the Nabertherm C440/450 type furnace: quenching, homogenization, artificial aging, and recrystallization. The homogenization temperature was 495 °C for 5 hours and followed by slow cooling in the furnace. For quenching, the samples were heated to the same temperature as the previous treatment and followed by cold water quenching. Alloys that underwent artificial aging were heated to 495 °C for 5 hours, followed by rapid cooling with water; heating to 140 °C for 2 hours and followed by slow cooling in the furnace. The recrystallization treatment was performed at 495 °C for 5 hours, followed by rapid cooling with cold water and heating to 310 °C for 3 hours in the furnace.

2.2.2 Micrography

Microstructure and phase observations were performed by OLYMPUS BX60 optical microscopy (OM) and scanning electron microscopy (SEM) model JSM-IT500HR at an accelerating voltage of 10KV. The specimens were polished to 400, 600, 800, 1000 and 1200 grit, then with 6-micron diamond paste, and finally polished to 1 micron and then etched with Flick's reagent (90 –100 mL water and 0.1–10 mL hydrofluoric acid).

2.2.3 X-ray Fluorescence

The phases of the treated samples were identified by X-ray fluorescence of type-Bruker D8 Advance. The specimens were polished to 400, 600, 800, 1000, and 1200 grit and then with 6-micron

Table 1. Characteristics of study sites.

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	Other elements
Composition%	0.5	0.5	3.8–4,9	0.3–0.9	1.2–1.8	0.1	0.25	0.15	90.7–94,7	0.05–0.15

diamond paste.

2.2.4 X-Ray Diffraction Analysis

XRD is used to identify the crystalline phases formed after heat treatment for aluminum alloy AA2024, using the diffractometer (Bruker D8 Advance), equipped with the Kα radiation of copper (λ = 0.15406 nm) produced at 40KV and the HighScore Plus (version: 3.0.0.123, Developer PANalytical B.V) software was used to identify the phases.

2.2.5 Weight loss

The mass loss was calculated by the difference between the mass of the sample before and after the climate chamber test; which is expressed by the following formula 1.

$$\text{Mass loss} = \Delta m/m0 = (mf-mi)/mi \quad (1)$$

Loss of mass by immersion: the samples are polished with silicate papers, from 400 to 1000 grains, and then exposed to the climatic chamber type EXCAL 1413-HA according to DIN 12880 for 60 cycles. Each cycle consists of 55 minutes from –30 °C to room temperature. After every six cycles, the samples were dried before weighing. Sample arrangement: The samples must never contact each other or with any metal object or body that might react aggressively, and each sample must be arranged so that the mist can flow freely over it.

3. RESULTS AND DISCUSSIONS

3.1. Effect of temperature on the microstructure of AA2024 T3

The morphologies of aluminum alloys resulting from the heat treatment tests were observed to study the effect of temperature on grain development, which were shown in Figures 2 and 3.

Figures (2) and (3) show that the 2024 T3 alloy (A) contains a large number of intermetallic

