Effect of T6 Heat Treatment on Microstructure Evolution and Tribological Performance of Conventionally Cast Al–30Mg_2Si–4Fe Alloy

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Abstract

Lightweight aluminium alloys reinforced with hard intermetallic phases have gained considerable attention for automotive and aerospace applications owing to their superior specific strength, stiffness, and wear resistance. Among these materials, hypereutectic Al–Mg_2Si alloys exhibit excellent tribological characteristics due to the presence of Mg_2Si particles. However, conventionally cast Al–Mg_2Si alloys often contain coarse primary Mg_2Si particles and needle-like Fe-rich intermetallic compounds, which adversely affect mechanical integrity and wear performance. In the present investigation, the influence of T6 heat treatment on the microstructure and dry sliding wear behaviour of conventionally cast Al–30Mg_2Si–4Fe alloy was systematically studied. The alloy was solution treated at **520°C for 2 h**, water quenched, and artificially aged at **220°C** for **2, 4, and 6 h**. Microstructural evolution was characterized using optical microscopy and scanning electron microscopy (SEM), while dry sliding wear tests were performed using a pin-on-disc tribometer under loads ranging from **10 to 50 N** and sliding speeds between **1.0 and 2.0 m s^{-1}**. The results revealed significant spheroidization and refinement of Mg_2Si particles together with fragmentation of needle-like β-Al_5FeSi intermetallics following T6 treatment. These microstructural modifications enhanced matrix strengthening and improved particle–matrix bonding. Consequently, the heat-treated alloys exhibited substantially lower volumetric wear rates and reduced coefficients of friction than the as-cast alloy. Among all ageing conditions, the alloy aged for **4 h** demonstrated the highest wear resistance because of the optimum balance between precipitation hardening and microstructural refinement. SEM examination of worn surfaces confirmed a transition from severe abrasive wear in the as-cast alloy to mild abrasive wear after T6 heat treatment. The study demonstrates that appropriate T6 heat treatment significantly enhances the tribological performance of Al–30Mg_2Si–4Fe alloy, making it a promising lightweight bearing and wear-resistant engineering material.

Keywords: Aluminium alloy; Mg_2Si; T6 heat treatment; Wear behaviour; Tribology; SEM; Microstructure; Age hardening.

1. Introduction

Lightweight aluminium alloys are increasingly used in automotive and aerospace industries because of their high strength-to-weight ratio, excellent corrosion resistance, and good thermal conductivity. However, their relatively poor wear resistance limits their application in tribological components. Hypereutectic Al–Mg_2Si alloys have emerged as promising wear-resistant materials due to the presence of hard Mg_2Si intermetallic particles, which possess low density, high hardness, high elastic modulus, and excellent thermal stability.

The addition of iron improves the high-temperature stability of Al–Mg_2Si alloys by forming Fe-rich intermetallic phases. However, conventional casting produces coarse Mg_2Si particles and needle-like β-Al_5FeSi intermetallics that act as stress concentrators, reducing wear resistance. Refinement of these phases is therefore essential to enhance the alloy's tribological performance.

T6 heat treatment, consisting of solution treatment, quenching, and artificial ageing, is an effective method for improving the microstructure and mechanical properties of precipitation-hardenable aluminium alloys. It promotes spheroidization of Mg_2Si particles, fragmentation of Fe-rich intermetallics, and precipitation hardening, thereby enhancing hardness and wear resistance.

The present study investigates the effect of T6 heat treatment on the microstructure evolution and dry sliding wear behaviour of conventionally cast Al–30Mg_2Si–4Fe alloy using optical microscopy, SEM, and pin-on-disc wear testing. The objective is to identify the optimum ageing condition that provides maximum tribological performance.

2. Literature Review

Recent studies have shown that T6 heat treatment significantly improves the hardness and wear resistance of Al–Si–Mg alloys through precipitation hardening and microstructural refinement. Solution treatment dissolves secondary phases, while artificial ageing produces fine Mg_2Si precipitates that strengthen the aluminium matrix.

Researchers have reported that heat treatment transforms coarse Mg_2Si particles and needle-like β-Al_5FeSi intermetallics into finer and more rounded morphologies, reducing stress concentration and improving particle–matrix bonding. Consequently, heat-treated alloys exhibit lower wear rates, reduced coefficient of friction, and improved resistance to abrasive wear.

Although considerable work has been reported on Al–Si–Mg alloys, limited studies have focused on conventionally cast Al–30Mg_2Si–4Fe alloys containing high Mg_2Si and Fe contents. Therefore, the present work evaluates the influence of T6 heat treatment on the microstructure and tribological performance of this alloy to determine the optimum ageing condition for enhanced wear resistance.

3. Methodology

The Al–30Mg_2Si–4Fe alloy was produced by the conventional casting process using high-purity aluminium and alloying elements. The chemical composition of the alloy was approximately **12 wt.% Si, 18 wt.% Mg, 4 wt.% Fe**, with aluminium as the balance. After casting, the specimens were machined for microstructural characterization and wear testing.

The cast specimens were subjected to **T6 heat treatment**, consisting of solution treatment at **520°C for 2 h**, followed by water quenching and artificial ageing at **220°C** for **2, 4, and 6 h** to obtain different precipitation conditions.

The microstructure of the as-cast and heat-treated alloys was examined using **optical microscopy (OM)** and **scanning electron microscopy (SEM)** after standard metallographic polishing and etching with Keller's reagent. These analyses were used to evaluate the morphology and distribution of Mg_2Si and Fe-rich intermetallic phases.

