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Effect of Ti reinforcement on the thermal behaviour of AZ91/Ti composites

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ABSTRACT

Despite magnesium's high strength-to-weight ratio and eco-friendly nature, its limited industrial applications due to low corrosion and wear resistance have prompted extensive research into enhancing these properties. Magnesium matrix composites have been developed with various reinforcements, including B_4C, SiC, carbon nanotubes, graphite, and titanium (Ti). Among these, Ti is particularly promising as it improves wear resistance while preserving mechanical strength and ductility. In this study, the influence of Ti volume fraction on the thermal properties of AZ91/Ti composites fabricated via powder metallurgy is explored. Results revealed a reduction in thermal conductivity up to 6 % Ti content (6 W/m·K), attributed to Ti's lower thermal conductivity compared to magnesium. However, the Mg + 8% Ti composite exhibited enhanced thermal conductivity (10.51 W/m·K), but mechanical properties degraded. After analysis of physical, mechanical, and thermal tests, it is concluded that 6 % Ti volume fraction is the optimum choice for balancing mechanical performance in Mg/Ti composites. This research contributes valuable insights for tailoring Mg/Ti composites to specific engineering needs, offering a potential solution to the challenge of wear resistance in magnesium-based materials.

KEYWORDS

AZ91 Mg alloy • powder metallurgy • titanium • composites • thermal conductivity • thermal diffusivity

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Introduction

Magnesium has garnered significant attention across various industries owing to its remarkable attributes, notably its high strength-to-weight ratio, surpassing that of other common metallic structural materials such as aluminum, copper, and iron [1–3]. Furthermore, magnesium is hailed for its eco-friendly nature. However, despite its commendable low density and high biocompatibility, the widespread industrial applications of magnesium remain limited due to its inherent shortcomings, primarily its low resistance to corrosion and wear [4,5]. To address this limitation, researchers worldwide have diligently focused on the development of magnesium matrix composites with superior corrosion and wear resistance [6,7].

Magnesium alloys were chosen over aluminum or copper alloys for their superior strength-to-weight ratio and specific properties crucial for wear and strength applications, including lightweight design, corrosion resistance, and mechanical performance. These characteristics align with the specific requirements of electronic devices applications such as laptop and mobile body.

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To enhance the wear resistance of magnesium, ceramic and carbonaceous reinforcements have been employed, which have indeed shown promising results [8,9]. However, the introduction of ceramic reinforcements, while bolstering wear resistance, is often accompanied by a reduction in toughness and thermal conductivity [10,11]. On the other hand, the addition of carbonaceous reinforcements enhances strength and wear resistance, but agglomeration issues and thermal concerns persist [12,13]. To surmount these challenges, the introduction of metallic reinforcements, specifically aluminum (Al) and titanium (Ti), into the magnesium matrix has become a focal point for researchers [14–16]. These metallic reinforcements not only augment strength and wear resistance but also provide enhanced ductility and improved thermal conductivity [17–20].

The present research endeavors to delve into the impact of Ti reinforcement on the thermal behavior of AZ91/Ti composites, which have been meticulously fabricated using the powder metallurgy technique [21–24]. This method was chosen over alternative composite fabrication techniques due to its advantageous features, including high material utilization, minimal scrap generation, and reduced machining requirements [25–28]. In the context of the growing concern regarding heat dissipation in electronic devices, this study aims to shed light on the potential of AZ91/Ti composites to address this issue effectively, further enhancing the overall functionality of electronic devices.

Materials and Methods

In this study, two crucial materials played a pivotal role in the creation of composite materials tailored for electronic device applications. The matrix material selected was magnesium alloy AZ91, which was acquired in powder form from Parshwamani Metals, located in Mumbai, India. This magnesium powder, characterized by irregular particle shapes, exhibited an average particle size of approximately 50 μm. The supplier indicated a purity level of about 99 % for the magnesium powder. Additionally, titanium (Ti) was chosen as the reinforcing material, and this too was sourced in powdered form from the same supplier. The titanium powder displayed similar irregular particle morphology, albeit with a slightly smaller average particle size of about 30 μm and was also reported to maintain an impressive purity level of around 99 %, as provided by the supplier.

