International Journal of Applied Science and Engineering

Effect of heat treatment on the mechanical properties of the aluminium alloys AA2024 with nanoparticles

Hamid M. Mahan[1,3*], S.V. Konovalov[1,2], Irina Panchenko[2]

[1] *Samara National Research University, Moskovskoye road, 34, 443086, Samara, Russia*
[2] *Siberian State Industrial University, Kirov str., 42, 654007, Novokuznetsk, Russia*
[3] *Technical Institute of Baquba, Middle Technical University, Baghdad 10074, Iraq*

ABSTRACT

An aluminum alloy, AA2024, was reinforced with different mass fractions of titanium dioxide nanoparticles (0%, 2.5%, 5% and 7.5%) by stir casting, this was followed by a solution treatment at 500°C for 3 h, quenching in water, and aging at 175°C for 3 h. The purpose was to investigate the effect of TiO_2 nanoparticles on the microstructure and mechanical properties of the stir-cast aluminium alloy AA2024. Through ageing treatment, the effects of heat treatment conditions on the homogeneity of the impact toughness and microhardness of AA2024 with nanoparticles were studied. After heat treatment and ageing treatment, the hardness values and impact resistance in different positions of the composite aluminium are greatly improved compared to the unreviewed samples. Furthermore, the distribution of elements existed in the interior of the grain boundary, and the grain was homogeneous after heat treatment, which increased the intercrystallite hardness values. The results showed that 5 wt.% TiO_2 was the optimum fraction to achieve the highest microhardness and impact resistance. Using the optimum content of TiO_2 and heat treatment, the microhardness and impact resistance were significantly improved over the unreinforced aluminium matrix, specifically due to an increased number of fine precipitates that were uniformly distributed after the heat treatment.

Keywords: Metal matrix, Nanoparticles, Charpy impact, Temperature, Energy absorption, Aging.

OPEN ACCESS

Received: November 23, 2022
Revised: March 12, 2023
Accepted: April 03, 2023

Corresponding Author:
Hamid M. Mahan
hamid.m.mahan@mtu.edu.iq

Publisher:
Chaoyang University of Technology
ISSN: 1727-2394 (Print)
ISSN: 1727-7841 (Online)

1. INTRODUCTION

One of the most challenging aspects of producing strong, lightweight, and affordable engineering materials is achieving a high strength-to-weight ratio suitable for use in vehicles. The global demand for such materials in the automotive and aerospace industries has drawn the attention of researchers in the field of composite materials. The dependable in-service performance of materials is critical for strategic applications. Strength and ductility are both important properties for reliable performance. Therefore, high-strength, ductile metallic alloys have received considerable attention for both fundamental research and industrial applications. Alloys have been the most common material for commercial and military aircraft structures for approximately 80 years, and this trend will continue for some time (Chaudhry et al., 2019), owing to their well-established mechanical response, ease of design, mature production techniques, and inspection procedures (Andersen et al., 2018; Aybarç et al., 2021). Thus, aluminum alloy manufacturers must continue to invest significant efforts in enhancing the thermo-mechanical properties of their products, as non-metallic materials provide a highly competitive alternative (Doebelin et al., 2015; Clement et al., 2022), notwithstanding the concerns highlighted earlier. Parameters such as impact strength, Young's modulus, density, corrosion resistance, fatigue resistance, and fracture toughness require improvement (Gong et al., 2021). Some components require material qualities that are superior to what polymer composites can provide (Isadare et al., 2013; Heiba et al., 2016). Processing control and chemical composition the microstructural features such as degree of recrystallization, grain size, precipitates, dispersions, shape, intermetallic constituent particles and crystallographic texture (Mahan et al., 2018; Guner et al., 2019), which affect the mechanical, corrosion, and physical qualities of aluminium alloys. As a result, material manufacturers working closely with aircraft designers have been able to develop several metallic alloys with mechanical and physical properties tailored to the specific requirements (Joel et al., 2019).

The mechanical properties of the materials have been optimised, which can lead to longer times between services and lower repair costs. Machine makers and material producers are concentrating their efforts on the development of new materials to fulfil the requirements of their customers in order to cut costs (Kaneko et al., 2009). As a result, a current challenge is to develop materials that can be used in machining manufacturing with improvements in both life cycle cost and structural performance (Karpikhin et al., 2016). According on the design tests, lowering the density of the materials is a good way to make the machine lighter. Increases in elastic modulus, tensile strength, and damage 3e tolerance 4 are found to be 3–5 times more effective than decreasing density (Kilic et al., 2019).

