

Influence of Tin addition on microstructure, mechanical, and tribological properties of magnesium matrix

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Abstract: In this study, the effect of Tin (Sn) addition on the microstructure, mechanical properties, and wear resistance of pure magnesium (Mg) was examined. Mg-Sn alloys were synthesized using stir casting technique with Sn concentrations of 2.5%, 5%, and 7.5% by weight. The specimens were prepared as per ASTM standards for their evaluation. Higher Sn concentrations result in a reduced volume fraction of the eutectic phase, while Mg₂Sn precipitates are observed in alloys with 5% or more Sn. Scanning electron microscopy (SEM) analysis of the Mg-7.5wt.% Sn alloy reveals the presence of Mg(OH)₂, with X-ray diffraction (XRD) confirming an oxygen content of 18% by weight. The addition of Sn minimizes casting porosity, enhancing the quality of the alloys. The findings demonstrate a positive correlation between increasing Sn content and enhanced strength and wear resistance. The Mg-7.5wt.% Sn alloy exhibits significantly enhanced tensile properties attributed to grain refinement and the formation of well-defined grain boundaries compared to alloys with lower Sn additions (2.5% and 5%), although a slight reduction in microhardness is observed. Tribological evaluation indicates reduced wear and friction, suggesting better surface performance. This research underscores the complex interplay between Sn content, microstructural evolution, and the resulting mechanical and tribological performance of Mg-Sn alloys.

Keywords: Sn element; magnesium; stir casting; microstructure; tensile strength

CLC numbers: TG146.22

Document code: A

Article ID: 1672-6421(2025)06-664-09

1 Introduction

Advanced metals, alloys, and composites remain foundational in engineering, offering advantages such as weight reduction, corrosion resistance, and fatigue

resistance. Among metallic elements, Mg stands out as one of the most challenging due to its intricate interplay of mechanical, chemical, and physical properties^[1]. The flow characteristics of Mg alloys are particularly complex, primarily due to the low stacking fault energies associated with their hexagonal close-packed (HCP) crystal structure, which limits their ductility and makes deformation through stretching challenging.

Efforts to develop magnesium alloys with enhanced strength, cost-effectiveness, and improved creep and corrosion resistance are expanding, unlocking opportunities in applications requiring lightweight materials. Alloying elements such as aluminium (Al), manganese (Mn), zinc (Zn), and rare earth elements play a pivotal role in enhancing the ductility, mechanical strength, wear resistance, and corrosion resistance of pure magnesium. Manufacturing processes for Mg and its alloys include die casting, sand casting, mould

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Received: 2024-12-10; Revised: 2025-01-24; Accepted: 2025-02-10

casting, investment casting, extrusion, forging, and rolling, particularly for structural applications.

Among commercial magnesium alloys, the AZ and AM series are the most widely used and cost-effective, finding significant applications in the automotive and aerospace industries^[2]. Wrought magnesium alloy products, such as sheets, plates, extrusions, and forgings, are essential components in automotive and aerospace structures^[3]. However, the structural characteristics of wrought Mg alloys are not yet fully optimized. Limited formability at room temperature, as seen in conventional wrought Mg alloy sheets like AZ31, remains a significant barrier to their broader adoption. Advancing manufacturing processes and developing more efficient production techniques are essential for increasing the utilization of magnesium alloys, heralding a transformative potential for lightweight materials in the 21st century^[4].

Alloy development often revolves around the formation of intermetallic phases during casting or subsequent heat treatments^[5]. Recent efforts have focused on binary Mg alloys incorporating additional elements, demonstrating enhanced creep resistance and suitability for structural applications. A significant milestone in this field was the initiation of research on Mg-Sn alloys at Mag-IC in 2000^[6]. These alloys, used in automobiles and electronic devices, exhibit unique properties due to the favourable interaction between magnesium and tin. Tin contributes to high-temperature performance through characteristics such as low diffusivity in Mg ($10 \times 10^{-14} \text{ m}^2 \cdot \text{s}^{-1}$ at 400 °C), low solid solubility (0.035% at room temperature), and high liquid solubility in molten Mg (100% at 800 °C)^[7]. The intermetallic Mg_2Sn phase (FCC, $a=0.676 \text{ nm}$, point group $m\bar{3}m$) has a high melting point (770 °C), exceeding those of phases in other binary alloys^[8].

Studies on as-cast Mg-(1wt.%–10wt.%) Sn alloys show significant mechanical performance, with Mg-5wt.% Sn standing out for its superior properties^[9]. Investigations of Mg-Sn alloys with 6wt.%–10wt.% Sn subjected to indirect extrusion revealed improved tensile and compressive behaviors, with reduced yield tension-compression asymmetry as Sn content increased^[10,11]. Enhanced strength, reduced ductility, and grain size refinement were observed in Mg-8wt.% Sn alloys with increased aging times. Corrosion resistance was significantly improved in Mg-5wt.% Sn alloys compared to pure Mg, as shown by immersion tests^[12]. The dispersive distribution of Mg_2Sn in the α -Mg matrix notably enhances creep resistance^[13]. However, wear resistance in Mg-5wt.% Sn alloys processed through multi-pass equal channel angular extrusion (ECAE) declined due to increased dislocation density and stress fields^[14].

Thankachan et al.^[15] utilized mathematical models to analyze the effect of Sn addition on Mg, revealing that Sn enhanced tensile strength and density while reducing yield strength. Kavimani et al.^[16] developed reduced graphene oxide (r-GO)-based Mg matrix composites through solvent-based powder metallurgy, finding that increased r-GO content improved hardness but reduced wear resistance. The incorporation

of Sn into Mg alloys significantly enhanced mechanical, tribological, and corrosion resistance properties compared to pure magnesium^[17,18]. This alloying strategy broadens the applicability of magnesium-based materials across diverse industries, improving overall performance^[19,20].