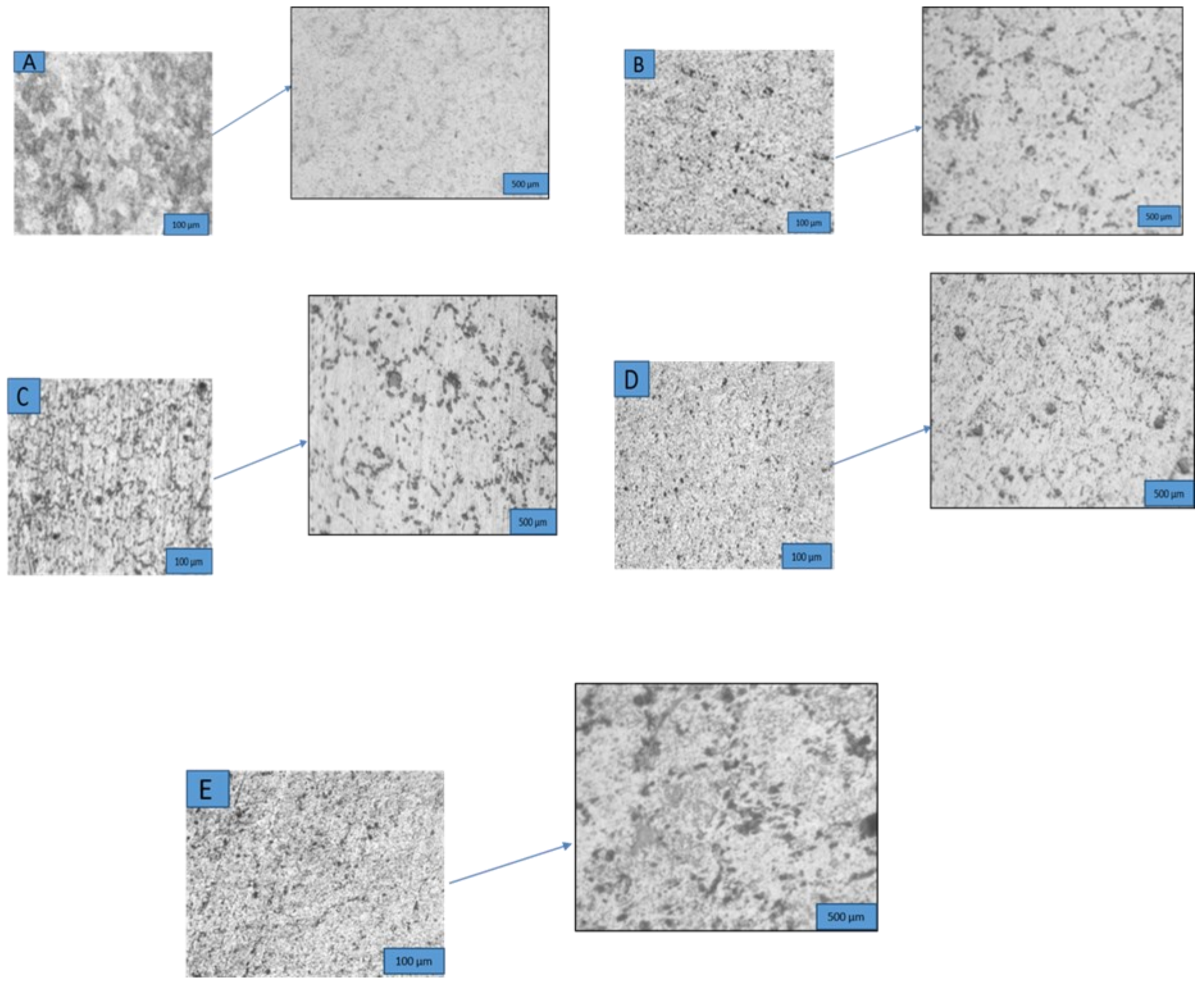

Figure 2. Micrographs of AA2024T3 materials: (A) control sample, (B) quenching sample, (C) homogenization sample, (D) artificial aging sample, and (E) recrystallization sample.

