STM JOURNALS
International Journal of
Fracture Mechanics and Damage Science
Volume 2, Issue 1, 2024
January–June
DOI (Journal): 10.37591/IJFMDS
https://journals.stmjournals.com/ijfmds

A Review on The Role of Nanoparticles in Modifying Mg Alloys and Composites

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Abstract

Reviewing and assessing magnesium's uses in the automobile sector, which have the potential to greatly improve fuel efficiency and environmental preservation, is the goal of this study. The report provides an overview of magnesium alloys' present benefits, drawbacks, technological obstacles, and future prospects in the automobile sector. The development of magnesium matrix composites has advanced to a new level thanks to the magnesium matrix nanocomposites' exceptional mechanical qualities. Dispersing nanoparticles in metal melts is a challenging task, particularly in magnesium melts, which differ from other metal melts and pose a risk during the casting process. This indicates that it is very difficult to manufacture a magnesium matrix nanocomposite.Further, the magnesium matrix nanocomposites possess a distinctive characteristic in deformation behaviour, strengthening and toughening mechanism due to their special size effect of nanoparticles. As a result, the deformation behavior, mechanical characteristics, and strengthening and toughening procedures will be the main topics of this review. Future research ideas, development trends, and prospective applications of magnesium matrix nanocomposite are also explored.

Keywords: Magnesium matrix nanocomposite; Microstructure; Mechanical properties; strengthening mechanism

INTRODUCTION

Light-weight magnesium which possesses extremely low density, good machinability and structural properties, can meet the requirements of energy saving and emission reduction in the transportation sector and other automotive application [1–3]. However, there are still some bottlenecks in a target application for magnesium such as low elastic modulus and ductility, poor creep and abrasion resistance and high corrosion rate [4]. To circumvent these limitations, the introduction of alloying elements or reinforcements to magnesium has been adopted in previous studies [5–8]. In particular, the addition of particulate reinforcements to magnesium matrix has been proven to further improve the mechanical properties in addition to precipitation strengthening, grain refinement strengthening and solid solution strengthening contributed by alloying element [9–12]. There are various types of particulate reinforcements available to prepare magnesium matrix composites (MMCs) such as carbides (SiC, TiC, B_4C, ZrC), oxides (Al_2O_3 , TiO_2), borides (ZrB_2 , TiB_2), nitrides (AlN, BN, ZrN, TiN) and metals (Ti, Cu, Mo, Ni) [12–15] . It has been shown that the MMCs containing one or more traditional micron size particulate reinforcements and continuous magnesium matrix have outstanding advantages over mono- lithic magnesium, such as high strength, high modulus and wear properties [16–18]. However, there is a

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Received Date: June 21, 2024
Accepted Date: June 25, 2024
Published Date: July 06, 2024

Citation: Amit Tiwari, Neeraj Kumar, Himanshu Vasnani, Sujeet Kumar Jha. A Review on the Role of Nanoparticles in Modifying Mg Alloys and Composites. International Journal of Fracture Mechanics and Damage Science. 2024; 2(1): 24–32p.

high probability that the addition of micron size particulate reinforcements can easily leads to particle cracking and void formation in the as- cast MMCs, which accelerates the failure during the following secondary processing. The emergence of magnesium matrix composites reinforced with nanoparticles over a decade ago demonstrated that the addition of nanoparticles not only exhibited a good strengthening effect but also preserved the initial matrix's toughness, pushing the field of magnesium matrix composites development to a new level. Nonetheless, the primary challenge in creating magnesium matrix nanocomposites with superior mechanical qualities is the limited wettability of the ceramic nanoparticles in relation to the molten magnesium matrix [21–22]. It is extremely difficult to disperse the nanoparticles in metal melt especially in magnesium melt, because the magnesium melt is easier to burn relative to other metal melts, which is more dangerous during alloy melting. This indicates that creating a magnesium matrix nanocomposite is extremely difficult.

The casting methodologies involving in either liquid based or solid based techniques [23–28] have been explored for preparing magnesium matrix composite containing nano-sized particle. Further, due to the special size effect of nanoparticles, there is also a distinctive characteristic in the grain refinement, the crushing of second phases, the improved distribution of reinforcement and the dynamic precipitation for the magnesium matrix nanocomposite during the secondary processing such as extrusion or rolling [29–30]. Moreover, the relation- ship between the mentioned microstructure and corresponding strengthening and toughening mechanism of the magnesium matrix nanocomposite has been explored in some literatures [31]. The present work will focus in detail on the important progress of lightweight magnesium matrix composites reinforced by nanoparticles in the preparation, forming, performance and toughening mechanisms. The principles and applications of different preparation technologies for magnesium matrix composites reinforced by nanoparticles will be presented.