The aluminium alloy (2xxx series) is the key alloys utilized in airplane structural applications where damage tolerance is the fundamental design criterion (Ma et al., 2014). The magnesium alloys of the 2xxx series have increased strength as a result of the precipitation of Al_2Cu and Al_2CuMg phases of destruction and high-quality damage resistant to fatigue crack propagation in comparison to other aluminium alloys (Ozer et al., 2017). Al-Cu-Mg alloys 2024 and 2014 are well-known examples of this. Compositional and processing modifications to 2224-T351 alloys resulted in enhanced characteristics compared to 7050 (Santos et al., 2021). A smaller volume proportion of intermetallic compounds enhanced fracture toughness. For example, 2224-T351 has a maximum iron concentration of 0.12 percent, whereas 7050 has a maximum silicon value of 0.10 percent (Suneesh et al., 2021). The aluminium alloy 2026 is based on the alloy 2024, it has a lower concentration of iron and silicon impurities. Moreover, 2026 has a trace quantity of zirconium, which prevents recrystallization (Xavior et al., 2021). The tensile strength, fatigue resistance, damage tolerance, performance, and fracture toughness of 2026 are all better than those of 2024. Intermetallic phase particles lower the alloy's wear rate even if Cu and Mg in the intermetallic phase give it excellent strength. Intermetallic phase particles lower the alloy's wear rate even if Cu and Mg in the intermetallic phase give it excellent strength (Zhao et al., 2021). The corrosion resistance and fatigue of 2000 series alloys have been improved in numerous studies. A stir casting approach was used by (Jaber et al., 2020) to create AA 6063-T6 supported by TiO_2 nanoparticles at 3, 5 and 7 wt.% TiO_2 nanoparticles. The results showed that in SEM pictures of 7 wt.% TiO_2 composites, the distribution of TiO_2 in the metal matrix was rather uniform. The magnetic tests showed that the nanocomposites performed better than the base metal. There was no difference in magnetic characteristics between AA 6063-T4 / 7 wt.% TiO_2 and the bulk matrix.

Using the stir casting liquid technique (Patel et al., 2022), we conducted a study to reinforce the AA5052 matrix with 5 wt.% SiC particulates of 63μm particle size. The optical and SEM micrographs of the AA5052/SiC-p MMC showed a uniform distribution of SiC particles, while XRD analysis ascertained the presence of SiC in the AA5052 matrix. Also, the study found that with the addition of 5 wt.% SiC particles, the density of the AA5052 rises by 0.8%. and developed compositions have a very low percentage of porosity.

The AA2024 aluminium alloy was selected as the base metal due to its outstanding properties, including low density, specific strength, and widespread use in the aerospace industry. Metallic nanocomposites have garnered significant attention from researchers for their broad range of applications in the aerospace industry, automotive and energy production technologies, and biomedical engineering, owing to their unique nanoscale architecture and superior mechanical properties. In this study, the microhardness and impact strength of the AA2024 aluminium alloy were investigated with varying weights of nanoparticles, along with the effect of heat treatment on the mechanical properties of the AA2024 aluminium composite.

2. MATERIALS AND METHODS

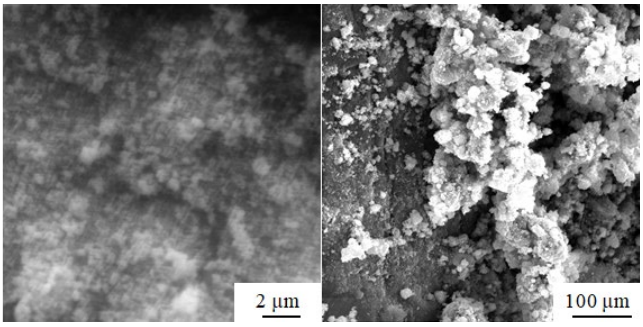
For this study aluminum alloy AA2024 was chosen. Aluminum samples were chemically analyzed. The obtained results confirm that the type of the examined alloys was AA2024 as shown in the Table 1.