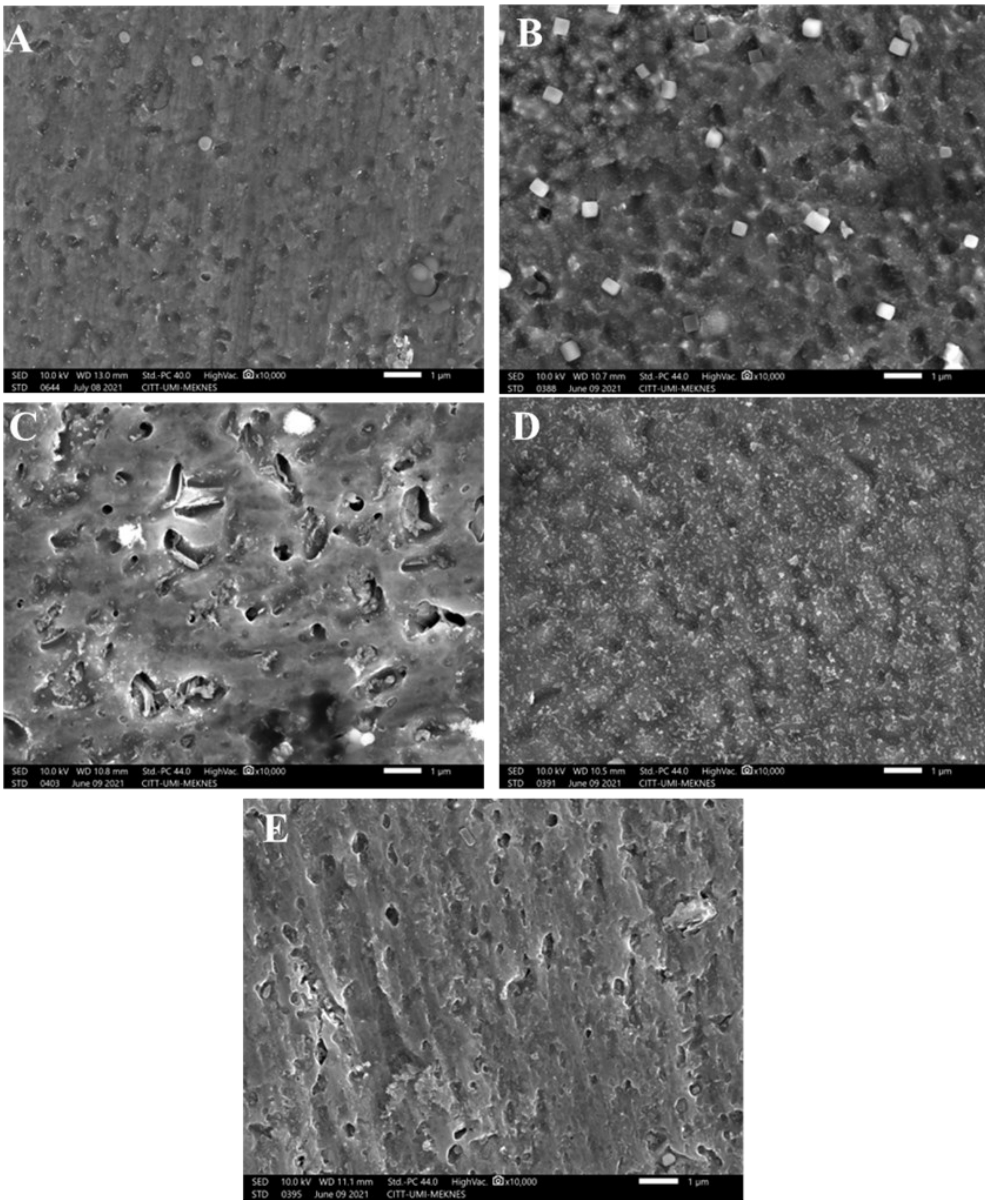

Figure 3. SEM photomicrograph of AA2024 T3 alloys: (A) control sample, (B) quenching sample, (C) homogenization sample, (D) artificial aging sample, and (E) recrystallization sample.

compound particles, which are divided into two main groups, Fe- and Mn-rich particles and Mg-rich particles. Another report by Buchheit et al. [26] has already observed this morphology. After quenching (Figures 2 and 3 (B)), we observe an increase in the number of particles and a high density of vacancies, as well as a coexistence of large and fine particles rich in Cr, Mn and Cu, in the solid solution. The micrographic observations of the 2024 alloys after solution treatment reveals a granular structure in the presence of an important quantity of intermetallic particles. These particles are the consequence of impurities such as Fe, Si and Mn as shown in figures 2 and 3 (C). Ghosh et al. [27] observed the exposure of severe dendritic segregation and the formation of secondary eutectic phases in the form of Mg (Zn, Cu, Al). They also noticed a coarse arrangement of Al_2Cu and Al_7Cu_2Fe during casting and dissolution during homogenization. The presence of two eutectic phases of Al_2CuMg and Cu_3Sn was found during the six-hour homogenization and fine dispersoids [27]. These intermetallic particles are not only large (several microns), isolated and irregularly shaped particles