LITERATURE REVIEW

Preparation of Magnesium Matrix Composite Reinforced by Nanoparticles

In order to improve the strength of the magnesium, microsize ceramic particles have been introduced into magnesium matrix, but unfortunately, they severely degrade the plasticity and machinability of magnesium. In this situation, the low concentration of nanoparticles which have the potential to improve strength while maintaining or even improving the plasticity of magnesium, has been introduced to the magnesium matrix. However, it is difficult to disperse the nanoparticles uniformly in magnesium matrix due to the strong van der Waals force between the nanoparticles and the very poor wettability with the magnesium matrix [32]. The commonly employed processing techniques to synthesize magnesium matrix nanocomposite includes ultrasonic vibration [33–34]. the combination of ultrasonic vibration and semisolid stirring [35] disintegrated melt deposition (DMD), in situ synthesis method [36], friction stir processing [37], powder metallurgy [38], etc.

Strengthening mechanisms of magnesium matrix composite reinforced by nanoparticles

In general, there are different strengthening mechanisms such as grain refinement strengthening, Orowan strengthening, Taylor strengthening and load transfer mechanism for the metal matrix composites. It has been shown that Hall Petch strengthening mechanism is the most important factor regardless of the type of the reinforcement for the magnesium matrix composites. Besides, this effect depends more on the volume fraction of the reinforcements relative to particle size. The Orowan strengthening has been reported to be not a major factor for the magnesium matrix composite reinforced by micro particles. Due to that the Orowan bowing can bypass the nanoparticles, Orowan strengthening becomes more favorable in magnesium matrix composites reinforced by highly-dispersed nano-size particles (smaller than 100 nm) even for only a small volume fraction (< 1%). Additionally, Orowan loops are anticipated to place a back burden on instability sources following secondary processing like extrusion. Therefore, it is necessary to consider the Orowan strengthening for the Strengthening mechanisms of magnesium matrix composite reinforced by nanoparticles (Figure 1).