The rationale behind the selection of titanium as the reinforcement material is grounded in the advantageous properties it brings to the composite. Notably, titanium possesses exceptionally low solid solubility when combined with magnesium. This attribute is particularly advantageous since it precludes the formation of tertiary hard phases within the composite. Significantly, the inclusion of titanium in the composite is geared towards a substantial enhancement of its strength, a critical factor for electronic device applications such as laptop and mobile body. Equally important is the fact that while increasing the strength of the composite, the introduction of titanium does not compromise the material's ductility. This pivotal characteristic ensures that the composite retains its ability to deform plastically without fracturing under load, which is essential in the context of electronic device applications. Considering the specific challenges and demands associated with electronic devices, the judicious selection of magnesium alloy AZ91 as the matrix material and titanium as the reinforcing component forms the cornerstone of this research. The aim is to create composite materials that not only possess enhanced strength but also exhibit superior thermal characteristics, well-aligned with the requirements for effective heat management in electronic devices.

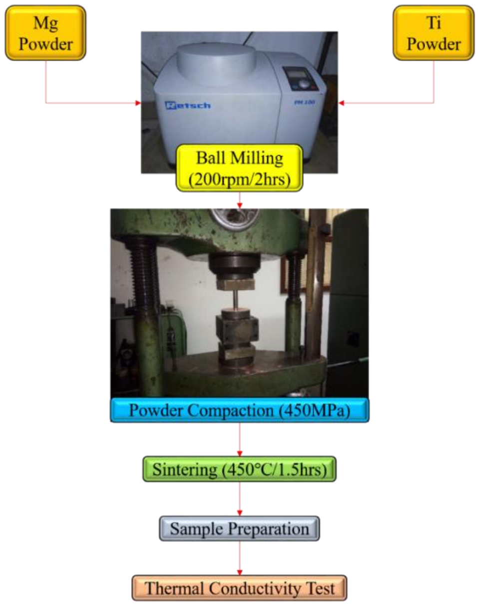

Fig. 1. Flow diagram of powder metallurgy process

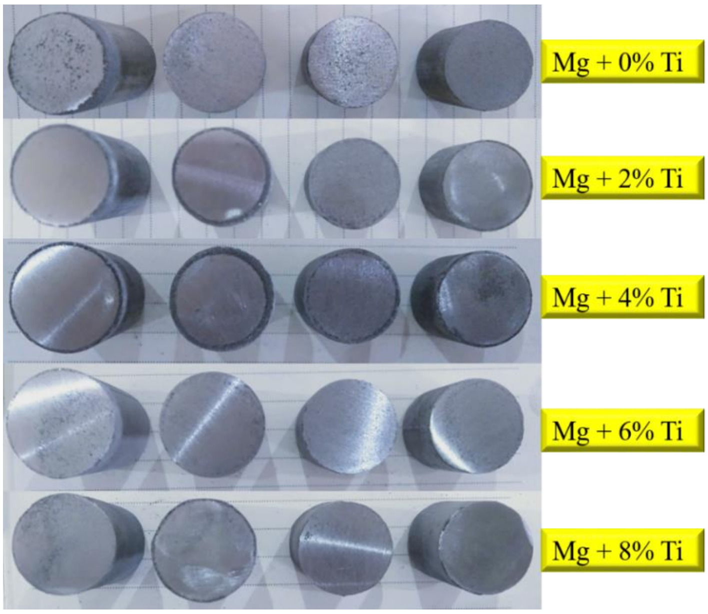

Fig. 2. A photograph of sintered Mg alloy and Mg/Ti composites

The fabrication of Mg/Ti composites was carried out via a well-structured powder metallurgy technique, as outlined in Fig. 1 [29–32]. To investigate the influence of varying volume fractions of matrix and reinforcement materials, five distinct sample types were meticulously prepared, as detailed in Table 1. The selection of the volume percentage of titanium was based on established findings in the existing literature.