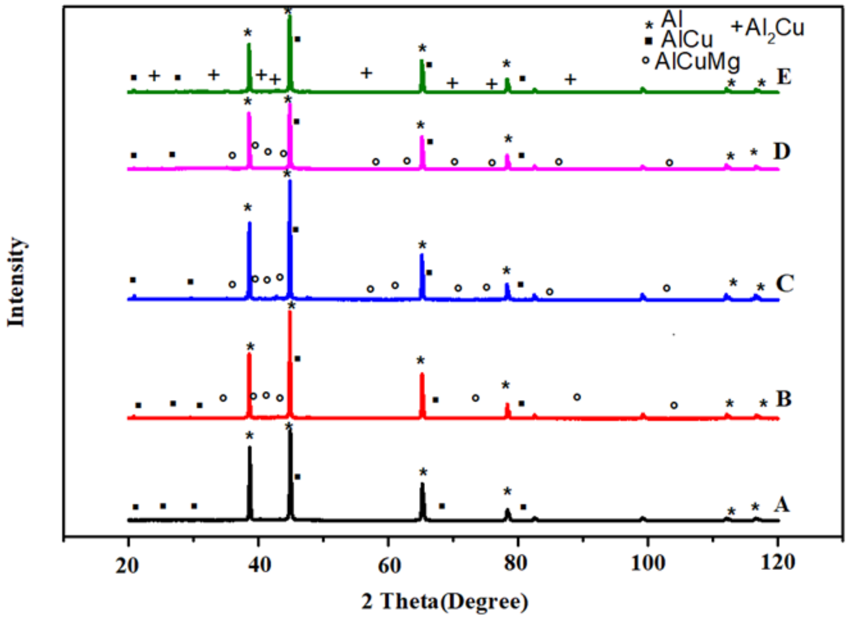

Figure 4. XRD of heat treated 2024 aluminum alloys; (A) control sample, (B) quenching sample, (C) homogenization sample, (D) artificial aging sample, and (E)recrystallization sample.

but also observed in clusters of several particles. Fine particles were observed to be homogeneously distributed within the grains. Whatever the homogenization treatment, some large particles already observed in the raw state remain insoluble. However, a significant increase in their size can be noticed. The eutectic phases evolve along with the microstructural and crystallographic textures. Yang et al. [28] found that the average cooling rate has a significant impact on the morphology of the primary AL; thus, a lower cooling rate can promote the transformation of the primary grain (Al) from a dendrite or rosette to a spherical shape. For artificial aging and recrystallization, which are shown in Figures 2 and 3 (D) and (E) respectively, we have unevenly distributed coherent and spherical dispersions that are quite absent in some regions. In contrast, they are heterogeneously distributed in other regions. In order to analyze the elements in the surfaces of each alloy, we performed X-ray fluorescence spectrometry and X-ray Diffraction.

3.2. Effect of Temperature on The Composition of AA2024 T3

The table 2 shows the composition of each element. Table 2 shows the percentage of each element on the surface of each alloy studied. The percentages of magnesium and aluminum are modified. We notice a significant increase in the percentage of magnesium and a decrease in aluminum. This can be explained by a replacement of aluminum-rich with magnesium-rich phases due to the increase in temperature. This is consistent with the results of figures (2) and (3).

