EXPLORING THE HEAT TREATMENT OF ALUMINIUM MATRIX COMPOSITES: A REVIEW

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Varun Singhal*, Department of Mechanical Engineering, GLA University, Mathura 281406, Uttar Pradesh, India, **Lavish Kumar Singh**, School of Engineering, Jawaharlal Nehru University, New Delhi 110067, India, **Devender Kumar,** Chitkara Centre for Research and Development, Chitkara University, Himachal Pradesh, India, and **Yadaiah Nirsanametla**, Centre of Research Impact and Outreach, Chitkara University, Rajpura, Punjab, India

*Corresponding author. Varun Singhal (Email): v.singhal20@gmail.com, varun.singhal.me@gla.ac.in

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SUMMARY

The primary synthesis and secondary treatment of aluminum matrix composites are thoroughly reviewed in this work. further treatments that are intended to improve the properties of the synthesized composites—such as heat treatment, forging, and other thermomechanical processes—are covered. An overview of the benefits and limitations of several main synthesis pathways and secondary treatments for the production of ceramic-reinforced AMCs is provided in a clear and comprehensive manner through a synthesis of previous investigations. A noteworthy vacuum exists in the literature regarding the synergistic application of several synthesis pathways and secondary treatment procedures for the production of AMCs, despite substantial research efforts in this area.

KEYWORDS

Stir casting, Wear rate, Heat treatment, COF

NOMENCLATURE

AMC	Aluminium metal composite
MMC	Metal matrix composite
FA	Fly Ash
COF	Coefficient of friction
MML	Mechanical mix layer
PM	Powder metallurgy
POD	Pin on disc
SF	Short fiber
WT	Wear Track
WD	Wear debris
EDS	Energy Dispersive X-ray Spectroscopy
SEM	Scanning Electron Microscope
CS	Counter Surface
RCP	Reactive casting process
XRF	X-ray fluorescence
XRD	X-ray Diffraction
PKSA	Palm kernel shell ash
HEP	High-Entropy Alloy
EDAX	Electron Dispersive X-ray Analysis
MAS	Microwave Assisted Sintering
SPS	Spark Plasma Sintering
FESEM	Field Emission Scanning Electron Microscopy
CTE	Coefficient of thermal expansion