However, research gaps remain in optimizing alloying elements, understanding microstructure-property relationships, improving high-temperature performance, advancing additive manufacturing techniques, and conducting multi-scale modelling of Mg-Sn alloys^[21]. This study investigated Mg-Sn alloys with varying Sn content, uniquely fabricated via stir casting under a protective gas mixture of sulfur hexafluoride (SF_6) and ultra-pure argon to minimize oxidation and enhance alloy integrity. This research aims to enhance the mechanical and wear characteristics of these alloys, offering potential for applications in high-performance components. These findings emphasize the role of processing conditions and alloy chemistry in shaping the microstructure and properties of Mg-Sn alloys.

2 Materials and methods

The primary material utilized in this study was commercially available pure magnesium (Mg) with a purity of 99.85%, procured in ingot form. High-purity tin (Sn, 99.99%) was used as the secondary material, incorporated into Mg to produce Mg-Sn alloys via the stir casting method, a liquid metallurgy process^[22]. Sn was added in concentrations of 2.5%, 5.0%, and 7.5% by weight (referred to as 2.5% Sn, 5.0% Sn, 7.5% Sn). Alloy production was carried out using an electrical resistance bottom-pouring melting furnace (Swam-Equip, Chennai, India). Raw materials were accurately weighed using a calibrated four-decimal point scale and melted in a mild steel crucible. To ensure alloy purity and prevent magnesium ignition, a protective gas mixture of sulfur hexafluoride (SF_6) and ultra-pure argon was introduced^[23].

The melt was maintained at 750 °C and mechanically stirred at 300 rpm using a vertical stainless-steel stirrer (SS310 grade) to homogenize the composition. The molten alloy was then poured into a preheated permanent steel mould (200 °C) via an automated bottom-pouring system. The mould, featuring two cylindrical cavities (30 mm diameter $\times$ 300 mm length), allowed natural air cooling of the cast ingots to room temperature. Test specimens were machined from the ingots and prepared for microstructure analysis through mechanical polishing and chemical etching. The etchant consisted of picric acid (6 g), acetic acid (5 mL), ethanol (100 mL), and distilled water (10 mL).

Microstructural examinations were conducted using an optical microscope (Model: OLYMPUS BX53M). Phase identification was performed via X-ray diffraction (XRD) using a Bruker D2 Phaser with $\text{CuK}\alpha$ radiation ($\lambda=0.154 \text{ nm}$) at 30 kV and 100 mA. Diffraction peaks were indexed based on Bragg's Law and standard diffraction data. Tensile tests adhered to ASTM E8 standards, and Vickers hardness measurements were conducted with a 25 gf load and a dwell time of 15 s. This methodology

ensured a comprehensive evaluation of the mechanical and tribological properties of the Mg-Sn alloys.

Dry sliding wear tests followed the ASTM G99 standard using a pin-on-disc tribometer (Ducom Instruments TR 20 NEO). The tribometer featured a disc (EN 31, 165 mm in diameter, 8 mm in thickness, hardened to 58-62 HRC) and accommodated pins (6 mm diameter×30 mm length) machined from the Mg-Sn alloys. Test surfaces were ground flat and cleaned with acetone to remove debris. Testing parameters were designed using the L9 Taguchi orthogonal array, with varying loads (20 N, 30 N, and 40 N), rotational speeds (200 rpm, 300 rpm, and 400 rpm), and a wear track diameter of 100 mm. Each test ran for 500 s at room temperature, with mass loss measured using an analytical balance (± 0.0001 g accuracy). The results represent the average of three trials.

3 Results and discussion

3.1 XRD spectra

Figures 1(a, b, and c) show the XRD spectra of samples with 2.5%, 5.0%, and 7.5% Sn additions, respectively. Diffraction peaks corresponding to Mg are observed in all samples, whereas Mg_2Sn peaks are detected only in alloys with 5% and 7.5% Sn additions. Notably, the presence of Mg_2Sn intermetallic precipitation increases with increasing Sn content. In the 2.5% Sn sample [Fig. 1(a)], no peak is observed up to $2\theta=20^\circ$, but α -Mg peaks become prominent at higher 2θ values. For the 5.0% Sn sample [Fig. 1(b)], the Mg_2Sn peak appears between 20° and 50° , while in the 7.5% Sn sample [Fig. 1(c)], the Mg_2Sn peak extends from

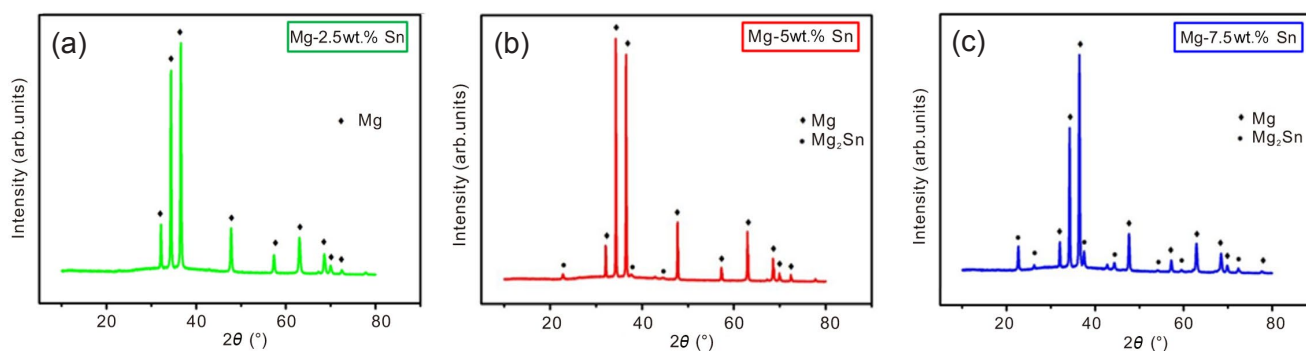


Fig. 1: XRD analysis of Mg-Sn alloy samples: (a) 2.5% Sn; (b) 5.0% Sn; and (c) 7.5% Sn

20° to 70° . This shift in peak positions is attributed to the aggregation of Sn atoms with Mg atoms.