Table 2. XRF of heat treated 2024 aluminum alloys

	Control	Homogenization	Quenching	Artificial aging	Recrystallization
Mg%	1.68	8.90	6.32	4.63	5.72
Al%	92.77	85.63	88.54	90.15	88.98
Cu%	4.51	4.20	4.23	4.24	4.25
Si%	0.10	0.40	0.04	0.11	0.18
Mn%	0.58	0.55	0.53	0.54	0.55
Fe%	0.19	0.19	0.19	0.19	0.18
Cr%	0.02	0	0.01	0	0.01
Zn%	0.10	0.10	0.10	0.10	0.10

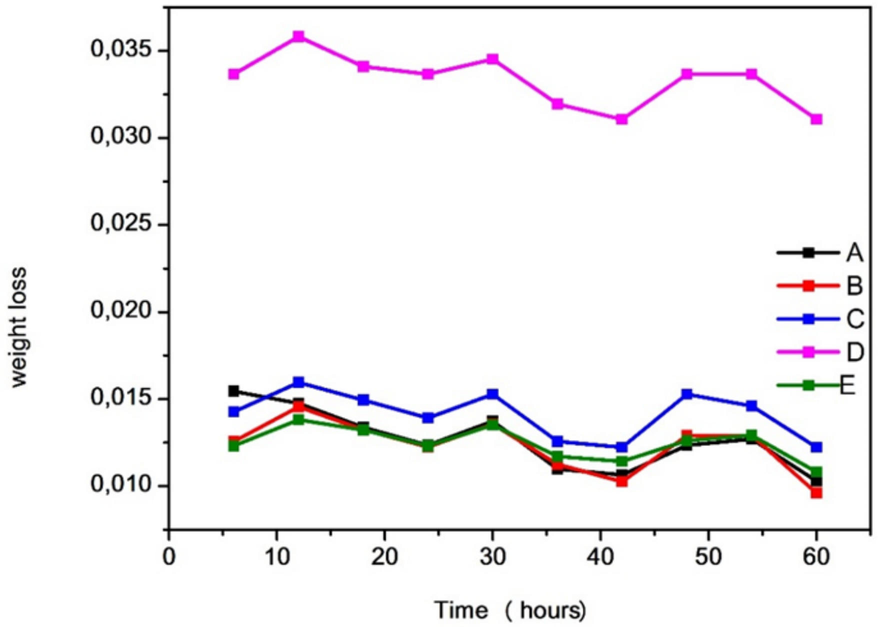

Figure 5. mass loss of the alloy as a function of immersion time in the AA2024 T3 climatic chamber (A) control sample, (B) quenching sample, (C) homogenization sample, (D) artificial aging sample, and (E) recrystallization sample.

3.3 *Effect of Heat Treatment on The XRD of AA2024 T3 Alloy*

Figure 4 shows the XRD diagrams corresponding to the 2024 aluminum alloy after the heat treatments. The phase analysis of all materials shows the presence of the Al phase and the Cu-containing intermetallic compounds generated during the melting of the alloy (Al Cu, Al_2Cu, and Al_2CuMg). It is noticed that all the alloys present characteristic peaks of the Al Cu phase (monoclinic, C2/m, a = 0.9889 nm, b = 0.4105 nm, c = 0.6913 nm) [29]. The Al_2Cu phase (tetragonal, 14/mcm, a = 0.6066 nm, c = 0.4878 nm) is present only in the recrystallization treatment, we also notice the absence of the Al_2CuMg (S) phase (orthorhombic, Cmcm, a = 0.400 nm, b = 0.923 nm, c = 0.580 nm) which suggests that they may have been dissolved during the solution heat treatment which is following the literature [30]-[33]. Mu et al. [34] speculated that θ and S phases would form in the heat-treated samples; but would be very difficult to detect by XRD due to their tiny sizes and low-volume fractions.

3.4 *Effect of Heat Treatment on The Mass Loss of AA2024 T3 Alloy*

Mass loss measurements were performed for each heat treatment. The samples were exposed to the climatic chamber in different cycles. Each cycle consists of one hour and every six cycles mass loss measurement is performed. Figure 5 shows the variation of mass loss as a function of immersion time for the different heat treatments. Curve D, which represents the artificial aging treatment curve, is very different from the other curves. Its mass loss is significantly large compared to the other treatments that underwent degradation of the solid-liquid interface resulting from oxidation of the alloy. Therefore, the sample that underwent the artificial aging treatment has better corrosion resistance compared to samples A, B, C, and E. Meyveci et al. [35] found that the wear resistance of AA 2024 aluminum alloys decreased with extreme age. Samples that were aged at 220 °C showed the most loss in mass. On the other hand, the samples of AA 2024 aluminum alloy, which had the highest hardness values and were aged at 180 °C, showed the best wear resistance. The longer the aging period, the lower the rate of mass loss. This is the result of how aging works.