1. INTRODUCTION

The development of new materials, including composites, has been prompted by the increasing demand for structural components with improved in-service performance, a high strength-to-weight ratio, a prolonged service life, and cost effectiveness (Singhal & Pandey, 2021b, 2022; Singhal & Prakash Pandey, 2022). In order to create composites with better qualities that differ from the original materials, at least two unique chemical ingredients are combined and arranged in a three-dimensional structure (Chin et al., 2020; P. K. Gupta & Srivastava, 2018; Kumar et al., 2020; Kumar & Rai, 2018; Obande et al., 2019; Varvani-Farahani, 2010). These materials' mechanical qualities, which greatly broaden the range of applications possible for them, are the main factor driving their rising use (Aweda et al., 2018; Hussain et al., 2020; Kahlani & Jafarzadeh, 2020; Kim et al., 2020). MMCs are frequently made from aluminum alloys because of their remarkable qualities, which include high strength, low density, excellent fatigue and wear resistance, thermal conductivity, corrosion resistance, recyclability, and ease of shaping, rolling, drawing, extruding, and welding (Keshavamurthy et al., 2016; T P et al., 2020). By adding reinforcement, the material's mechanical and microstructural integrity is intended to be improved (Ramnath et al., 2014). Many industries, such as aviation, aerospace, automotive, weapons, electrical, and electronic engineering, use aluminum composite materials (Włodarczyk-Fligier et al., 2008). Nanocomposites, which have at least one constituent that exists as a nanoparticle (1 nm or 10^9 m), are a unique class of composites. Nanocomposite materials are promising materials for the twenty-first century because they have special design features and a mix of qualities not seen in traditional composites (Camargo et al., 2009; El-Labban et al., 2014). Based on the materials that make them up, metal, ceramic, and polymer nanocomposites can be distinguished from one another. Fe-Cr/Al_2O_3, Ni/Al_2O_3, Co/Cr, Fe/MgO, and Al/CNT are examples of metal matrix nanocomposites (Al-Muntaser et al., 2022; Chaturvedi et al., 2022; Sharma et al., 2023). These composites are made of ductile metals or alloys with nanoscale reinforcement elements inserted to enhance their modulus, toughness, ductility, and strength (Camargo et al., 2009). The great strength and compatibility of metal matrix nanocomposites for high-temperature conditions make them useful in structural, automotive, and aeronautical materials (Tjong et al., 2004, 2005). Aluminum metal is strengthened by the addition of a variety of reinforcing elements, including fibers, FA, ZrO_2, B_4C, SiC, Al_2O_3, Si_3N_4, TiO_2 (Babić et al., 2013). SiC improves the tensile strength, hardness, density, and wear resistance of aluminum, while alumina enhances its compressive strength and wear resistance. B_4C reinforcement yields high elastic modulus and fracture toughness, albeit with minimal improvement in wear resistance (Ipekoglu et al., 2017; Khodabakhshi et al., 2018; Kishore Babu et al., 2017; Nanjan & Janakiram, 2019; Palanikumar et al., 2019; Tiku et al., 2020). Metal matrix composites, resulting from the combination of chemically non-reactive materials, offer the prospect of creating a unique material platform with superior characteristics. As matrix metals, titanium, aluminum, and magnesium are frequently used. Reinforcing materials are non-metallic substances such FA, graphite, Al_2O_3, and SiC (Kumar et al., 2023; Surappa, 2003). Among the notable engineering components with better mechanical and physical characteristics than monolithic alloys are SiC AMC, which is of specific attention. The incorporation of SiC or SF consumes proven cost-effective, rendering the resulting AMC materials virtually isotropic (Lim et al., 2003). In engineering, metal matrix composites are becoming more and more popular due to their strength, stiffness, resistance to corrosion, and ability to function at high temperatures—especially while treated to creep conditions. This makes them valuable in aircraft and automobile engine technologies (Shuvho et al., 2020; Weinert & König, 1993). SiC AMC have become increasingly important for applications in transportation, aviation, chemical industries, and cryogenic fields. Achieving even spreading of reinforcement within the matrix presents a significant challenge in AMC material fabrication, directly impacting the characteristics and quality of the final product (Singla et al., 2015). The mechanical properties of a material can be precisely tailored through suitable heat treatment conditions.

1. HEAT TREATMENT

The T4 and T6 heat treatment tempers are the most widely employed among the different types of tempers that are available. The process of enhancing the strength of aluminum alloys through heat treatment typically involves three steps:

Solution heat treatment: This step involves the dissolution of soluble phases within the alloy.

Quenching: Following solution heat treatment, the alloy is rapidly cooled to room temperature, leading to the expansion of super saturation.

Age hardening: During this stage, solute atoms precipitate within the material. This precipitation can occur naturally at room temperature, referred to as natural aging or T4, or it can be induced at higher temperatures through artificial aging or precipitation heat treatment, known as T6.

During solution heat treatment, the maximum concentration of hardening solute dissolves into the solution, creating a single solid phase (Singhal et al., 2022). To avoid eutectic melting, great care is taken to guarantee that overheating is avoided. Consequently, rapidly quenching the alloy, a super-saturated solution forms between the solute and the matrix. This process prevents solute atoms from precipitating out of the solution. Quenching involves rapid cooling to preserve the solute in solution, preventing solid-state diffusion and phase precipitation. Hardening of the material can occur either at room temperature, known as natural aging, or through artificial aging following solution treatment and quenching.

2. HEAT TREATMENT IMPACT ON THE MECHANICAL AND WEAR CHARACTERISTICS

The aging sequence for both 6061 Al alloy and its AMC counterparts unfolds as follows: It commences with a super-saturated solid solution, progresses through the formation of clusters comprising solute atoms and vacancies (Primitive Guinier-Preston [GP] zones), then transitions to needle-shaped GP zones, followed by the emergence of rod-shaped, metastable, semi-coherent β' phase, culminating in the formation of stable, incoherent, Mg_2Si precipitates (β phase).