3.2 Optical microstructure

The microstructural analysis of the Mg-2.5wt.% Sn alloy, as shown in Figs. 2x(a-d), reveals key features. Grain structures with an average size of approximately $50\ \mu\text{m}$ are distinctly visible in Figs. 2x(a) and (b). Lamellar phases resembling a “feather-like structure”^[24] are observed in Figs. 2x(c) and (d), alongside dot-like porosities attributed to air entrapment during casting.

At the grain boundaries, black feather-like morphologies are evident, likely caused by Sn segregation during solidification. The formation of Mg-Sn intermetallic phases is minimal and scattered. These microstructural features result from the interplay of factors such as cooling rate, alloy composition, and nucleation and growth kinetics. Localized cooling rate variations due to temperature gradients within the alloy contribute to the observed structural diversity. Additionally, Sn segregation and phase separation during solidification influence the formation of distinct regions with varied morphologies.

Figures 2y(a-d) show the microstructure of the Mg-5wt.% Sn alloy. The grain formation is well-defined, with reduced feather-like structures compared to the Mg-2.5wt.% Sn alloy. As seen in Fig. 2y(b), the grains are uniformly distributed, with sizes ranging from 30 to $50\ \mu\text{m}$. A minimal amount of eutectic phase (black shade) is observed along the grain

boundaries. Significant grain refinement is observed in the Mg-5.0wt.% Sn alloy, attributed to the grain boundary pinning mechanism, where alloying elements hinder the migration of grain boundaries, promoting smaller grain formation. The casting exhibits reduced porosity, and a considerable amount of intermetallic phases is present.

Figures 2z(a-d) present the microstructure of the Mg-7.5wt.% Sn alloy. Grain refinement is the most significant in the 7.5% Sn alloy, with a higher number of grains per square inch and grain sizes ranging from 20 to $50\ \mu\text{m}$ [Fig. 2z(a)]. Some black spots are observed, indicating Sn segregation or porosity. The overall grain refinement and microstructural evolution highlight the impact of Sn content on the alloy’s microstructure. The feather-like structure is less pronounced in the Mg-7.5wt.% Sn sample compared to the 2.5% and 5.0% Sn samples.

Increased Sn content promotes the formation of the Mg_2Sn intermetallic phase, which influences the casting properties. Black eutectic phases are observed at the grain boundaries in all samples, with more aggregation in the Mg-2.5wt.% Sn alloy. This aggregation decreases as Sn content increases. The presence of the Mg_2Sn phase, despite its brittleness, contributes to the improved elasticity. In particular, the Mg-7.5wt.% Sn alloy exhibits higher strength and more well-defined grain boundaries, which correlate with superior mechanical properties compared to the 2.5% and 5.0% Sn variants.

According to Mg-Sn phase diagram (Fig. 3), at high temperatures (above 500°C), Mg alloys with lower Sn

