Experimental Method for Processing and Mechanical Behaviour of ZE42 Magnesium Hybrid Composites Reinforced with TiO_2 and Graphene Nanoparticles

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Abstract: This research work explores the experimental method for fabricating and mechanical performance of ZE42 magnesium alloy-based hybrid composites strengthened with TiO_2 and graphene nanoplatelets (GNP) and manufactured through stir casting method. Four compositions comprising mono and hybrid reinforcements were synthesized to assess the effect of secondary graphene nanoplates on microstructure, hardness, tensile and compressive strength, wear, and corrosion properties. The combination of 3 wt.% TiO_2 with base alloy refined grain structure, enhanced strength and hardness through heterogeneous nucleation and load transfer. Hybrid metal matrix composites demonstrated synergetic strengthening, where an optimal amount of strength and ductility is increased with 1 wt.% GNP, while 3 wt.% GNP increased hardness, but marginally decreased elongation due to agglomeration. Fractography analysis explored ductile to fracture transitions leading by the crack deflection, graphene pull-out and bridging mechanisms. Finally, ZE42/TiO_2/GNP hybrid metal matrix exhibited the greater mechanical characteristics compared to single reinforced composites, demonstrating its potentiality for structural and lightweight applications.

Keywords: ZE42 magnesium alloy, stir casting, hybrid composites, TiO_2, graphene nanoplatelets, mechanical properties

Introduction

Magnesium alloys have attained the considerable focus over the last decade because of lightweight, excellent machinability, low density and high strength, focusing them appropriate for biomedical, aerospace and automotive applications [1]. Among the Magnesium alloys, ZE-series such as ZE42 exhibits the enhanced corrosion resistance, excellent castability, and creep resistance due to existence of rare earth components such as neodymium and cerium [2]. However, the low ductility and inadequate wear resistance of ZE42 constrain its extensive structural applications under severe working conditions [3]. Metal matrix composites strengthened with ceramic particulates have developed as a prominent approach for enhancing thermal, tribological and mechanical performances to overcome these difficulties [4]. Ceramic reinforcements like TiO_2, SiC and Al_2O_3 provide the enhanced wear resistance, dimensional stability and hardness owing to their greater chemical stability and elastic modulus [5]. Titanium Oxide is used specifically for its good thermal stability, and biocompatibility and it has potentiality to enhance hardness and high-temperature performance when integrated with Mg matrices [6].

Concurrently, the development of 2D carbon-based nanomaterials such as graphene nanoparticles (GNPs), has acquired new strategy for designing structural materials with outstanding strength to weight ratios [7]. GNPs demonstrate the greater load transfer efficiency, higher fracture toughness and exceptional thermal conductivity owing to their higher basic strength and aspect ratio [8]. The hybrid reinforcement method combined with ceramic particulates and GNPs, provide the synergetic strengthening through dislocation pining and grain refinement [9]. Hybrid composites strengthened with GNPs and TiO_2 are comparatively unique, but provide the unique characteristics like improved corrosion, mechanical and tribological performances compared to single phase reinforcements [10]. Such combination can enhance the stress transfer efficiency, and interfacial bonding, eventually affecting hardness, wear resistance and strength [11]. The manufacturing method is playing a vital role for attaining homogeneous grain refinements and methods such as powder metallurgy, stir casting and ultrasonic assisted casting have been used for manufacturing hybrid composites [12]. Despite many literature studies on Mg composites, very few literatures existed on ZE42 based hybrid composites. Additionally, the concurrent studies of mechanical performance, microstructural formation, and processing parameters are also less for such hybrid composites [13].

This research work addresses the gap experimentally for fabricating ZE42 hybrid composites reinforced with GNPs and TiO_2 and assessing the mechanical performance. This research paper investigates the manufacturing technique, microstructural study, and mechanical performance of ZE42 hybrid composites.

Experimental Planning

The magnesium alloy ZE42 has the basic components of Zn and rare earth (E). This rare earth components have the outstanding wear and corrosion resistance, reasonable strength, insubstantial lightweight properties and enhanced creep resistance compared to conventional Mg alloys. The standard chemical composition of ZE42 is mentioned in Table 1 as per ASTM B954. Rare earth elements (Zr & Ce) are exhibiting the important role in solid solution for improving mechanical performance and Zn enhances strength and castability.