Table 1. Sample specifications

Sample	Composition
Mg	100 vol.% Mg + 0 vol.% Ti
Mg + 2% Ti	98 vol.% Mg + 2 vol.% Ti
Mg + 4% Ti	96 vol.% Mg + 4 vol.% Ti
Mg + 6% Ti	94 vol.% Mg + 6 vol.% Ti
Mg + 8% Ti	92 vol.% Mg + 8 vol.% Ti

The production process commenced by accurately weighing the requisite quantities of the purchased matrix material (Mg) and reinforcement material (Ti) powders based on the predetermined volume fractions. This weighing was executed with precision using an electronic weighing balance. Subsequently, the meticulously weighed powders were combined and subjected to mechanical blending in a planetary ball milling machine. This milling process operated at 200 revolutions per min (rpm) for a duration of 2 h, maintaining a ball-to-powder weight ratio of 10:1.

Following the completion of the ball milling step, the blended powders were further processed. They were compacted under a uniaxial split-die configuration using a universal testing machine, applying a compaction pressure of 450 MPa. The outcome of this compaction step was the production of green compacts, serving as the initial stage of the composite material.

Subsequently, the green compacts underwent sintering within a muffle furnace, executed under a controlled nitrogen environment. The sintering process was conducted at a temperature of 450 °C, with a sintering duration of 90 min. Fig. 2 provides a visual representation of the sintered samples.

After the completion of the sintering process, the samples were allowed to cool in the furnace to reach room temperature. Once cooled, thermal conductivity test samples were precisely cut from the sintered compacts using wire-cut electrical discharge machining (EDM). This systematic methodology was rigorously applied to ensure the consistent and precise production of Mg/Ti composites for subsequent analysis and testing.

In light of the paramount importance of high thermal conductivity in materials employed for applications such as braking systems, electronic devices, and automotive components, comprehensive thermal conductivity assessments were conducted on all five distinct sample types. These tests were executed at the Mechanical Engineering Department of the esteemed Indian Institute of Technology, Kanpur.

The thermal conductivity tests were meticulously conducted using a Thermal Constants Analyzer, specifically the TPS 500 model, incorporating a hot disc apparatus. This analytical approach operates on the fundamental principle of the Transient Plane Method.

With a focus on precision and reliability, these tests were instrumental in quantifying the thermal conductive properties of the composite materials. This information is vital for understanding how effectively these composites can dissipate heat, which holds critical implications for their suitability in applications like braking systems and electronic gadgets.

The results and in-depth discussions stemming from the thermal conductivity testing are elaborated upon in the subsequent section. These findings provide valuable insights into the thermal behavior of the Mg/Ti composites, shedding light on their potential for enhancing heat dissipation rates in applications demanding efficient thermal management.

To identify the various phases, present within both the crystalline powders and the prepared composites, X-ray diffraction (XRD) examinations were conducted. These analyses were performed utilizing a high-precision X-ray diffractometer, specifically the Rigaku MiniFlex 600, which is available at the Applied Sciences Department of the Indian Institute of Information Technology, Allahabad, India.

The XRD measurements were carried out under controlled conditions to ensure accuracy. The scan speed was set at 0.2 sec per step, with a step size of 0.01°, and the scan range encompassed an angular range from 10 to 80°. An operating voltage of 40 kV was employed to facilitate the analysis.

This XRD analysis is fundamental in characterizing the structural composition of the materials under investigation, enabling the identification of distinct phases and crystalline structures present in both the raw powders and the composite materials. The results derived from this examination serve as a critical foundation for understanding the material's properties and its potential performance in various applications.

Results and Discussion

The XRD patterns of all five sintered samples are vividly depicted in Fig. 3, offering a detailed examination of the structural composition of the Mg/Ti composites and revealing crucial phase transitions.