Das et al. (Das et al., 2008) (2008) investigate the combined effects of heat treatment and silicon carbide (SiC) particle reinforcement on the LM13 Al alloy two-body abrasive wear behavior at different loads and abrasive diameters. Both the alloy and the AMC underwent an 8-hour solution treatment at 495°C, followed by aging for 6 hours at 175°C with air cooling. Subsequently, the cast and heat-treated alloy and AMC specimens were evaluated for their two-body abrasive wear behavior against abrasives of

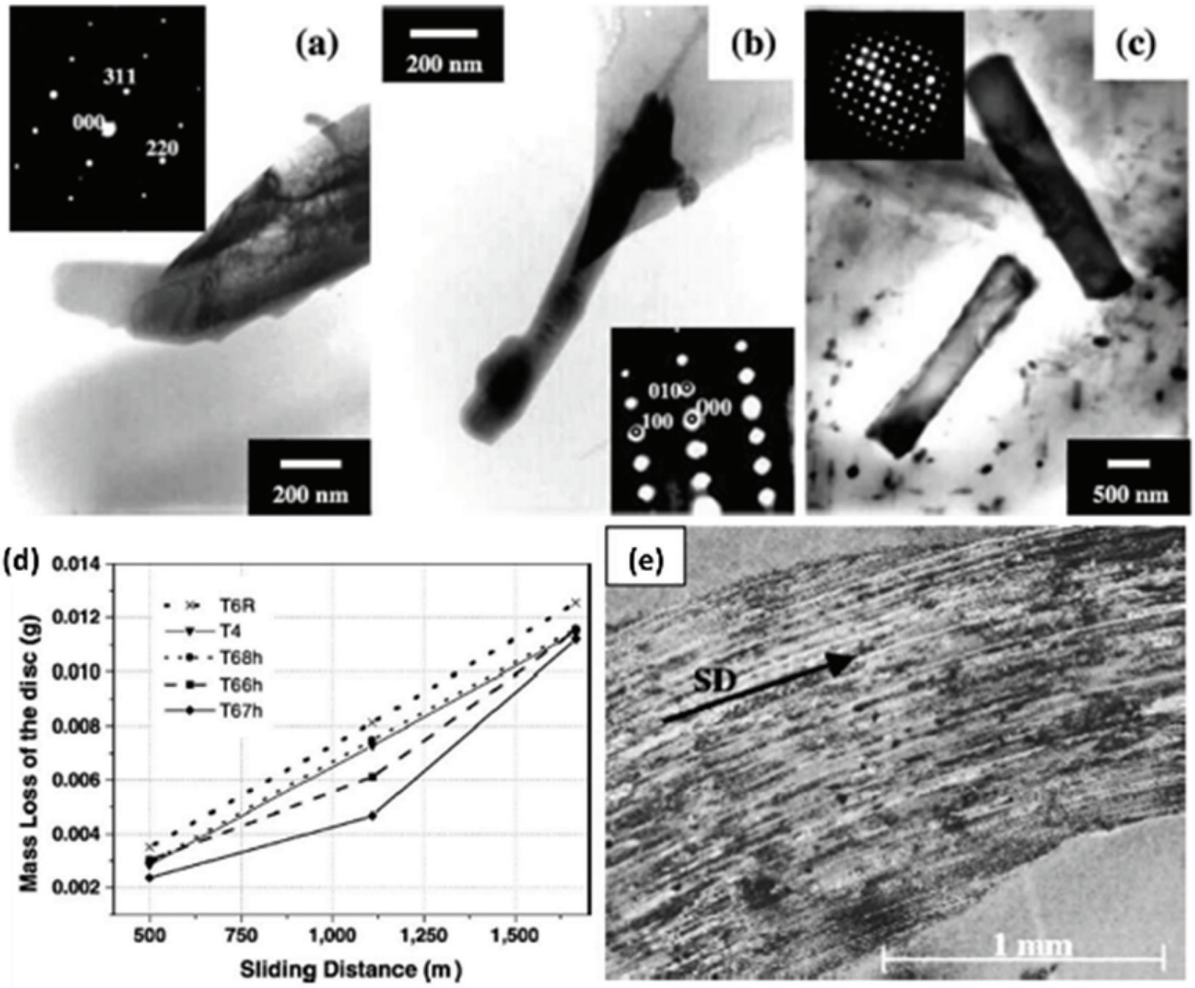

Figure 1. The matrix composites with heat treatment T6 show the following phases in (a-c) TEM images. (d) Difference in mass loss of AA6092/SiC_{25}p AMC (e) SEM of WT of an AA6092/SiC_{25}p AMC

different diameters (40 µm, 60 µm, and 80 µm). The two-body abrasive wear behavior of the cast and heat-treated alloy and AMC specimens was further examined over a sliding distance of 108 m, employing abrasives of various diameters (40 µm, 60 µm, and 80 µm) and variable applied loads (1-7N) as shown in Figure 1.