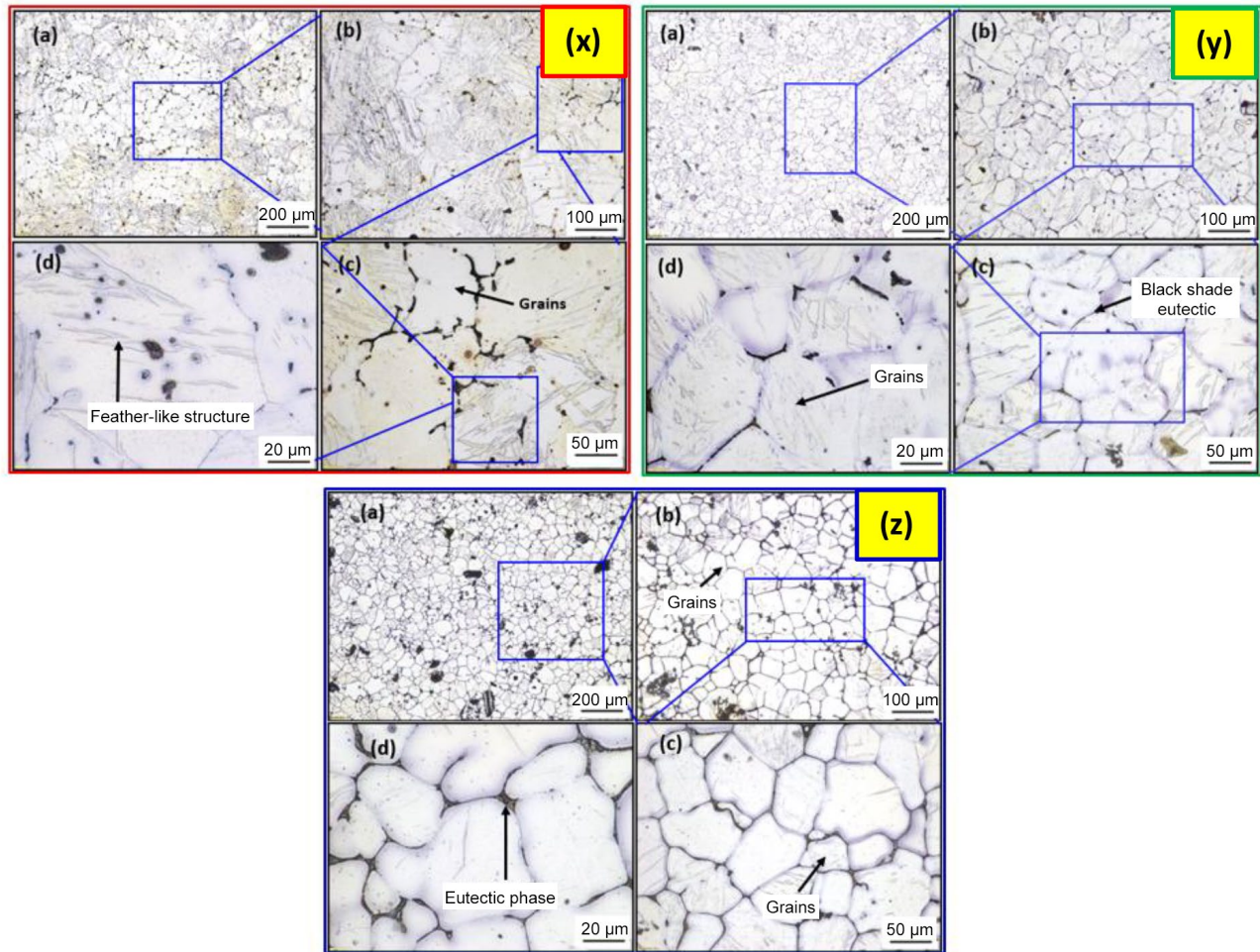


Fig. 2: Optical microstructures: (x) 2.5%; (y) 5.0%; and (z) 7.5% Sn alloys

contents exist predominantly in the Mg-HCP phase. At higher Sn concentrations, Mg_2Sn intermetallic precipitates form, contributing to the precipitation strengthening of the alloy. Whereas, at lower Sn concentrations and temperatures, the Mg-HCP phase dominates, representing the solid solution of Sn in Mg. Sn has limited solubility in Mg-HCP at room temperature, leading to the precipitation of Mg_2Sn as the Sn content increases. As temperature decreases, Mg_2Sn intermetallic phases precipitate, influencing the mechanical properties of the alloy. Alloys with Sn content below 6wt.% can achieve optimal mechanical properties through solid-solution strengthening and the formation of fine Mg_2Sn precipitates.

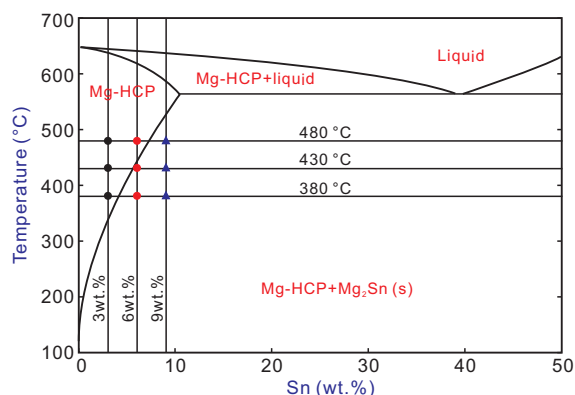


Fig. 3: Mg rich Mg-Sn binary phase diagram^[25]

3.3 SEM morphology with EDS

The SEM images of the specimens with 2.5%, 5.0%, and 7.5% Sn are presented in Figs. 4y(a-c). Figure 4y(a) shows the α -Mg phase, while Fig. 4y(b) depicts Mg-Sn particles around 50 μm in size, along with the intermetallic phase Mg_2Sn . Figure 4y(c) reveals a grass-like structure, which may result from the addition of Sn to magnesium. According to the EDS spectra, no elements other than Mg and Sn are detected in the composition. For the Mg-2.5wt.% Sn alloy, the EDS results shown in Figs. 4z(a) and (b) indicate a Sn content of 2.8wt.%.

A peak for oxygen (O) is observed in the 2.5% Sn sample, with the oxygen content ranging from 15%–17% by weight. Figures 4z(c) and (d) correspond to the Mg-5.0wt.% Sn alloy, while Figs. 4z(e) and (f) depict the Mg-7.5wt.% Sn alloy. The high temperatures during processing promote the precipitation of Mg_2Sn , which becomes more stable as the Sn content increases.

3.4 Tensile property

The tensile testing was used to calculate the stress, strain, force, and displacement, and the test results are presented in Figs. 5(a) and (b). The load-displacement tensile curve illustrates the mechanical response of Mg alloys with varying Sn contents (2.5%, 5%, and 7.5%) under tensile loading. Alloys with higher Sn contents (5% and 7.5%) reach higher