4. CONCLUSIONS

In this project, we have characterized the behavior of AA 2024 alloys and determined the effect of heat treatments on the alloys. From the SEM and optical microscope observations, some microstructural textures were developed on the surface of AA 2024 alloys after heat treatment. The variation of each element on the surface of each alloy changes after heat treatment. Furthermore, the role of heat treatment is to slow down the corrosion of the studied alloy in an aggressive environment.

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Conflicts of Interest

The authors declare no conflict of interest.

REFERENCES

[1] D. Brough and H. Jouhara. (2020). "The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery". *International Journal of Thermofluids.* **1-2** https://doi.org/10.1016/j.ijft.2019.100007.

[2] D. Varshney and K. Kumar. (2021). "Application and use of different aluminium alloys with respect to workability, strength and welding parameter optimization". *Ain Shams Engineering Journal.* **12** (1): 1143-1152. https://doi.org/10.1016/j.asej.2020.05.013.

[3] Z. Wang, M. Li, Q. Han, X. Yun, K. Zhou, L. Gardner, and F. M. Mazzolani. (2022). "Structural fire behaviour of aluminium alloy structures: Review and outlook". *Engineering Structures.* **268** https://doi.org/10.1016/j.engstruct.2022.114746.

[4] M. Aamir, K. Giasin, M. Tolouei-Rad, and A. Vafadar. (2020). "A review: drilling performance and hole quality of aluminium alloys for aerospace applications". *Journal of Materials Research and Technology.* **9** (6): 12484-12500. https://doi.org/10.1016/j.jmrt.2020.09.003.

[5] A. Gloria, R. Montanari, M. Richetta, and A. Varone. (2019). "Alloys for Aeronautic Applications: State of the Art and Perspectives". *Metals.* **9** (6): https://doi.org/10.3390/met9060662.

[6] R. S. R. R. P. S. Das. (2012). "Reviews on the Influences of Alloying elements on the Microstructure and Mechanical Properties of Aluminum Alloys and Aluminum Alloy Composites". *International Journal of Scientific and Research Publications.* **2** (6): 1-7.

[7] L. Hemmouche, A. Meghalet, and A. Henni Chebra. (2018). "Influence of Heat Treatments on the Fracture Toughness of 2017A Aluminium Alloy". *Physics of Metals and Metallography.* **119** (3): 301-308. https://doi.org/10.1134/s0031918x18010118.

[8] A. Cochard, K. Zhu, S. Joulié, J. Douin, J. Huez, L. Robbiola, P. Sciau, and M. Brunet. (2017). "Natural aging on Al-Cu-Mg structural hardening alloys – Investigation of two historical duralumins for aeronautics". *Materials Science and Engineering: A.* **690** 259-269. https://doi.org/10.1016/j.msea.2017.03.003.

[9] C. G. Rhodes, M. W. Mahoney, W. H. Bingel, R. A. Spurling, and C. C. Bampton. (1997). "Effects of friction stir welding on microstructure of 7075 aluminum". *Scripta Materialia.* **36** (1): 69-75. https://doi.org/10.1016/s1359-6462(96)00344-2.

[10] V. K. Yadav, V. Gaur, and I. V. Singh. (2020). "Effect of post-weld heat treatment on mechanical properties and fatigue crack growth rate in welded AA-2024". *Materials*

Science and Engineering: A. **779** https://doi.org/10.1016/j.msea.2020.139116.

[11] H. Chen, C. Zhang, D. Jia, D. Wellmann, and W. Liu. (2020). "Corrosion Behaviors of Selective Laser Melted Aluminum Alloys: A Review". *Metals.* **10** (1): https://doi.org/10.3390/met10010102.