(Raza et al., 2011) (2011) reported that proper heat treatment increases the yield strength of Al alloys and their AMC by reducing the tendency for cracking and enhancing precipitation hardening. Traditionally, Al alloy composites undergo under-aged condition heat treatment for easier shaping, followed by peak-aged condition treatment post-fabrication to bolster mechanical strength. While heat-treated alloys and AMC exhibit superior hardness, excessive ageing may lead to significant softening. For instance, AA 2219 underwent solution heat treatment at 535℃ for 48 minutes, followed by water quenching and ageing at 210℃, 230℃, and 240℃ for varying durations. The highest UTS of 410 MPa was achieved after 4 hours of ageing at 210℃, which decreased to 352 MPa thereafter. Similarly, UTS peaked at 370 MPa after 3.5 hours of ageing at 230℃ and at 368 MPa after only 1.5 hours of ageing at 240℃. Results indicate an increase in strength up to the peak-aged condition, followed by a decline due to over- ageing, attributed to precipitate formation. Maximum hardness of 113.76 HV was attained at 210℃ after 4 hours of ageing, as depicted in Figure 2. Higher temperatures and prolonged ageing time led to diminished extreme strength and hardness.

Kini et al. (Chandrakant R Kini et al., 2015) (2015) investigated the mechanical performance of Al 2024-FA AMC was examined both before and after heat treatment. The process involved quenching the specimens in water, followed by aging treatment at 150°C for durations ranging from one to three hours in a muffle furnace. Subsequently, the specimens underwent solution heat treatment at 550°C for one hour. Kaushik et al. (Kaushik & Rao, 2016) (2016) study aimed to evaluate the improvements in mechanical

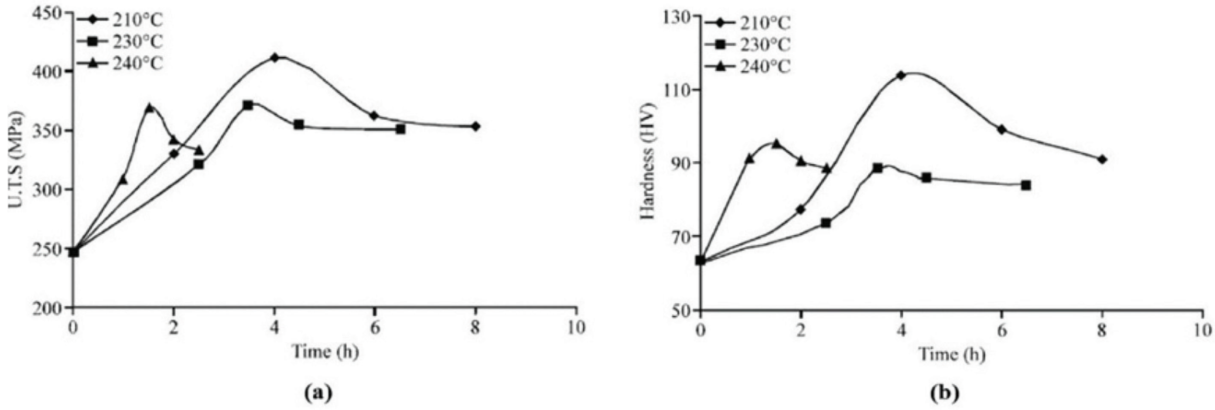

Figure 2. Represent the changes in (a) ultimate tensile strength and (b) hardness over time at varying ageing temperatures of 210°C, 230°C, and 240°C (Raza et al., 2011)