Table 1. Typical chemical composition of ZE42 magnesium alloy (wt.%)

Zinc	Zirconium	Cerium	Silicon	Manganese	Nickel	Iron	Magnesium
2.55 %	0.67 %	3.21 %	0.03 %	0.02 %	0.002%	0.04%	93.3 %

The investigational work has been carried out to blend ZE42 magnesium alloy with different reinforcements using stir casting technique. Four compositions were prepared as (a) ZE42 (Base Alloy), (b) ZE42 + 3 wt.% TiO_2, (c) ZE42 + 3 wt.% TiO_2 + 1 wt.% GNP and (d) ZE42 + 3 wt.% TiO_2 + 3 wt.% GNP. The commercial ZE42 ingots were utilized as the prime matrix material. Titanium particles having submicron/nano size typically 50-180nm, were selected as ceramic reinforcement owing to their excellent interfacial bonding and thermal stability with ZE42 alloy. GNPs having size 10-15nm, were utilized as secondary reinforcement. Before blending, both powders were preserved in desiccators and dried at 100 to 115°C for 2 to 3 hours to eliminate moisture and avoid clustering during casting. This preheating was also carried out for proper binding of both reinforcements. Both powders were blended with a small amount (≈1 wt.% of reinforcement mass) magnesium-aluminate flux or potassium hexafluorotitanate (K_2TiF_6) to improve wettability, when required. Stir casting was carried in medium frequency induction furnace with a steel crucible. Stir casting was carried out in an induction resistance furnace equipped with a graphite crucible. The required amount of Mg ingot alloyed with required metals with percentages was charged into the crucible. This charge was melted to the temperature range of 650–750 °C using power capacity of 175kw. The protective inert gas atmosphere was used to avoid oxidation and burning of magnesium. The mechanical stirring was performed using eddy currents and stirrer rotating speed range of 1500 to 3000 rpm to avoid contamination. The stirring arrangement is aligned centrally with adjustable speed and immersion depth for consistent turbulence generation. Figure 1 shows the stir casting setup.