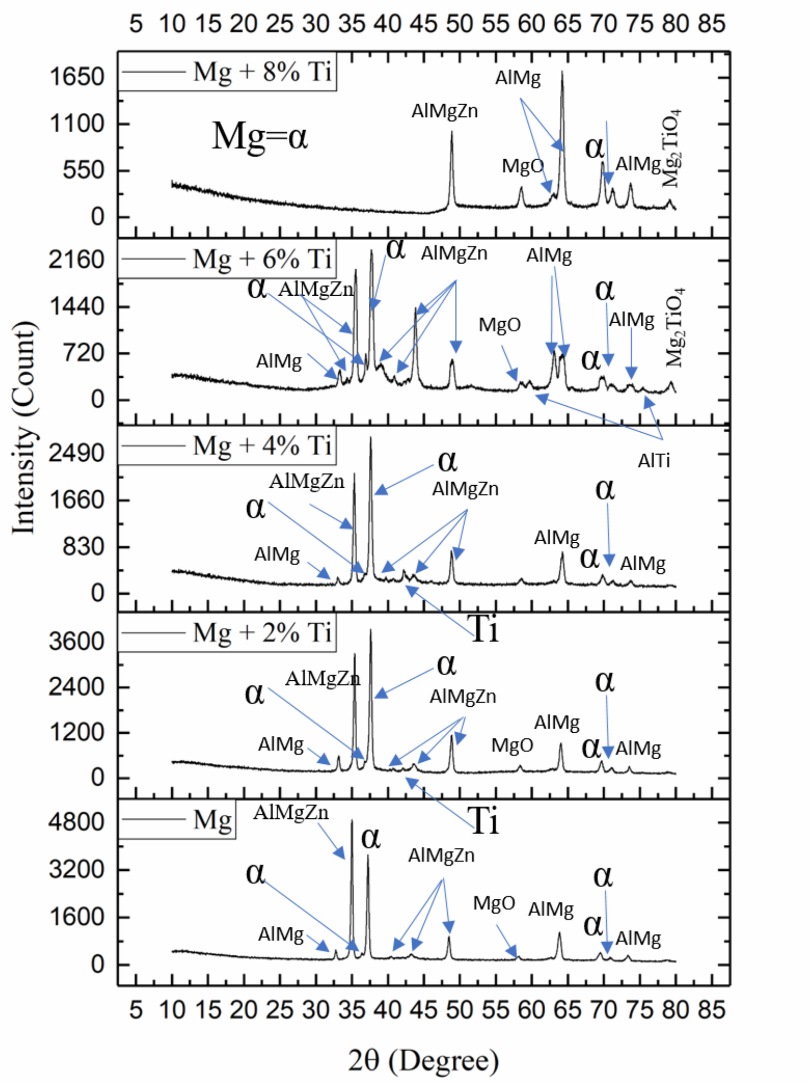

Fig. 3. The matched XRD patterns of sintered Mg alloy and Mg/Ti composites

An intriguing observation is the consistent reduction in the intensity of the highest peak as the titanium (Ti) content increases. This decrease in intensity is attributed to the concurrent emergence of secondary phases within the composites, indicative of complex structural transformations.

Remarkably, the presence of magnesium oxide (MgO) was common across all samples (composites and unreinforced magnesium samples). This observation indicates that an oxidation process occurred during the sintering phase, impacting the material's structural composition.

Notably, the XRD pattern of the Mg/8%Ti composite exhibits distinct characteristics, setting it apart from the other composite samples. It portrays a unique structural arrangement, possibly due to reaction of Mg with Ti in the presence of oxygen. Reaction initiated after 6 vol. % of Ti and its effect was notable in case of 8 vol. % Ti sample.

The presence of free titanium (Ti) in all Mg/Ti composites, except Mg/8%Ti, signifies that Ti remained unreacted with the magnesium matrix. This unreacted Ti is evident through the distinctive XRD patterns. In case of Mg/8%Ti, Mg reacted with titanium and oxygen to form complex. Kumar et al. [29] have studied the effect of Ti volume fraction on the physical and mechanical properties of Mg/Ti composites. Ti and other phases are shown in optical micrographs.

Moreover, the $MgTiO_4$ phase was identified, which was confirmed during the X'Pert HighScore peak matching exercise. This finding signifies a chemical reaction between Ti and Mg, resulting in the formation of the $MgTiO_4$ phase. This reaction led to the dissolution of the high-intensity magnesium peak and the emergence of novel phases.

Furthermore, as the Ti volume fraction exceeded 6 %, the intensity of the AlMg phase, located within the 2θ range of 63-65°, significantly increased. This increase was coupled with the dissolution of other high-intensity peaks within the 30 to 45° range. Additionally, peak shifting was observed, reflecting heightened lattice strain as the Ti volume fraction increased.