During the study, the alloy is reinforced using various weight percentages (0, 2.5, 5 and 7.5 wt.% TiO2) where the nanoparticles have a size of 30 ± 5 nm Fig. 1. Before adding TiO2 nano powder with the different weight percent of 2.5, 5 and 7.5 wt.%, AA2024 aluminium alloy was

Table 1. Standard and experimentetall chemical compositions of AA2024 alloy (wt.%)

Element	Mg	Si	Cu	Mn	Ti	Cr	Zn	Fe	Al
Standard	1.2-1.8	Max 0.5	3.8-4.9	0.3-0.9	Max 0.15	Max 0.1	Max 0.25	Max 0.5	90.7-94.7
Measured	1.06	0.098	4. 5	0.67	0.03	0.009	0.15	0.25	Balance

preheated to 700°C (more than the matrix melting temperature) in a graphite crucible using an electrical furnace to ensure the complete melting of all its components. The stir casting technique was utilized for 4 min at 200 rpm.



(a) (b)

Fig. 1. SEM micrographs of TiO_2 nanoparticles

Then the molten material was poured into a mould and removed after solidification. The samples were then solution annealed by heating to 500°C for 3 h in an air-circulated furnace, water quenched at room temperature, and precipitation annealed (aged) at 175ºC for 3 h Fig. 2.

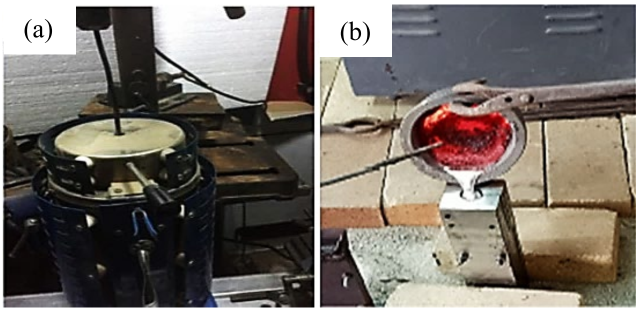


Fig. 2. (a) The stir casting furnace for melting and (b) casting mould

Samples of aluminum alloy AA2024 were tested for impact strength and hardness. In conformity with american norms, all studies were conducted at room temperature (ASTM). It was done utilizing a micro hardness device for the hardness test vickers method (Axiovert-200M), and the prepared hardness test specimens have the following dimensions: 20 × 20 × 5 mm. The impact strength of the created composites was evaluated in line with ASTM-E23 by conducting a charpy impact test. This test measures a material's resistance to sudden shocks. The prepared impact test specimens had dimensions of 55 × 10 × 10 mm.

3. RESULTS AND DISCUSSION

3.1 Micro Hardness

In Fig. 3, it can be observed that the addition of nanoparticles has an impact on the hardness of various materials. The average hardness of samples with 2.5% and 5 wt.% TiO_2 increased to 84 and 95 HV, respectively, compared to the sample without nanoparticles, which had a hardness of 77 HV. The microhardness of the samples improved with an increase in the amount of nanoparticles, which can be attributed to a more even distribution of precipitates and particles in the microstructure, as tiny precipitates form after the introduction of nanoparticles. The development of uniform and fine precipitates and intermetallic compounds (IMCs) creates more strain fields, which interact with dislocations to reduce dislocation motion and, thus, increase the hardness strength of the samples. As the weight percent of titanium oxide increases, the amount of Al-Ti-based IMCs also increases, and their high hardness is expected to be the most significant factor in increasing the alloy's hardness by adding titanium oxide, which is consistent with the findings of (Jaber et al., 2020).

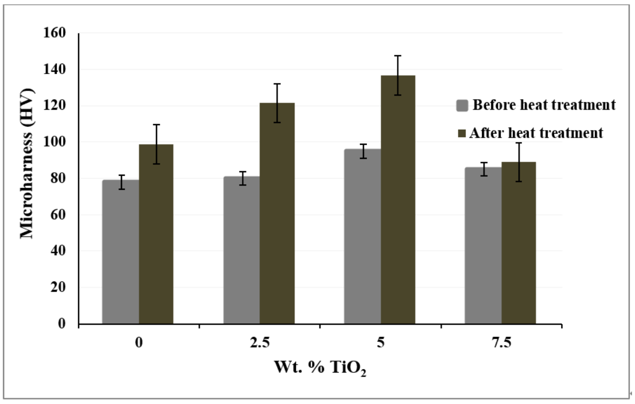
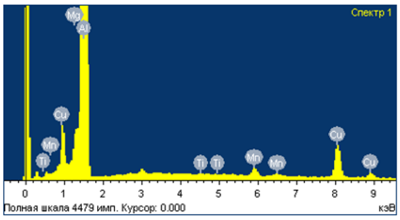