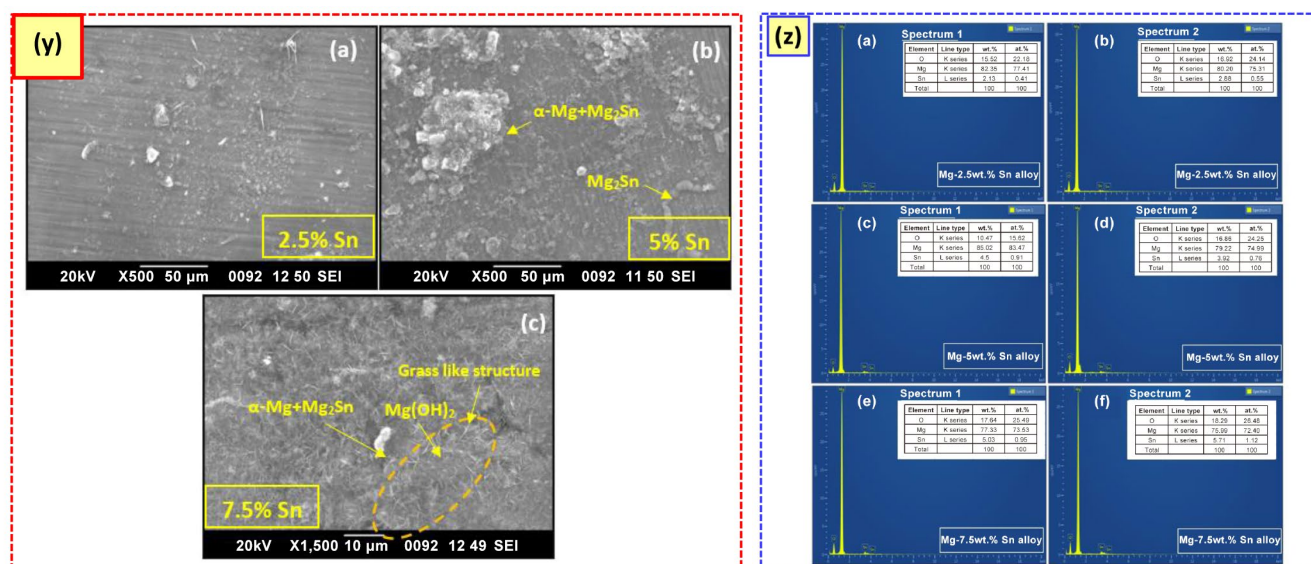


Fig. 4: SEM images of Mg-Sn alloys y(a-c) and EDS spectra 1 and 2 of the castings z(a-f)

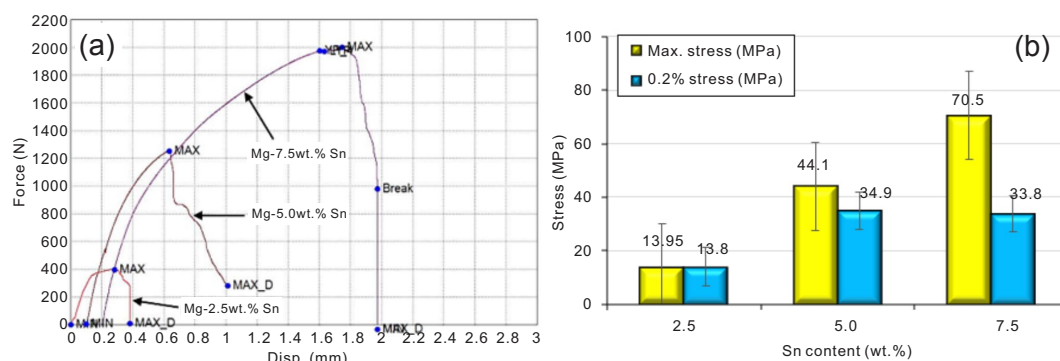


Fig. 5: Force-displacement curves from tensile testing (a) and stress-Sn composition relationship (b)

peak loads, suggesting greater tensile strength of alloys due to the refinement of grains and precipitation strengthening of Mg₂Sn phases. The yield point, where plastic deformation begins, shifts to higher forces as Sn content increases, indicating improved strength due to the Sn addition. The ultimate tensile strength (UTS) was observed to be around 70.5 MPa for the 7.5% Sn specimen, followed by 44 MPa for the 5.0% Sn specimen. The 2.5% Sn addition results in a lower strength, with a UTS of approximately 14 MPa. These results demonstrate that Sn addition enhances the tensile strength of Mg-Sn alloys.

The increase in UTS with Sn addition can be attributed to the formation of a solid solution, where Sn atoms are incorporated into the magnesium matrix. This solid solution hinders the motion of dislocations within the crystal lattice, making deformation more difficult and increasing the tensile

strength. Additionally, the Sn addition can influence grain size, with smaller grain sizes often leading to higher strength due to the restriction of dislocation movement. Further analyses were conducted to determine the maximum force, maximum strain, 0.2% strain, and displacement for the alloys, as shown in Table 1. The stress-strain curve indicates that the force and strain at 0.2% for the 5.0% Sn alloy are higher than those observed for the 7.5% Sn alloy. Microstructural analysis confirms the reduced grain size with increasing Sn content, while the presence of fine Mg₂Sn precipitates at grain boundaries and within the matrix supports the observed enhancement in tensile strength.

The inclusion of Sn element to Mg alloy has a significant impact on grain size and the formation of Mg₂Sn intermetallic phases. Increasing the Sn content results in smaller, more uniformly distributed grains, which enhances mechanical properties such as strength and ductility through grain

Table 1: Tensile testing results

Specimen	Max force (N)	Max strain (%)	Force at 0.2% (N)	0.2% strain (%)	Max. disp. (mm)
Mg-2.5wt.% Sn	395.69	0.58885	390.148	0.49766	0.28265
Mg-5.0wt.% Sn	1249.85	1.11337	992.640	0.62300	0.53442
Mg-7.5wt.% Sn	1999.85	3.22092	958.808	0.58420	1.54604

boundary strengthening. Furthermore, Sn promotes the formation of Mg_2Sn intermetallic precipitates, which improve the alloy's strength by hindering dislocation movement, thereby providing precipitation strengthening. However, excessive Sn content can lead to the coarsening of Mg_2Sn precipitates, which increases brittleness and may compromise the mechanical properties^[26]. Therefore, controlling the Sn content is essential to achieving an optimal balance between strength and ductility in Mg alloys.