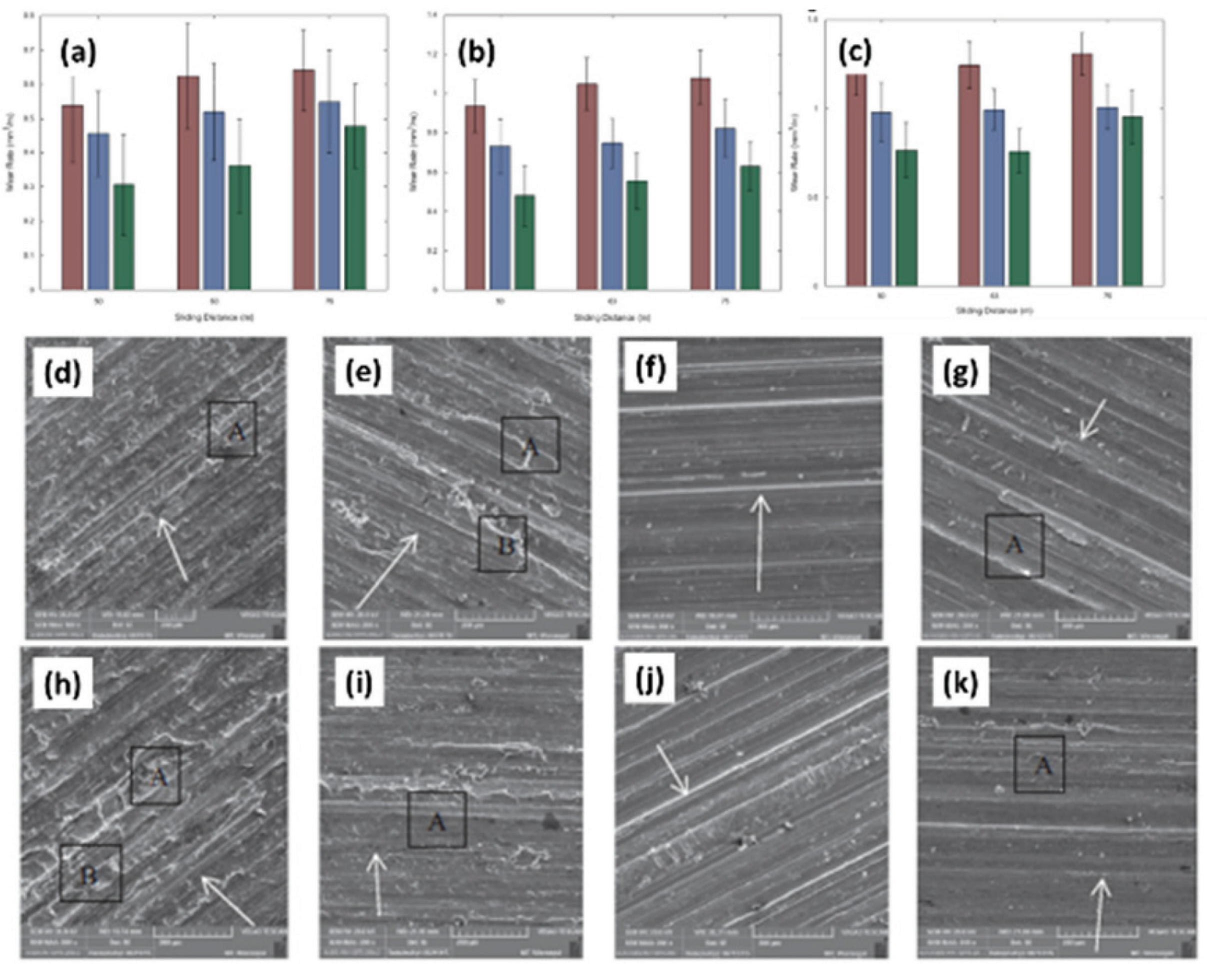

Figure 3. Wear rate of T6 heat-treated alloy and its composites (a) 5N, (b) 10N, and (c) 15N, under applied load. The WT analysis of (d) Al6082 alloy at a 5N load (e) Al6082 alloy at a 15N load (f) Al6082–SiC–Gr AMC at a 5N load (g) Al6082–SiC–Gr AMC at a 15N load. T6 heat treatd sample WT analysis (h) Al6082 alloy tested at a 5N load (i) Al6082 alloy tested at a 15N load (j) Al6082–SiC–Gr AMC tested at a 5N load (k) Al6082–SiC–Gr AMC tested at a 15N load