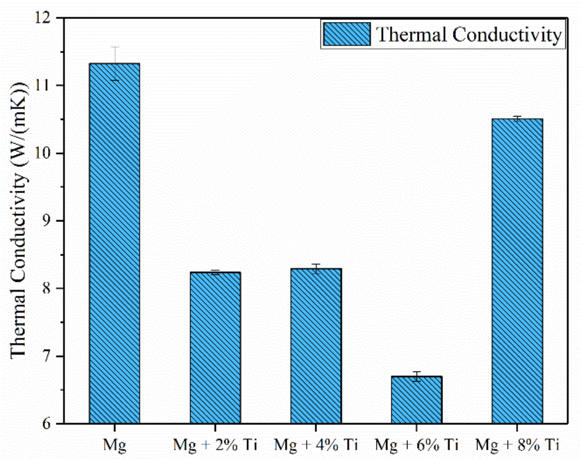

Fig. 4. Variation in thermal conductivity of Mg/Ti composites with increase in Ti volume fraction

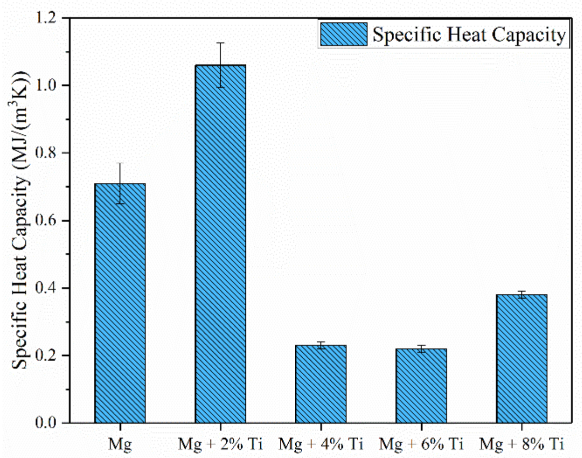

Fig. 5. Variation in specific heat capacity of Mg/Ti composites with increase in Ti volume fraction

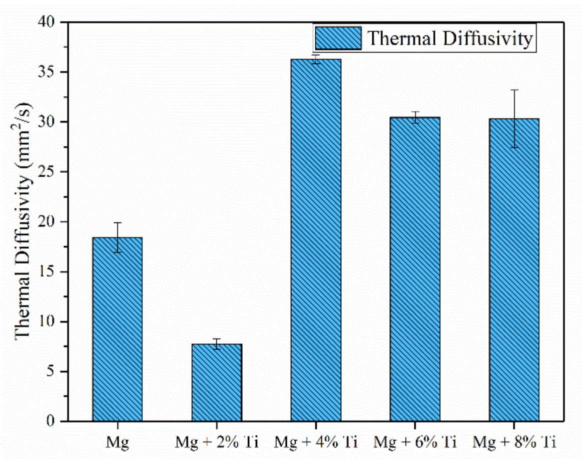

Fig. 6. Variation in thermal diffusivity of Mg/Ti composites with increase in Ti volume fraction

The thermal conductivity data, as depicted in Fig. 4, provides valuable insights into the influence of varying titanium (Ti) content on the thermal behavior of the Mg/Ti composites. Notable trends in the results can be elucidated to better understand the observed variations.

The initial phase of the thermal conductivity evaluation reveals a consistent reduction as the volume fraction of titanium within the composite increases. This decrease in thermal conductivity is particularly pronounced up to 6 vol. % Ti. The underlying mechanism behind this decline can be attributed to the distinct thermal conductivities of the constituent materials. Magnesium exhibits a relatively high thermal conductivity, approximately 72 W/m·K, while titanium, in contrast, has a substantially lower thermal conductivity of around 17 W/m·K [23]. Consequently, the introduction of titanium, especially in minor quantities, serves as a diluent within the composite, effectively lowering the overall thermal conductivity. This behavior stems from the dominant influence of the lower thermal conductivity of titanium.

However, an intriguing departure from this initial trend is observed when the Mg/Ti composite is reinforced with 8 vol. % Ti. Here, the thermal conductivity of the composite surpasses that of the Mg/Ti composite reinforced with 6 vol. % Ti. This unanticipated upturn in thermal conductivity can be attributed to complex changes occurring within the composite [17]. The X-ray diffraction (XRD) patterns provide crucial insights, indicating the dissolution of primary phases in magnesium and the emergence of new phases. These structural transformations likely contribute to the altered thermal properties, resulting in an increase in thermal conductivity. The formation of these new phases may possess thermal conductivities that differ from the original constituents, thereby influencing the composite's overall thermal behavior.