3.5 Vickers microhardness

Vickers microhardness testing results (average values) are presented in Fig. 6 for 2.5%, 5.0%, and 7.5% Sn. Three trials were conducted at different sections of each specimen, and the variation in hardness with increasing Sn content is evident. The addition of Sn up to 5.0wt.% significantly enhances the hardness compared to the 7.5wt.% Sn added alloy. At lower Sn concentrations, solid solution strengthening dominates, resulting in increased hardness.

The Sn atoms dissolve into the magnesium matrix, hindering dislocation movement and thereby improving hardness. At higher Sn concentrations, the formation of precipitates or intermetallic phases, such as Mg_2Sn , can further contribute to increased hardness. However, beyond a certain Sn

concentration, excessive precipitation can cause intermetallic phase coarsening, which may reduce hardness. Additionally, changes in Sn content can affect the grain size, with finer grains generally leading to higher hardness and coarse grains resulting in lower hardness. The Mg_2Sn phase, a cubic fluorite-type intermetallic compound, contributes to the alloy's hardness^[27].

The highest hardness value of around 65 HV is observed for the 5% Sn specimen. The increased Sn content refines the grain structure and promotes the formation of Mg_2Sn intermetallic compounds, resulting in enhanced precipitation strengthening and higher hardness values. These factors contribute to the observed hardness improvements with up to 5% Sn addition, after which the hardness decreases due to the excess precipitation.

3.6 Tribological property

Wear testing was conducted on the prepared cast samples at room temperature, with trials labelled T1 through T9, as detailed in Table 2. The results are presented in Fig. 7, where Fig. 7(a) illustrates the coefficient of friction (COF) and corresponding frictional forces (N), and Fig. 7(b) shows the wear measurements in microns. The results indicate that both the Sn content, applied load and speed play crucial roles in determining the wear characteristics of the Mg-Sn alloy. Higher applied loads consistently lead to greater wear depths across all Sn concentrations. Conversely, higher rotational speeds also contribute to increased wear but shows some variability depending on the specific combination of Sn content and applied load.

Wear rate evaluation involved recording the initial weight of each pinned specimen, followed by measuring the final weight post-testing. The wear rate was determined as the difference between these weights. Table 2 summarizes the weight loss data obtained from all wear trials. Trial T4, performed on the 5% Sn sample, records the lowest weight loss of 0.010 g under a 20 N load and 300 RPM, demonstrating enhanced wear resistance relative to all other test conditions. These findings highlight the beneficial effect of Sn addition on enhancing the

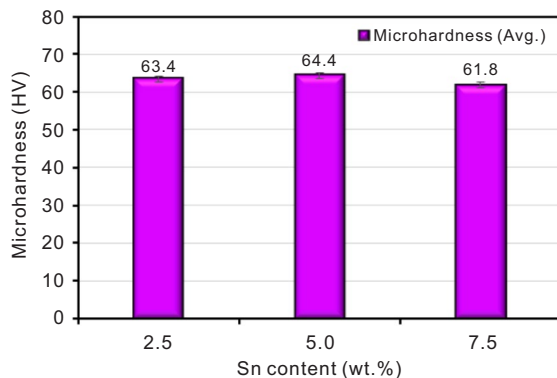


Fig. 6: Vickers microhardness test results for Mg with 2.5%, 5.0%, and 7.5% Sn addition

Table 2: Wear testing trials and weight loss measurement

Trials	Sn addition (%)	Applied load (N)	Speed (RPM)	Initial weight (g)	Final weight (g)	Weight loss (g)
T1	2.5	20	200	1.492	1.472	0.020
T2	2.5	30	300	1.482	1.428	0.054
T3	2.5	40	400	1.428	1.347	0.081
T4	5	20	300	1.490	1.480	0.010
T5	5	30	400	1.481	1.426	0.055
T6	5	40	200	1.430	1.345	0.085
T7	7.5	20	400	1.487	1.420	0.067
T8	7.5	30	200	1.420	1.369	0.051
T9	7.5	40	300	1.369	1.331	0.038

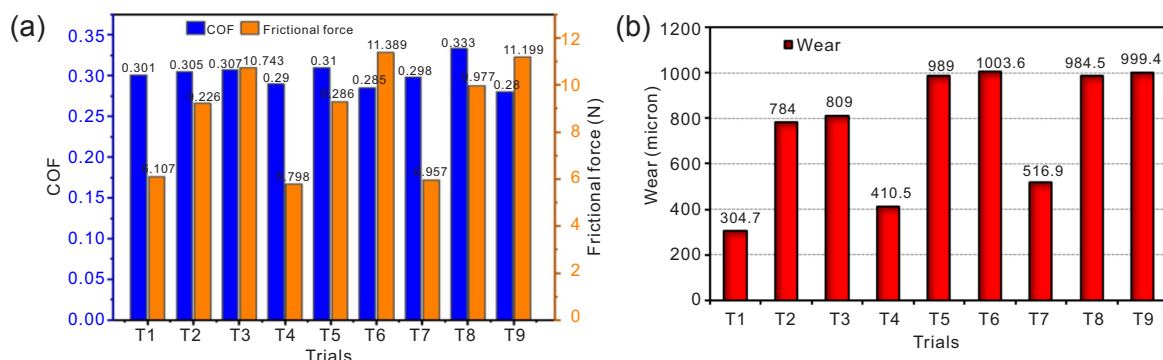


Fig. 7: Frictional force estimated and COF of all trials (a) and wear estimation of Mg-Sn alloys developed with different trials (b)

hardness and wear resistance of the cast alloy, particularly at lower rotational speeds. At a constant speed, the 7.5% Sn alloy exhibits a frictional force approximately 2 N higher than the 5% and 2.5% Sn alloys, contributing to increased material loss. This highlights the combined influence of alloy composition and speed on wear behaviour.