Fig. 3. Effect nanoparticles on the hardness AA2024 composite

As shown in Fig. 4, the alloying elements were uniformly dispersed in the solid solution, and the presence of nano-reinforcements in the matrix increased the nucleation centers, this resulted in the formation of numerous new grains and an improvement in the strength, resistance, and microstructure of the material. The increase in hardness can be attributed to the uniformity of the microstructure and the more even distribution of Al_2CuMg precipitates, which act as strengthening factors in aluminum alloys with nanoparticles. As more titanium particles are added, the formation of Al_2CuMg compounds decreases, and the formation of Al_2Ti_7Cu compounds increases. Consequently, after heat treatment, the hardness increases significantly due to the formation of numerous titanium-rich intermetallic compounds.

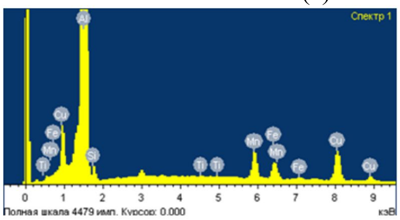
After heat treatment and ageing heating of the samples, the material reached its maximum hardness due to the presence of micro-segregations in its structure. This increased hardness is achieved through the improved distribution of AA2024 compounds. Finer intermetallic compounds are better able to pin grain boundaries and enhance hardness, which is consistent with previous research (Kaneko et al., 2009). This finding is consistent with previous research that has shown that solid solution and grain refinement also contribute to the hardening of Al-

MgCu alloys. Additionally, fine-grained materials, which have more grain boundaries, tend to be harder and stronger than coarse-grained materials with fewer grain boundaries (Ma et al., 2014). Aged-hardened materials have more grain boundaries than as-cast and annealed samples, and this hampers dislocation motion during deformation, making them harder and stronger. However, when the amount of TiO_2 was increased to 7.5 wt.%, the hardness of the material decreased significantly. This is because the sample with 7.5 wt.% TiO_2 had more precipitates, which could alter the microstructure of the aluminum composite.



Element	Wt.%	At%
Mg K	1.04	1.21
Al K	90.87	95.09
Mn K	0.96	0.49
Fe K	0.68	0.34
Cu K	6.46	2.87
Ti K	0.11	0.13

(a)



Element	Wt.%	At%
Mg K	0.60	0.68
Al K	93.25	95.74
Ti K	0.11	0.16
Mn K	0.61	0.31
Fe K	0.31	0.15
Cu K	3.63	1.58

(b)

Fig. 4. EDS results of different particles and precipitates for 5% nanoparticle sample (a) before and (b) after heat treatment

3.2 Impact Resistance

The impact tests conducted on the samples revealed that the 5 wt.% TiO_2 sample had the highest percentage and best impact strength, as shown in Fig. 5. When these particles are added to the composite, they make it harder for cracks to form and prevent their propagation. Additionally, the reinforcing particles raise the stress threshold required for dislocations to move, which makes the nanocomposites stronger. However, as the number of particles in the sample increases (7.5 wt.% TiO_2), the impact strength values decrease, as shown in Fig. 5. This is because these particles are brittle and act as stress concentration regions from which the failure initiates. Moreover, weakness in their ability to resist an impact load may also contribute to the decline in impact strength.

The improvement in impact strength after heat treatment can be attributed to the difference in grain size at the microstructural level. Finer grains impose more limitations, and movement across these grain boundaries is necessary for plastic deformation. Because the crystallographic orientations of polycrystalline grains fluctuate at grain borders, a dislocation travelling from one grain to the next must change its direction of motion. Such changes in direction weaken impact strength and hinder dislocation movement. As aged samples have the highest number of grain boundaries, dislocation movement becomes increasingly difficult during plastic deformation, which explains why age-hardened samples exhibit the highest impact strength. Moreover, the presence of nano-reinforcements in the matrix increases the nucleation centers, leading to the formation of many new grains and improving the strength, resistance, and microstructure of the material. The heat treatment resulted in the formation of numerous new grains, which significantly increased the strength and resistance of the material, and improved its microstructure. After heat treatment, the precipitates containing the chemical compound $CuAl_2$ became smaller, and a band without precipitates formed near the areas between the dendrites. As a result, copper elements were able to move into the intermetallic compounds with high iron content, causing the areas between the dendrites to become low in copper. This stopped the formation of Al_2CuMg precipitates in those areas, and the significant increase in hardness and impact resistance was due to the formation of a large amount of titanium-rich intermetallic compounds.