[12] P. Lequeu, P. Lassince, T. Warner, and G. M. Raynaud. (2001). "Engineering for the future: weight saving and cost reduction initiatives". *Aircraft Engineering and Aerospace Technology.* **73** (2): 147-159. https://doi.org/10.1108/00022660110386663.

[13] L. H. Zhan, Y. G. Li, and M. H. Huang. (2011). "Effect of Process Parameters on Microstructures of 7055 Aluminum Alloy in Creep Age Forming". *Applied Mechanics and Materials.* **80-81** 40-45. https://doi.org/10.4028/www.scientific.net/AMM.80-81.40.

[14] C. K. S. Moy, M. Weiss, J. Xia, G. Sha, S. P. Ringer, and G. Ranzi. (2012). "Influence of heat treatment on the microstructure, texture and formability of 2024 aluminium alloy". *Materials Science and Engineering: A.* **552** 48-60. https://doi.org/10.1016/j.msea.2012.04.113.

[15] Y. T. Lin, D. P. Wang, M. C. Wang, Y. Zhang, and Y. Z. He. (2016). "Effect of different pre- and post-weld heat treatments on microstructures and mechanical properties of variable polarity TIG welded AA2219 joints". *Science and Technology of Welding and Joining.* **21** (3): 234-241. https://doi.org/10.1179/1362171815y.0000000087.

[16] H. K. Pabandi, H. R. Jashnani, and M. Paidar. (2018). "Effect of precipitation hardening heat treatment on mechanical and microstructure features of dissimilar friction stir welded AA2024-T6 and AA6061-T6 alloys". *Journal of Manufacturing Processes.* **31** 214-220. https://doi.org/10.1016/j.jmapro.2017.11.019.

[17] J. Gu, J. Ding, S. W. Williams, H. Gu, J. Bai, Y. Zhai, and P. Ma. (2016). "The strengthening effect of inter-layer cold working and post-deposition heat treatment on the additively manufactured Al–6.3Cu alloy". *Materials Science and Engineering: A.* **651** 18-26. https://doi.org/10.1016/j.msea.2015.10.101.

[18] J. Y. Bai, C. L. Fan, S. B. Lin, C. L. Yang, and B. L. Dong. (2017). "Mechanical Properties and Fracture Behaviors of GTA-Additive Manufactured 2219-Al After an Especial Heat Treatment". *Journal of Materials Engineering and Performance.* **26** (4): 1808-1816. https://doi.org/10.1007/s11665-017-2627-5.

[19] Z. Qi, B. Cong, B. Qi, G. Zhao, and J. Ding. (2018). "Properties of wire + arc additively manufactured 2024 aluminum alloy with different solution treatment temperature". *Materials Letters.* **230** 275-278. https://doi.org/10.1016/j.matlet.2018.07.144.

[20] Z. Qi, B. Qi, B. Cong, H. Sun, G. Zhao, and J. Ding. (2019). "Microstructure and mechanical properties of wire + arc additively manufactured 2024 aluminum alloy components: As-deposited and post heat-treated". *Journal of Manufacturing Processes.* **40** 27-36. https://doi.org/10.1016/j.jmapro.2019.03.003.

[21] S. G. H. M. A. A.-S. A. M. T. M. Al-Waily. (2020). "Effect of Heat Treatment on Mechanical and Vibration Properties for 6061 and 2024 Aluminum Alloys". *Journal of Mechanical Engineering Research and Developments.* **43** (1): 48-66.

[22] L. Dong, G. Liu, X. Ye, and W. Wang. (2018). "Study on the Design of Container Highway and Railway Automatic Transfer Vehicle in Ocean Port". *Polish Maritime Research.* **25** (s3): 5-12. https://doi.org/10.2478/pomr-2018-0106.

[23] P. Rambabu, N. Eswara Prasad, V. V. Kutumbarao, and R. J. H. Wanhill. (2017). In: " Aerospace Materials and Material Technologies, (Indian Institute of Metals Series, ch. Chapter 2. " pp. 29-52. https://doi.org/10.1007/978-981-10-2134-3_2.