The presented data in Fig. 5 illustrates the variation in specific heat capacity with increasing titanium (Ti) volume fraction within the Mg/Ti composites. The results reveal certain noteworthy aspects that require elucidation.

One apparent observation is the significant variability in the specific heat capacity values as the Ti volume fraction increases. This substantial variation can be primarily attributed to the presence of uneven porosity within the samples (Kumar et al. [29] have studied the effect of Ti volume fraction on the density and porosity of Mg/Ti composites). The uneven distribution of porosity can significantly affect the heat capacity measurements, leading to inconsistent results.

From a theoretical perspective, it is anticipated that the specific heat capacity should exhibit an increasing trend with a rise in Ti volume fraction. This expectation is grounded in the fundamental properties of the constituent materials. Titanium (Ti) is known to possess a higher heat capacity (approximately 2.34 MJ/m^{3}K) compared to that of magnesium (about 1.9 MJ/m^{3}K) [21]. Therefore, as the volume fraction of Ti increases, it should theoretically contribute to a higher heat capacity in the composite material.

However, the observed fluctuations in specific heat capacity suggest that factors such as uneven porosity, sample heterogeneity, or other structural complexities might be influencing the results. Further investigations and potentially refined sample preparation techniques may be necessary to provide more consistent and reliable specific heat capacity data within the Mg/Ti composites.

The examination of thermal diffusivity, as delineated in Fig. 6, provides crucial insights into the material's ability to conduct and store heat as the titanium (Ti) volume fraction within the Mg/Ti composites increases. This variation can be better comprehended by considering the influence of thermal conductivity and specific heat capacity, which were discussed earlier.

It is essential to remember that thermal diffusivity encapsulates the rate at which heat can propagate through a material, contingent upon the interplay of thermal conductivity, density, and specific heat capacity. Generally, a higher thermal conductivity facilitates more efficient heat transfer, while greater specific heat capacity indicates the material's capacity to retain thermal energy.

The conspicuous, abrupt variation in thermal diffusivity as Ti content increases can be delineated through the prism of thermal conductivity and specific heat capacity. With the augmentation of Ti content, specifically from pure Mg to Mg + 2% Ti, a substantial reduction in thermal diffusivity is evident. This initial decrease can be attributed to the lower thermal conductivity of titanium, as discussed earlier. The inclusion of Ti acts as a diluent in the composite, impeding the efficient transmission of heat.

Progressing from Mg + 2% Ti to Mg + 4% Ti, there is a noteworthy upturn in thermal diffusivity. This transition likely stems from complex factors, such as evolving microstructure and alterations in thermal properties induced by the introduction of Ti. As a result, heat is able to propagate more effectively within the composite, resulting in higher thermal diffusivity.

From Mg + 4% Ti to Mg + 8% Ti, the thermal diffusivity displays a relatively stable pattern. This constancy indicates that the material's composition and structural characteristics stabilize as the Ti content reaches higher percentages. In this range, the materials exhibit consistent heat propagation characteristics.

Conclusions

In this study, Mg/Ti composites were successfully fabricated and analyzed to investigate the effect of Ti reinforcement on thermal behavior. Key findings and implications include:
1. Insights gained from the fabrication and investigation of Mg/Ti composites provide valuable understanding of their thermal behavior.
2. A consistent reduction in thermal conductivity was observed with increasing Ti content up to 6%, attributed to the lower thermal conductivity of titanium compared to magnesium.
3. The Mg/8%Ti composite exhibited enhanced thermal conductivity due to the dissolution of primary phases and formation of new phases, as confirmed by XRD patterns.
4. The observed trade-off between improved thermal properties and compromised mechanical characteristics emphasizes the importance of balancing material composition.
5. These findings highlight the potential for tailoring the heat transfer properties of Mg/Ti composites to meet specific engineering requirements.
6. This research contributes to advancing the understanding and application of Mg/Ti composites in various engineering and technological contexts.

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