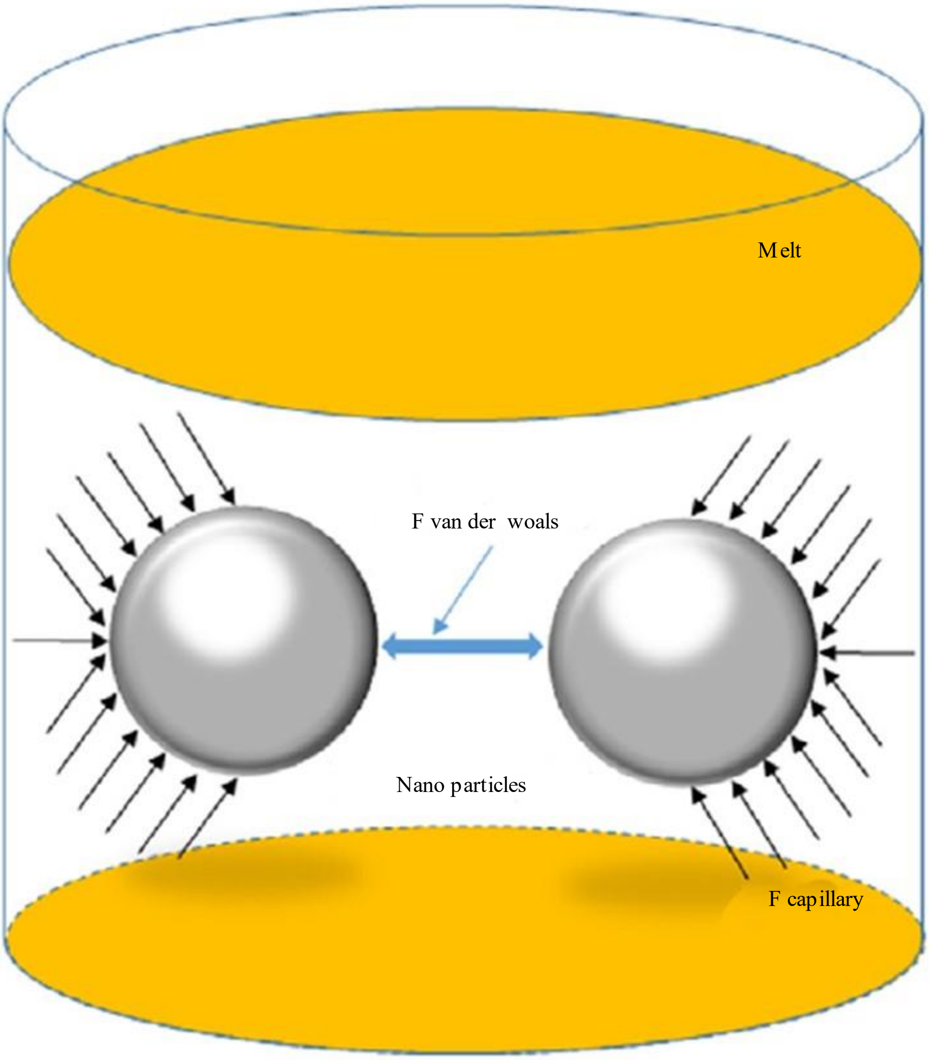


Figure 1. Two nanoparticle dispersion model [37–38].

Table 1. Mechanical properties of magnesium matrix composite reinforced by nanoparticles processed by different preparation or deformation methods [39–50].

Alloy (wt%)	**UTS (MPa)**	**TYS (MPa)**	**EL (%)**	**Ref.**
1 vol% nano-SiCp/AZ91 (as-cast)	392	377	2.0	[39]
14 vol% SiCp/Mg-2 Zn	345	304	20	[40]
0.5 wt%TiC p /Mg-4Zn-0.5Ca	309	230	7.5	[41]
1 wt% (SiC + TiC) p /AZ91	293	227	28.1	[42]
50 nm TiCp/ ZK60A(as-extruded)	231	169	23.0	[43]
40 nm SiCp/ Mg–8Al–1Sn(as-extruded)	293	164	21.5	[44]
Nano-(Al 2 O 3 + SiC)/Mg–3Al–1Zn(as-extruded)	252	188	33.1	[45]
Nano-Al 2 O 3 /AZ31(as-rolled)	340	221	15.1	[46]
Mg-1.0Sn-0.5Zn-0.5Ca	331	104	30.5	[47]
Mg-1.0Sn-0.5Zn-2.0Ca	300	180	17.9	[33]
Mg-8Sn-2Zn-0.5Cu	388	365	5.8	[48]
Mg-1.1Al-0.33Ca-0.44Mn	295	272	11.2	[49]
Mg-5Y-1Al	316	150	17	[50]

Other Properties of Magnesium Matrix Composite Reinforced by Nanoparticles

The mechanical properties (Table 1) of magnesium matrix composites are determined from different strength tests, these includes tensile strength, compression test, three-point flexural strength, hardness test, impact strength etc. Literature search shows that there are limited studies regarding to the friction, wear, fatigue, fracture, corrosion, damping etc. of the magnesium matrix nanocomposites reinforced by nano-sized particles while most literatures evaluating mechanical properties (including friction, wear, fatigue, fracture, corrosion, damping etc.) focus on the magnesium matrix composites reinforced by micro-sized particles. J.H. Zhang et al. [51] examined the wear characteristics and strength of an FSP-fabricated magnesium/silicon nanocomposite. The Mg–SiC nanocomposite's abrasive wear property was demonstrated to be confirmed in relation to the FSP process parameters. Zinc oxide nanoparticle-reinforced magnesium matrix composite's dry sliding wear behavior was described by D.D. Zhang et al. [52]. It was discovered that the load and sliding velocity increased the Mg/ZnO nanocompos- ite's wear rate.M. Zhang et.al. [53] studied the high cycle fatigue (HCF) behavior of AZ31B/1.5 vol.% Al_2O_3 nanocomposite at elevated temperatures. The results of HCF tests at 100°C and 200°C showed that enhanced ultimate tensile strength in the composite was the most important factor in modifying the HCF behavior at the higher temperature. Generally, magnesium and its alloys experience galvanic corrosion in a physio- logical environment due to their anodic behaviour when alloyed with other metals [54] (Figure 2)

G.L. Bi et.al. [55] reported that numerous fine precipitates in the ingot before extrusion can effectively refine DRXed structures during extrusion. Wrought Mg alloys containing a mass of single Mn phase can effectively restrict grain growth and result in fine microstructures. The Mg–3Mn alloys exhibit a high TYS of 212 MPa and an elongation of 30%. Thus far, Pan's group have verified that Mg–Sn and Mg–Zn systems with a high Mn content can become ultrafine grained wrought Mg alloys. The average grain size of high Mn content Mg Sn–Mn and Mg Zn–Mn could be refined to ∼2 μm [56]. The tensile and compressive strengths remarkably in- creased with an addition of high Mn content (2 wt%). The UTS, TYS and elongation of Mg–2Zn–2Mn are 315 MPa, 290 MPa, and 24%, respectively. The UTS, TYS and elongation of Mg–1Sn–2Mn are 321 MPa, 233 MPa, and 17.5%, respectively.