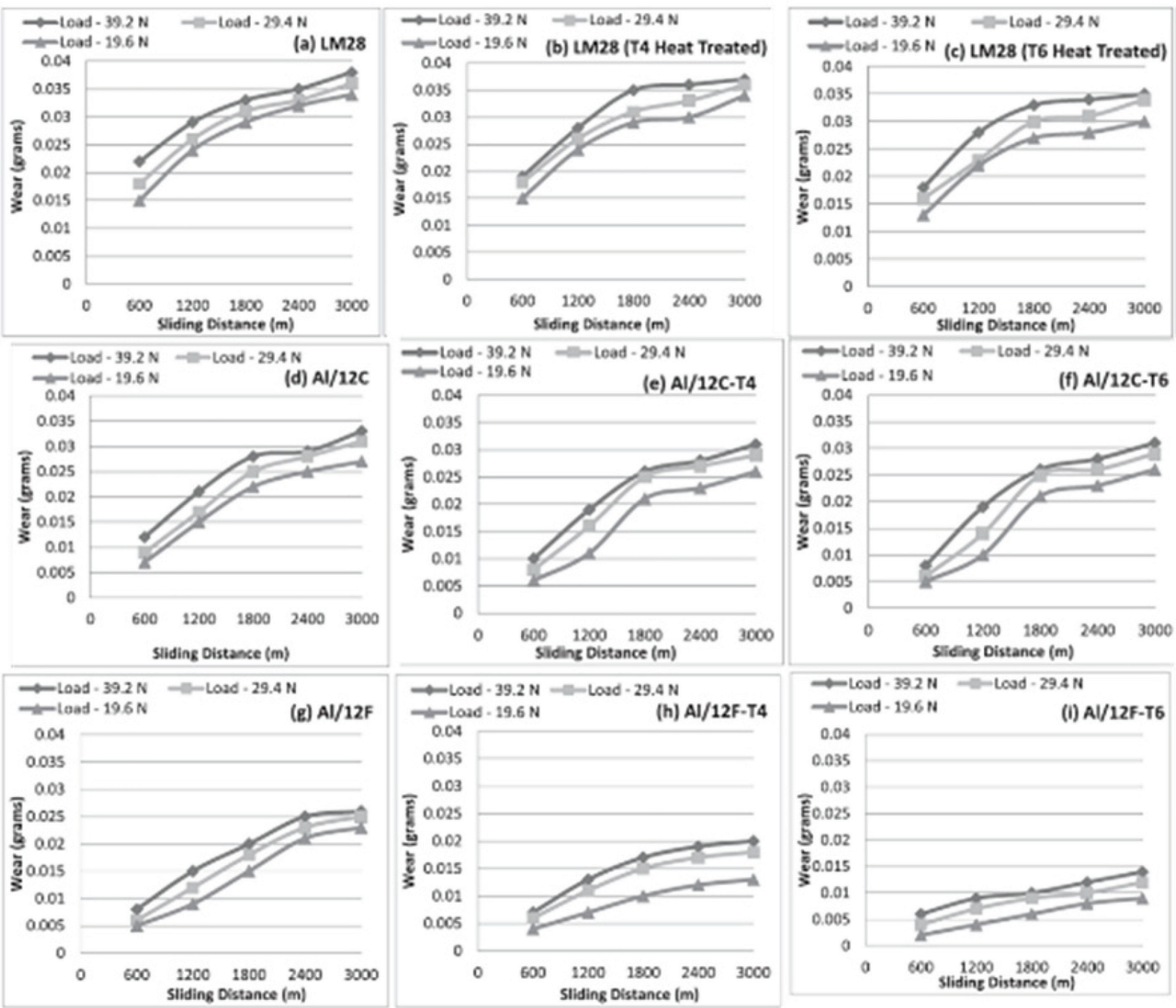

Figure 4. Wear behavior of (a) LM28 alloy (b) LM28 - T4 Heat Treated (c) LM28 –T6 Heat Treated (d) Al/12C (e) Al/12C- T4 (f) Al/12C-T6 (g) Al/12F (h) Al/12F-T4 (i) Al/12F-T6

and tribological properties relative to the unreinforced matrix alloy material. Al–SiC, Al–SiC–Gr, and Al 6082 alloy AMCs were utilized to investigate wear performance. The hybrid AMCs exhibited superior abrasive wear compared to both the single SiC AMC and the matrix alloy, as per the research findings. This improvement was attributed to the incorporation of graphite, which facilitated the formation of a graphitic layer was represent in Figure 3. This layer acted as a self-lubricating agent in the Al–SiC–Gr composites, contributing to enhanced wear resistance. Furthermore, the study assessed the enhancement of wear resistance in Al-SiC-Gr composites under both as-cast and T6 heat-treated conditions. The results indicated that the inclusion of graphite, along with SiC reinforcement, led to improved wear performance, highlighting the potential of these hybrid composites for various engineering applications. Stergiou et al. (Alexopoulos et al., 2016) (2016) utilized wrought aluminum alloy AA2024-T3, provided in sheet form. The study revealed that ductility decreased to an exceptionally high level of 26% after every aging temperature investigated. This reduction in ductility was consistent with the corrosion exposure observed for T3 and the following two hours. Additionally, the yield stress exhibited a decrease of approximately 5% due to corrosion, which was of similar magnitude, albeit less susceptible to changes in microstructure. These findings underscore the complex interplay between aging temperature, corrosion exposure, and mechanical properties in AA2024-T3 aluminum alloy, providing valuable insights for material characterization and potential engineering applications.