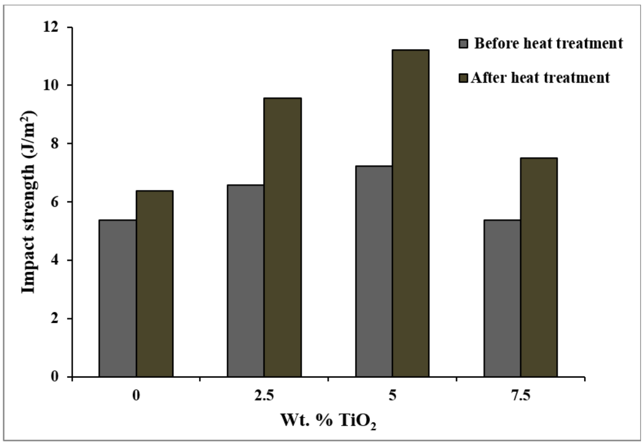


Fig. 5 Effect nanoparticles on the impact strength AA2024 composite

3.3 Microstructure of the Materials

Using an optical microscope, we studied the microstructure of the samples. We found that the AA2024 alloy in the transverse plane has a microstructure consisting of fine grains with a composition of Al-Mn-Mg-Cu, as shown in Fig. 6. This microstructure helped some inclusions to become spherical, and the presence of copper in the alloy is necessary to make it stronger. This is achieved by mixing the solid solution and letting the particles harden in place.

After artificial aging at 500°C for 3 h and 170°C for 3 h, precipitation hardening by structural precipitates of $MgCuZn_2$ generated during artificial aging is the primary strengthening mechanism in these alloys, as shown in Fig. 7. The precipitate particles act as obstacles to dislocation movement and thereby strengthen the heat-treated alloys. Moreover, the presence of nano-reinforcements in the matrix increases the nucleation centers, resulting in a large number of new grains. As a result, significant increases in strength, resistance, and hardness were observed, as reported by (Clement et al., 2022).

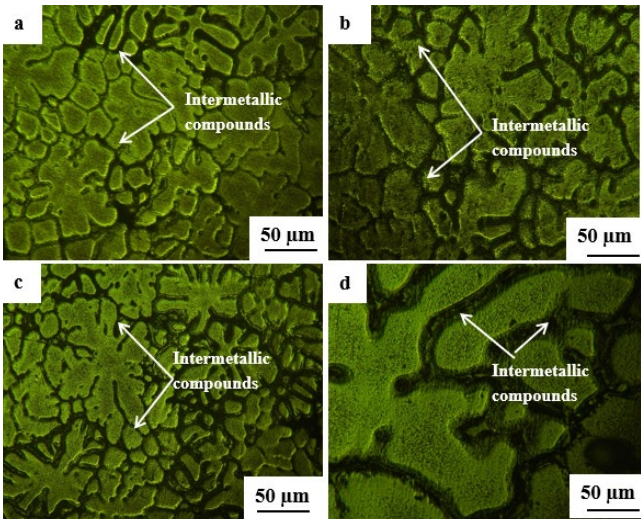


Fig. 6. SEM of the fabrication nanocomposites AA2024 before heat treatment with different volume fractions: (a) 0 wt.% TiO_2, (b) 2.5 wt.% TiO_2, (c) 5 wt.% TiO_2 and (d) 7.5 wt.% TiO_2

The heat-treated specimens exhibit a homogenized microstructure, but it is impossible to completely eliminate all the precipitates. Artificially aged specimens provided maximum hardness. This represents a 40% increase in hardness values obtained for heat-treated samples compared to as-built specimens due to precipitation hardening. Intermetallic particles form due to the presence of Ti in the alloy's chemical composition. Heat treatment induces diffusion and segregation of cu and Mg atoms, leading to the formation of $MgCu_2Al$ rich precipitates and the random distribution of Ti particles in the aluminum matrix This is consistent with the findings of (Ngnekou et al., 2019).