The maximum frictional force recorded is 11.38 N during trial T6, which was performed under the highest applied load of 40 N and the lowest speed of 200 RPM. The performance of the alloys was further analyzed through COF values, which ranged between 0.28 and 0.333, as shown in Fig. 7(a). The COF was calculated by dividing the frictional force by the normal force. Among all samples, the T8 sample, containing 7.5% Sn, exhibits the highest COF of 0.333. These results indicate that Sn addition enhances wear resistance at moderate speeds and loads, higher Sn content correlates with increased frictional forces and COF values, underscoring the trade-offs in material performance with varying Sn concentrations.

The COF is directly correlated with frictional force, with higher COF values generally indicating increased wear rates. Trial T4 exhibits notably low wear, suggesting superior wear resistance for the 5% Sn alloy under those conditions. In contrast, trials T6 and T9 show higher wear, indicating that wear resistance may vary with processing or testing parameters despite similar compositions. A lower COF is often associated with increased hardness in cast alloys; however, this relationship is influenced by factors such as microstructure, surface finish, and testing conditions. For instance, in the 2.5% Sn trial at 400 RPM, elevated friction leads to a non-slippery interface between the disc and pin, suggesting that surface interactions can override compositional effects.

The wear measurements in microns for all trials are depicted in Fig. 7(b), suggesting an abrasive wear mechanism. The wear depth, ranging from 304 to 1,003 μm , influenced by factors such as frictional force, rotational speed, material properties, temperature, and applied load. Trial T1 records the lowest wear depth at approximately 304.7 μm , while trial T6 displays the highest wear depth at 1,003 μm . A strong positive correlation is observed between increasing COF and wear depth, particularly under higher load and speed conditions. This suggests that elevated frictional forces intensify material removal, leading to deeper wear tracks.

Among the parameters examined, applied load and rotational speed are identified as the most significant factors influencing wear behavior in Mg-Sn alloys. At higher speeds, increased loads result in intensified frictional contact. This condition causes the specimens to resist frictional effects, leading to non-slippery behavior and increased wear, as observed in trial T9. These findings emphasize the critical interplay of alloy composition, load, and speed in determining the tribological performance of Mg-Sn alloys.

3.7 Worn surface analysis

Figure 8 presents the SEM images of the worn surfaces of the pinned specimens after wear testing, highlighting the influence of Sn addition on the wear mechanisms and fractography. Understanding these wear mechanisms is crucial for optimizing material design to enhance wear resistance. The dominant wear mechanism observed is adhesive wear, occurring due to direct contact between two surfaces, which resulted in material transfer and interaction. This process leads to the formation of wear debris and surface damage. Microscopic tearing at asperities (surface irregularities) contributes to the wear observed in the specimens.

Figures 8(a–c) show the worn surfaces of the Mg-2.5wt.% Sn alloy at different magnifications, emphasizing the sliding effect. Figure 8(a) illustrates a prominent sliding effect, resulting in a slippery interaction between the disc and pin surfaces. In contrast, Figs. 8(d–f), corresponding to the Mg-5wt.% Sn alloy, indicate restricted sliding, attributed to increased friction between the disc and pin. This friction contributes to higher wear resistance compared to the 2.5% Sn alloy. However, the wear is more pronounced for the Mg-7.5wt.% Sn alloy, as seen in Figs. 8(g–i). Higher loads and rotational speeds lead to increased wear and friction, emphasizing the sensitivity of this composition to operational conditions.

Figures 9(a–c) display SEM images of wear debris generated during the wear test of Mg-7.5wt.% Sn alloy sample. Figures 9(a) and (b) show large, irregularly shaped debris particles. The large flakes and irregular shapes suggest a dominant abrasive wear mode, with some contribution from adhesive and delamination wear. The debris exhibits distinct aloe-vera-like structures [Fig. 9(c)], potentially highlighting fibrous or needle-like formations on relatively undisturbed hard