[24] H. Subawi and Sutarno. (2014). "The Phenomenon of Pitting Corrosion Attack on the Milled Aluminium Alloy Al 2618 Plate during Surface Preparation through Sulphuric Acid Anodising". *Advanced Materials*

Research. **896** 596-599. https://doi.org/10.4028/www.scientific.net/AMR.896.596.

[25] M. Cabrini, S. Lorenzi, C. Testa, T. Pastore, D. Manfredi, M. Lorusso, F. Calignano, and P. Fino. (2019). "Statistical approach for electrochemical evaluation of the effect of heat treatments on the corrosion resistance of AlSi10Mg alloy by laser powder bed fusion". *Electrochimica Acta.* **305** 459-466. https://doi.org/10.1016/j.electacta.2019.03.103.

[26] R. G. Buchheit, R. P. Grant, P. F. Hlava, B. McKenzie, and G. L. Zender. (2019). "Local Dissolution Phenomena Associated with S Phase (Al2CuMg) Particles in Aluminum Alloy 2024-T3". *Journal of The Electrochemical Society.* **144** (8): 2621-2628. https://doi.org/10.1149/1.1837874.

[27] A. Ghosh, M. Ghosh, A. H. Seikh, and N. H. Alharthi. (2020). "Phase transformation and dispersoid evolution for Al-Zn-Mg-Cu alloy containing Sn during homogenisation". *Journal of Materials Research and Technology.* **9** (1): 1-12. https://doi.org/10.1016/j.jmrt.2019.08.055.

[28] B. Yang, W.-m. Mao, and X.-j. Song. (2013). "Microstructure evolution of semi-solid 7075 Al alloy slurry during temperature homogenization treatment". *Transactions of Nonferrous Metals Society of China.* **23** (12): 3592-3597. https://doi.org/10.1016/s1003-6326(13)62905-2.

[29] S. C. Wang and M. J. Starink. (2013). "Precipitates and intermetallic phases in precipitation hardening Al–Cu–Mg–(Li) based alloys". *International Materials Reviews.* **50** (4): 193-215. https://doi.org/10.1179/174328005x14357.

[30] Y. L. Zhao, Z. Q. Yang, Z. Zhang, G. Y. Su, and X. L. Ma. (2013). "Double-peak age strengthening of cold-worked 2024 aluminum alloy". *Acta Materialia.* **61** (5): 1624-1638. https://doi.org/10.1016/j.actamat.2012.11.039.

[31] Y. Meng, H. Zhang, X. Li, X. Zhou, H. Mo, L. Wang, and J. Fan. (2022). "Tensile Fracture Behavior of 2A14 Aluminum Alloy Produced by Extrusion Process". *Metals.* **12** (2): https://doi.org/10.3390/met12020184.

[32] J. Chen, J. Zhang, H. Shen, H. Liao, and H. Li. (2021). "Alloying effect of Mg on microstructure and mechanical properties at 300 °C of Al–5Cu–1Mn–0.5Ni heat-resistant alloy". *Materials Research Express.* **8** (8): https://doi.org/10.1088/2053-1591/ac1d67.

[33] S. P. Ringer and K. Hono. (2000). "Microstructural Evolution and Age Hardening in Aluminium Alloys". *Materials Characterization.* **44** (1-2): 101-131. https://doi.org/10.1016/s1044-5803(99)00051-0.

[34] D. Mu, Z. Zhang, J. Liang, J. Wang, and D. Zhang. (2022). "Investigation of Microstructures and Mechanical Properties of SiC/AA2024 Nanocomposites Processed by Powder Metallurgy and T6 Heat Treatment". *Materials (Basel).* **15** (10): https://doi.org/10.3390/ma15103547.

[35] A. Meyveci, İ. Karacan, U. Çalıgülü, and H. Durmuş. (2010). "Pin-on-disc characterization of 2xxx and 6xxx aluminium alloys aged by precipitation age hardening". *Journal of Alloys and Compounds.* **491** (1-2): 278-283. https://doi.org/10.1016/j.jallcom.2009.10.142.