4. CONCLUSIONS

The composite material, consisting of a different weight percentage of TiO_2 nanomaterials as reinforcement in the AA2024 alloy matrix, was fabricated using the stir casting method and heat treatment. The experimental investigation yielded the following findings, which were then compared with the mechanical properties of the base material from several trials.

The nanocomposite AA2024-TiO_2 exhibited superior comprehensive properties, demonstrating improved impact strength and hardness values. The high strength of AA2024 TiO_2 nanocomposite was mainly attributed to ultra-fine grains and dislocation strengthening caused by TiO_2 nanoparticles. Enhanced mechanical properties of the composite were also observed. It is evident that there is good bonding between the matrix and the reinforcement particles, resulting in better load transfer from the matrix to the reinforcement material.

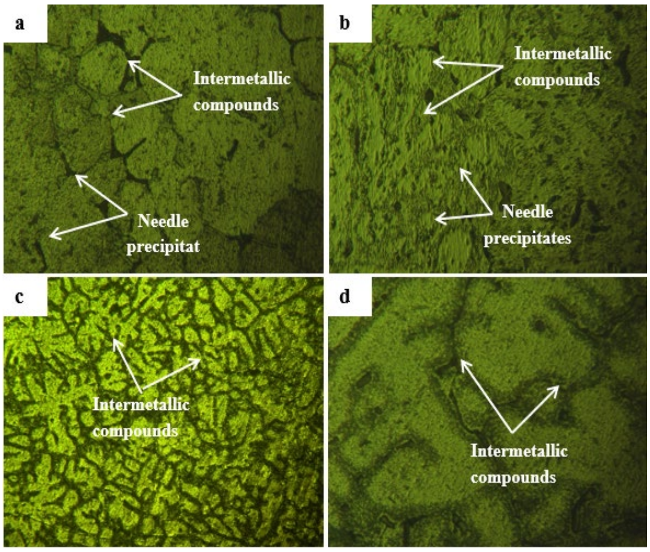


Fig. 7. SEM of the fabrication nanocomposites AA2024 before heat treatment with different volume fractions: (a) 0 wt.% TiO_2, (b) 2.5 wt.% TiO_2, (c) 5 wt.% TiO_2 and (d) 7.5 wt.% TiO_2

$MgCu_2Al$ precipitation is observed at ageing temperatures of 170°C. The spread of $MgCu_2Al$ dispersions increase the strength. When $MgCu_2Al$ precipitates are aged at these temperatures for an extended period of time, the microstructure softens. The fast solidification process and heat treatment were shown to significantly improve several mechanical properties and reduce micro segregation. The operation of age hardening by heat treatment was discovered to boost hardness values and impact strength. Therefore, annealing treatment of the alloy will be suitable for applications involving high toughness and ductility, while age hardening treatment will be suitable for applications that require high impact strength and hardness values.

ACKNOWLEDGEMENT

The researcher would like to extend their sincerest gratitude to the staff at the Samara National Research University, 443086, 34 Moskovskoye Shosse, Samara, Russia, and the Materials Engineering Department, samara, Russia

REFERENCE

Andersen, S.J., Marioara, C.D., Friis, J., Wenner, S., Holmestad, R. 2018. Precipitates in aluminium alloys. Advances in physics: X, 3, 1479984.

Aybarç, U., Ertuğrul, O., Seydibeyoğlu, M.Ö. 2021. Effect of Al_2O_3 particle size on mechanical properties of ultrasonic-assisted stir-casted Al A356 matrix composites. International Journal of Metalcasting, 15, 638–649.

Chaudhry, M.A., Ali, L., Ghauri, K.M., Iqbal, J. 2019. Development and characterization of nanoparticle metal matrix composites: (Al 2024-SiC np). Materials Research Express, 6, 095032.

Clement, C.D., Masson, J., Kabir, A.S. 2022. Effects of heat treatment on microstructure and mechanical properties of alsi10mg fabricated by selective laser melting process. Journal of Manufacturing and Materials Processing, 6, 52.

Doebelin, N., Kleeberg, R. 2015. Profex: A graphical user interface for the Rietveld refinement program BGMN. Journal of Applied Crystallography, 48, 1573–1580.

Gong, W., Xie, M., Zhang, J. 2021. Giant bake hardening response of multi-scale precipitation strengthened Al-Mg-Si-Cu-Zn alloy via pre-aging treatments. Materials Characterization, 181, 111464.