Singh et al. (Singh & Sharma, 2021) (2021) investigated the impact of T4 and T6 heat treatments on the wear characteristics of LM28 cast composites reinforced with coarse and fine WC. They determined that the AMC underwent T4 and T6 heat treatments following conservative procedures. For T4 heat treatment, the composites were subjected to heating at 450 °C for

Table 1. Studies on heat treatment effects on mechanical properties

Study	Year	Material	Findings
D. Ramesh et al. (Ramesh et al., 2012)	2012	Al6061, Frit	Heat treatment significantly influences microstructural characteristics, density, and hardness of both alloys and composite materials
Tan et al. (Tan et al., 2001)	2001	Al-2618, SiC, Al_2O_3	Heat treatments have comparable effects on UTS regardless of reinforcement type. T4 treatment results in higher elongation compared to T6 treatment. SiC particles demonstrate superior abilities in strain accommodation, fracture toughness, and low thermal expansion.
Tiryakioğlu et al. (Tiryakioğlu, 2006)	2006	Cast Al-Si-Mg alloys	Optimal Si particle shape and matrix strength achieved after artificial aging for 10-20 hours.
N.R. Prabhu et al. (Prabhu Swamy et al., 2010)	2010	Al6061/SiC	Assessment of different heat treatment conditions on mechanical properties and microstructural characteristics of Al6061/SiC composites.
Reddappa et al. (Reddappa et al., 2011)	2011	Al6061, 10% beryl	Cold quenching following solution heat treatment influences wear rate of Al6061 AMC reinforced with 10% beryl.
Yang et al. (Zhu et al., 2012)	2012	Al-Si alloys	Presence of Mg and Mg-Si precipitates, along with T6 thermal treatment, improves tensile characteristics of Al-Si alloys.
Nam et al. (Nam et al., 2012)	2012	Al–Cu/CNT composite	Increased hardness observed with CNT reinforcement in Al–Cu matrix.
Gopi Alaneme et al. (Alaneme, 2013)	2013	Al 6063-Alumina	Examination after Solution heat treatment at 550°C for 1 hour, water quenching the mechanical properties to understand performance of Al 6063-Alumina AMC.
K.R. et al. (Gopi K.R et al., 2013)	2013	Al 6061, zircon sand, graphite	Assessment of heat treatment effects on microstructure and mechanical properties of AMC samples.
Chacko and Nayak et al. (Melby Chacko & Jagannath Nayak, 2014)	2014	Al 6061, 15% SiC	Analysis of aging parameters on hardness properties of Al 6061-15% SiC composites.
Sridhar Bhatt et al. (Bhat & Mahesh, 2014)	2014	Al, FA, SiC	Assessment of T6 thermal treatment effects on microstructure and mechanical properties of composites.

2–3 hours, followed by oil quenching and natural aging for 6–40 days at room temperature. A similar cycle was used for the T6 heat treatment, adding artificial aging at 180–220 °C for three–seven hours, and then returning to normal cooling. The T6 heat-treated composites exhibited optimal hardness compared to T4 heat-treated and non-heat-treated counterparts. POD tests discovered that T6 heat-treated composites exhibited the best wear resistance and coefficient of friction under varying sliding distances and loads. These T6 AMC demonstrated superior wear resistance and hardness, making them well-suited for applications where high wear resistance is crucial was revealed from Figure 4. Moreover Table 1 represents the findinds of various researches.

3. CONCLUSION

Heat treatment, particularly through the widely employed T4 and T6 tempers, significantly enhances the mechanical properties of aluminum alloys and their composites. This process involves solution heat treatment, quenching, and age hardening, which collectively influence the microstructural characteristics, density, and hardness of the material. The precipitation of fine particles within the microstructure during heat treatment contributes to the improved mechanical properties, including enhanced strength and wear resistance. Further research is essential to optimize heat treatment parameters for maximizing the performance and reliability of aluminum alloys and composites in various applications.

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