Dry sliding wear tests were performed on a **DUCOM pin-on-disc tribometer** following **ASTM G99-05** standards. Cylindrical specimens (Ø8 × 30 mm) were tested against an EN-32 steel disc (65 HRC) under applied loads of **10–50 N**, sliding speeds of **1.0–2.0 m s^{-1}**, and a constant sliding distance of **2000 m**. The wear rate was determined from the weight loss of the specimens, and the worn surfaces were examined using SEM to identify the dominant wear mechanisms.

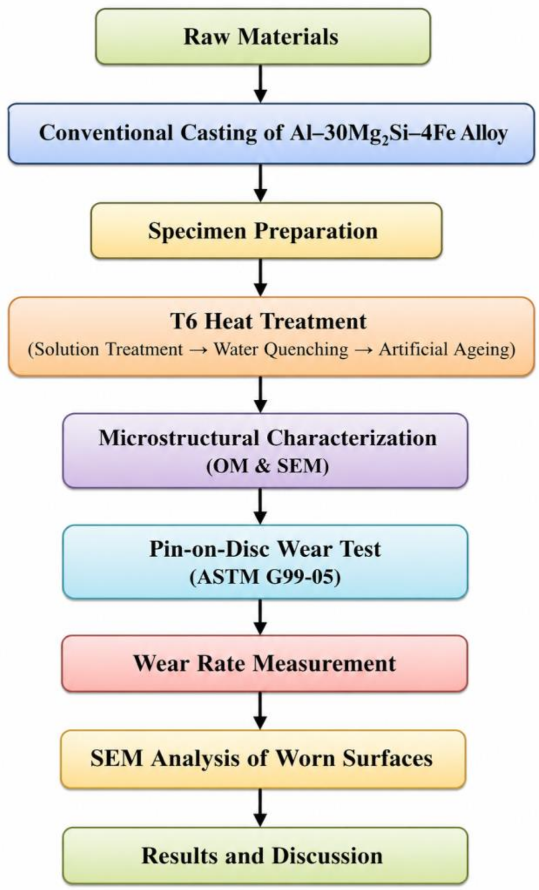

Figure 1. Methodology Flow Diagram

4. Results and Discussion

4.1 Microstructural Evolution

The optical and SEM analyses revealed that the as-cast Al–30Mg_2Si–4Fe alloy contained coarse block-shaped Mg_2Si particles and needle-like β-Al_5FeSi intermetallic phases randomly distributed in the aluminium matrix. These coarse intermetallics acted as stress concentrators, reducing the alloy's resistance to deformation and wear. After T6 heat treatment, significant spheroidization and refinement of Mg_2Si particles together with fragmentation of Fe-rich intermetallics were observed. The solution treatment dissolved secondary phases into the aluminium matrix, while artificial ageing promoted fine precipitate formation, resulting in improved particle–matrix bonding and a more homogeneous microstructure. The alloy aged for **4 h** exhibited the most refined and uniformly distributed microstructure, indicating optimum precipitation hardening.

4.2 Wear Behaviour

The wear rate increased with increasing applied load for both the as-cast and heat-treated alloys because of higher contact stresses and plastic deformation during sliding. However, all T6 heat-treated specimens exhibited significantly lower wear rates than the as-cast alloy. The alloy aged for **4 h** showed the minimum volumetric wear rate under all test conditions, demonstrating the best wear resistance. This improvement is attributed to precipitation hardening, refinement of Mg_2Si particles, reduction in the size of Fe-rich intermetallics, and enhanced matrix hardness. At higher sliding speeds, the wear rate decreased slightly due to the formation of a protective oxide layer on the sliding surface.

4.3 Coefficient of Friction

The coefficient of friction decreased gradually with increasing applied load for all alloy conditions. Among the tested specimens, the **4 h aged alloy** exhibited the lowest coefficient of friction, while the as-cast alloy showed the highest values. The reduction in friction is attributed to improved precipitation strengthening, spheroidization of Mg_2Si particles, and stronger particle–matrix bonding produced by T6 heat treatment.

4.4 SEM Analysis of Worn Surfaces

SEM examination of the worn surfaces indicated severe abrasive wear in the as-cast alloy, characterized by deep grooves, pits, and extensive plastic deformation. In contrast, the T6 heat-treated alloys exhibited smoother wear tracks with shallow grooves and fewer pits, indicating a transition to mild abrasive wear. The **4 h aged specimen** showed the least surface damage, confirming its superior wear resistance. The improved wear behaviour is primarily due to the refined microstructure, increased hardness, and reduced stress concentration after heat treatment.

5. Conclusions

- T6 heat treatment effectively refined the microstructure of conventionally cast Al–30Mg_2Si–4Fe alloy by spheroidizing Mg_2Si particles and fragmenting needle-like β-Al_5FeSi intermetallic phases.
- The refined microstructure improved particle–matrix bonding and enhanced precipitation hardening, leading to increased resistance against plastic deformation and wear.
- Wear rate increased with increasing applied load for all specimens; however, heat-treated alloys consistently exhibited lower wear rates than the as-cast alloy.
- The alloy aged for **4 h** showed the optimum tribological performance, exhibiting the lowest wear rate and coefficient of friction due to the combined effects of microstructural refinement and peak ageing.
- SEM observations confirmed that the dominant wear mechanism changed from severe abrasive wear in the as-cast alloy to mild abrasive wear after T6 heat treatment.
- The study demonstrates that T6 heat treatment significantly improves the tribological performance of Al–30Mg_2Si–4Fe alloy, making it a promising lightweight material for wear-resistant automotive and bearing applications.

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