Guner, A.T., Dispinar, D., Tan, E. 2019. Microstructural and mechanical evolution of semisolid 7075 Al alloy produced by SIMA process at various heat treatment parameters. Arabian Journal for Science and Engineering, 44, 1243–1253.

Mahan, H.M., Mahjoob, D.S., Mahmood, K.I. 2018. Mechanical properties of alumina nano-particles and glass fiber, Kevlar fiber reinforced composites. Journal of Engineering and Applied Sciences, 13, 9096–9100.

Heiba, Z.K., Mohamed, M.B., Wahba, A.M. 2016. Effect of Mo substitution on structural and magnetic properties of Zinc ferrite nanoparticles. Journal of Molecular Structure, 1108, 347–351.

Isadare, A.D., Aremo, B., Adeoye, M.O., Olawale, O.J., Shittu, M.D. 2013. Effect of heat treatment on some mechanical properties of 7075 aluminium alloy. Materials Research, 16, 190–194.

Jaber, M.H., Aziz, G.A., Mohammed, A.J., AL-AIKawi, H.J. 2020. Electrical conductivity, magnetic and fatigue properties of aluminum matrix composites reinforced with nano-titanium dioxide (TiO_2). Nanocomposites, 6, 47–55.

Joel, J., Xavior, A. 2019. Effect of alloying elements on the mechanical behavior of microwave synthesized composites. Procedia Manufacturing, 30, 208–215.

Kaneko, K., Hata, T., Tokunaga, T., Horita, Z. 2009. Fabrication and characterization of supersaturated Al-Mg alloys by severe plastic deformation and their mechanical properties. Materials transactions, 50, 76–81.

Karpikhin, A.E., Fedotov, A.Y., Komlev, V.S., Barinov, S.M., Sirotinkin, V.P., Gordeev, A.S., Shamrai, V.F. 2016. Structure of hydroxyapatite powders prepared through dicalcium phosphate dihydrate hydrolysis. Inorganic Materials, 52, 170–175.

Kilic, S., Kacar, I., Sahin, M., Ozturk, F., Erdem, O. 2019. Effects of aging temperature, time, and pre-strain on mechanical properties of AA7075. Materials Research, 22.

Ma, K., Wen, H., Hu, T., Topping, T.D., Isheim, D., Seidman, D.N., Lavernia, E.J., Schoenung, J.M. 2014. Mechanical behavior and strengthening mechanisms in ultrafine grain precipitation-strengthened aluminum alloy. Acta Materialia, 62, 141–155.

Ngnekou, J.N.D., Nadot, Y., Henaff, G., Nicolai, J., Kan, W.H., Cairney, J.M., Ridosz, L. 2019. Fatigue properties of AlSi10Mg produced by additive layer manufacturing. International Journal of Fatigue, 119, 160–172.

Özer, G., Karaaslan, A. 2017. Relationship of RRA heat treatment with exfoliation corrosion, electrical conductivity and microstructure of AA7075 alloy. Materials and Corrosion, 68, 1260–1267.

Patel, M., Sahu, S.K., Singh, M.K., Dalai, N. 2022. Micro-structural and mechanical characterization of stir cast AA5052/B4C metal matrix composite. Materials Today: Proceedings, 56, 1129–1136.

Santos, S.L.D., Toloczko, F.R., Merij, A.C., Saito, N.H., Silva, D.M.D. 2021. Investigation and nanomechanical behavior of the microconstituents of Al-Si-Cu alloy after solution and ageing heat treatments. Materials Research, 24.

Suneesh, E., Sivapragash, M. 2021. Behaviour of micro-and nano-alumina-reinforced Mg-3Zn-0.7 Zr-1Cu alloy composites processed at different sintering temperatures. Rare Metals, 40, 143–155.

Xavior, M.A., Ranganathan, N., Kumar, H.P., Joel, J., Ashwath, P. 2018. Mechanical properties evaluation of hot extruded AA 2024–Graphene Nanocomposites. Materials Today: Proceedings, 5, 12519–12524.

Zhao, K., Gao, T., Yang, H., Hu, K., Liu, G., Sun, Q., Nie, J. Liu, X. 2021. Enhanced grain refinement and mechanical properties of a high–strength Al–Zn–Mg–Cu–Zr alloy induced by TiC nano–particles. Materials Science and Engineering: A, 806, 140852.