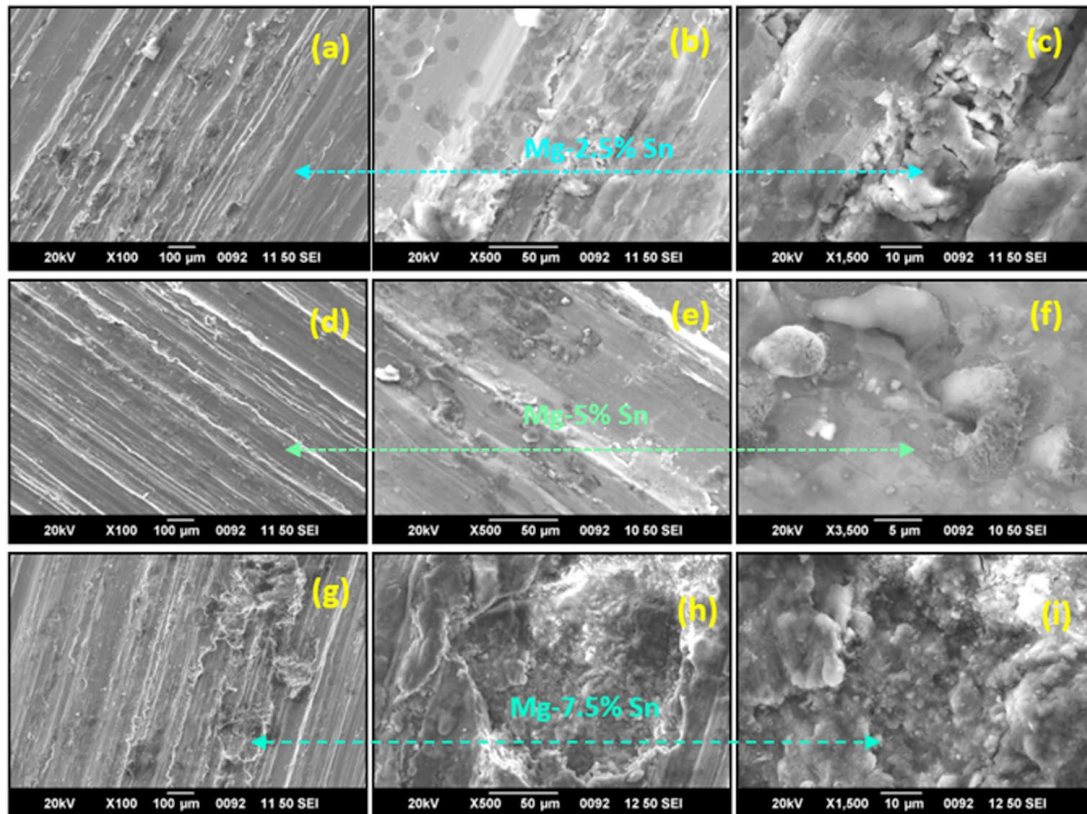


Fig. 8: SEM images of worn specimens after wear testing trials: (a-c) 2.5% Sn; (d-f) 5.0% Sn; (g-i) 7.5% Sn

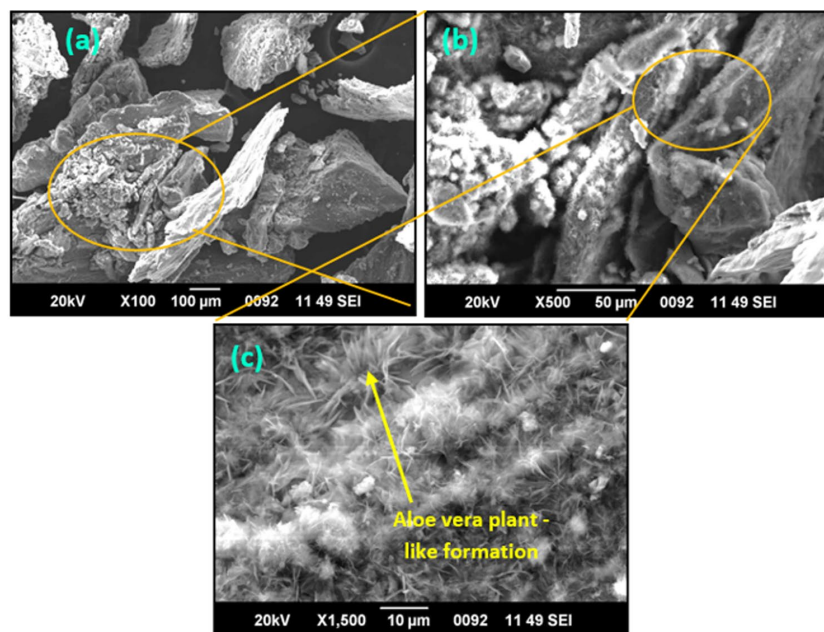


Fig. 9: SEM images of wear debris of the specimen with 7.5% Sn addition (a-c)

surfaces, indicating oxidation during wear testing forms oxide layers, which break apart into fine and brittle particles. High stress during wear might create elongated or fibrous features, as seen in the image [Fig. 9(c)]. These unique morphologies of wear debris provide insights into the wear mechanisms and the role of Sn in influencing wear resistance. These observations align with the earlier findings, demonstrating that the Sn content and operational parameters critically affect the wear behaviors of Mg-Sn alloys^[28].

4 Conclusions

This study investigated the effects of varying Sn concentrations on Mg-Sn alloys, focusing on their microstructure as well as tensile, microhardness, and wear properties. The key findings from the experimental work are summarized as follows:

(1) The addition of Sn to Mg alloy significantly refines grain size and promotes the formation of Mg_2Sn intermetallic precipitates. These precipitates enhance alloy strength by

impeding dislocation motion, enabling effective precipitation strengthening.

(2) At the grain boundaries, the volume fraction of Mg_2Sn intermetallic phase increases with an increase in Sn content and contributes significantly to the observed mechanical and tribological behaviors.

(3) Among the tested compositions, the 7.5% Sn alloy demonstrates an optimal balance of reduced microhardness and superior tensile properties. The tensile strength improves consistently with increasing Sn content, highlighting the higher solubility of Sn in the Mg matrix at 7.5% compared to 2.5%.

(4) The 7.5% Sn alloy exhibits relatively lower hardness compared to those with lower Sn contents.

(5) The 7.5% Sn alloy exhibits refined grains with distinct grain boundaries and delivers the highest tensile strength of 70 MPa. This improvement is attributed to the prominent Mg_2Sn precipitation observed in alloys containing at least 5% Sn.

(6) The COF and wear behavior demonstrate a complex dependence on Sn content, with the highest COF of 0.333 recorded at 5% Sn under a 10 N load and 100 rpm. Increasing Sn concentration generally reduces wear rates, attributed to enhanced surface hardness and formation of Mg_2Sn phase, although tribological performance also varies with applied load and rotational speed.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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