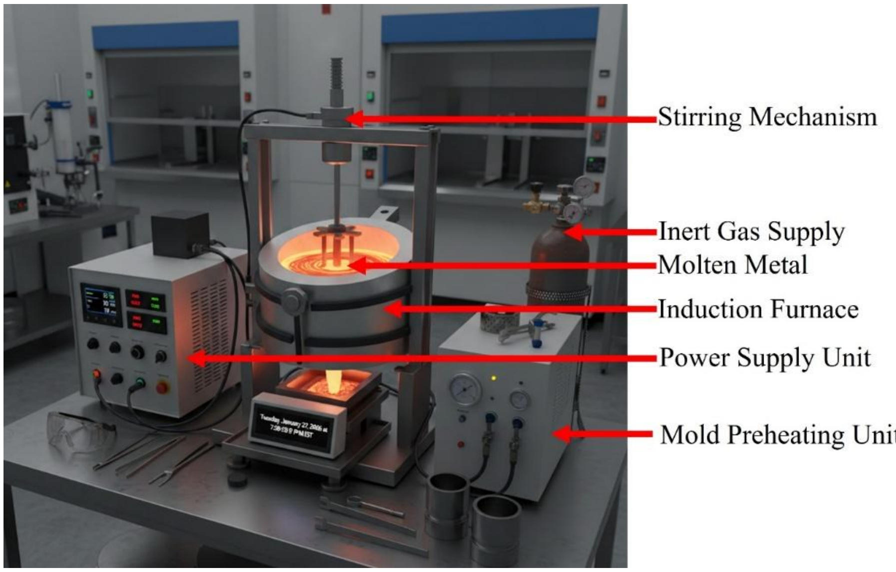

Figure 1. Stir Casting Setup

For the mono composite, the preheated TiO_2 particles were added into the molten ZE42 bath during stirring. The standard stirring speed was maintained between 1500 to 3000rpm for 5–10 minutes to attain homogeneous dispersion. For the hybrid composites, TiO_2 particles were added first and followed by GNP addition. GNP powders were ultrasonically dissolved in isopropyl alcohol or ethanol and subsequently dried before addition because of the intrinsic tendency of graphene to cluster. A double stage stirring approach was utilized to avoid GNP cluster and floating during mixing. The molten metal was permitted to undergo degassing using argon purging for 2-3 minutes to decrease the void defects. Sometimes fluxing agents such as $MgCl_2$-KCL was utilized to eradicate the dross and promote wetting. The molten composite slurry was transferred into cast-iron moulds-maintained 100-200°C to reduce solidification defects and thermal gradients. The solidification process was carried out at room temperature under natural convention. The solidified composite ingots were taken from cast-iron moulds, and solidified ingots were ejected from moulds and followed by fettling and surface finishing operations to eradicate oxides, dirt particles and slag.

Different solidified ingots were cut using wire cut EDM machine to standard dimensions for mechanical testing and microstructural study. The following test samples were prepared as per appropriate standards such as Hardness, Tensile and Compression Testing, Corrosion Testing and Wear Testing. The samples were cut perpendicularly to the casting direction for microstructural characterization. All samples were rubbed utilizing SiC papers from 100 to 2000grit and subsequently polished by alumina suspensions for fine finish. For ZE42 alloys, etching was done using acetic picral solution to reveal grain boundaries. The etched surface was investigated by optical microscopy and scanning electron microscopy. Energy dispersive spectroscopy (EDS) was used for element mapping.

Results and Discussion

The stir-cast ZE42 alloy demonstrated a standard α-Mg matrix with interdendritic with Mg–Zn–RE precipitates. The incorporation of 3% wt.% TiO_2 with the ZE42 alloy refined the grain structure because of enhanced interfacial bonding and heterogeneous nucleation, consequently, increase tensile strength and hardness. The hybrid reinforcement with GNP and TiO_2 refined the grain size and modified the fracture morphology demonstrating the synergetic strengthening.

Tensile testing explored that TiO_2 enhanced the tensile strength although supporting reasonable ductility. The hybrid composite system provided the extreme strengthening effect with 1 wt.% GNP supporting an optimal strength-ductility balance, whereas 3 wt.% GNP yielded greater hardness, but marginally decreased elongation owing to interfacial debonding and agglomeration. The compressive strength improved with the refinement of both hybrid reinforcements including GNP and TiO_2 because of load transfer and grain refinement.

Fractography of tensile and compressive specimens demonstrated ductile dimples in ZE42, mixed brittle-ductile features in TiO_2 composites and tortuous paths, crack bridging and graphene pull-out in hybrid variants. The enhancements were attributed to grain refinements, dislocation pinning, crack deflection and graphene bridging mechanisms.

Wear resistance enhanced substantially with reinforcement. Titanium oxide improved hardness and decreased material loss, whereas GNP supported solid lubrication. The hybrid composite system exhibited the lowest wear rate, while GNP excess provided the slight abrasive wear. The hybrid composite system demonstrated lower corrosion rate than base alloy. TiO_2 was worked as a protective barrier and consistently dispersed GNPs constrained electrolyte penetration. Higher GNP amount led to localized corrosion due to particle clustering.

The base magnesium alloy demonstrated coarse grains, whereas TiO_2 incorporation resulted grain distribution among the composite system. The hybrid composite system demonstrated the consistent reinforcement distribution and effective interfacial bonding with slight clustering, performed at greater GNP content.

Conclusion

The alloy-based mono and hybrid composites were effectively produced utilizing the stir casting method. The incorporation of 3 wt.% titanium oxide refined the microstructure and enhanced compressive and tensile strength, hardness, wear and corrosion resistance. The hybrid composite system with GNP creates the synergetic strengthening through grain refinement and effective load transfer. The hybrid composite having 3 wt.% GNP demonstrated the excellent wear and corrosion resistance, and strength whereas higher GNP propelled to minor property deprivation owing to agglomeration. However, TiO2 and GNP reinforcements with ZE42 alloy demonstrates the robust potentiality for tribological and lightweight structural applications.

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