Mg–Sn–Zn alloy has been considered as a low-cost al- loy with good strength and plasticity. In the past two years, a number of investigations were conducted to optimize the composition of this series of alloys [57]. The improvement of the microstructure and properties of Mg–Sn–Zn- based Alloy by alloying elements addition has been widely studied. Alloying elements included: Sc, Y, Al, Ca, and Cu, etc. [58]. For instance, weakening and deflecting of the basal texture in an as-rolled Mg–4.5Sn–5Zn–Sc alloy was observed due to Sc addition. The as-rolled Mg–4.5Sn–5Zn–0.3Sc alloy exhibits the optimum mechanical properties. The UTS, YS and elongation of the alloys were 293.0 MPa, 164.2 MPa and 21.5%, respectively [59].

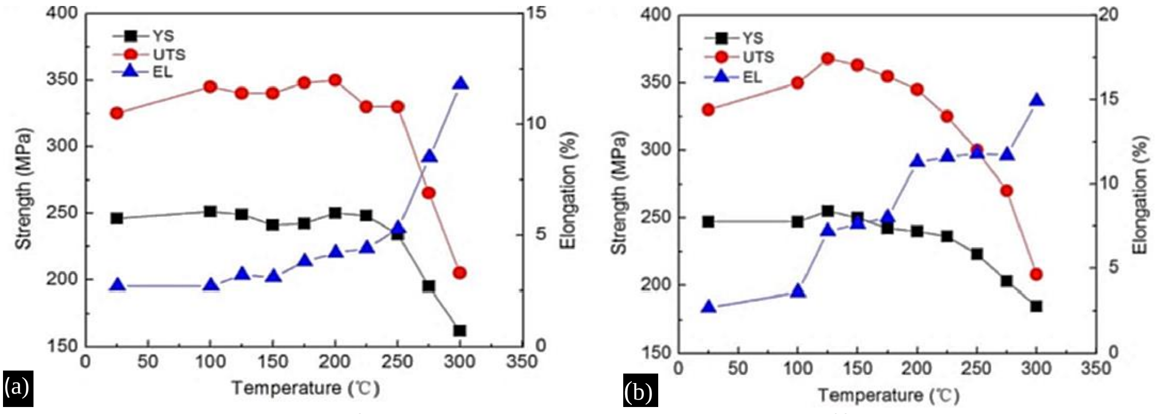


Figure 2. Tensile properties of the T6 treated GW103K alloys under different heat treatment conditions at different tensile test temperatures: (a) 525°C ×12 h + 225°C ×14 h, (b) 525°C ×12 h + 250°C ×12 h [58–59].

CORROSION BEHAVIOR OF MAGNESIUM ALLOYS

Environmental Corrosion of Magnesium Alloys

There are relatively fewer investigations into the influence of environmental factors on the corrosion performance of Mg. Song's group found that in the standard artificial sea water, the corrosion rate of the pure Mg was measured to be only a half of that in a 3.5 wt% NaCl solution, while the serious localized corrosion of Mg in the NaCl solution was even inhibited [60] as shown in (Figure.3). The main constituents $MgCl_2$ and Na_2 SO_4 in the artificial seawater appeared to be inhibitive for the corrosion of Mg. These findings would further clarify the corrosive and inhibitive effects of other anions and cations on Mg dissolution in the artificial seawater. The application of magnesium in the marine environment will benefit from the new understanding. Song's group also investigated the corrosion of magnesium alloys in Haze, which has recently become severe air pollution issue [61]. The most deleterious ion in haze is NH_4 +. The presence of NH_4 + in haze was found to accelerate the corrosion of Mg significantly, overwhelming the acceleration effect of Cl −. When NH_4 + is present in the solution, it can penetrate into the surface film and combine with the MgO in the inner layer, accelerating the dissolution of the MgO. After perforation of the thin protective MgO film by the NH_4 +, the Mg substrate will actively react with the solution, resulting in a high corrosion rate [62–67]. (Figure 3).

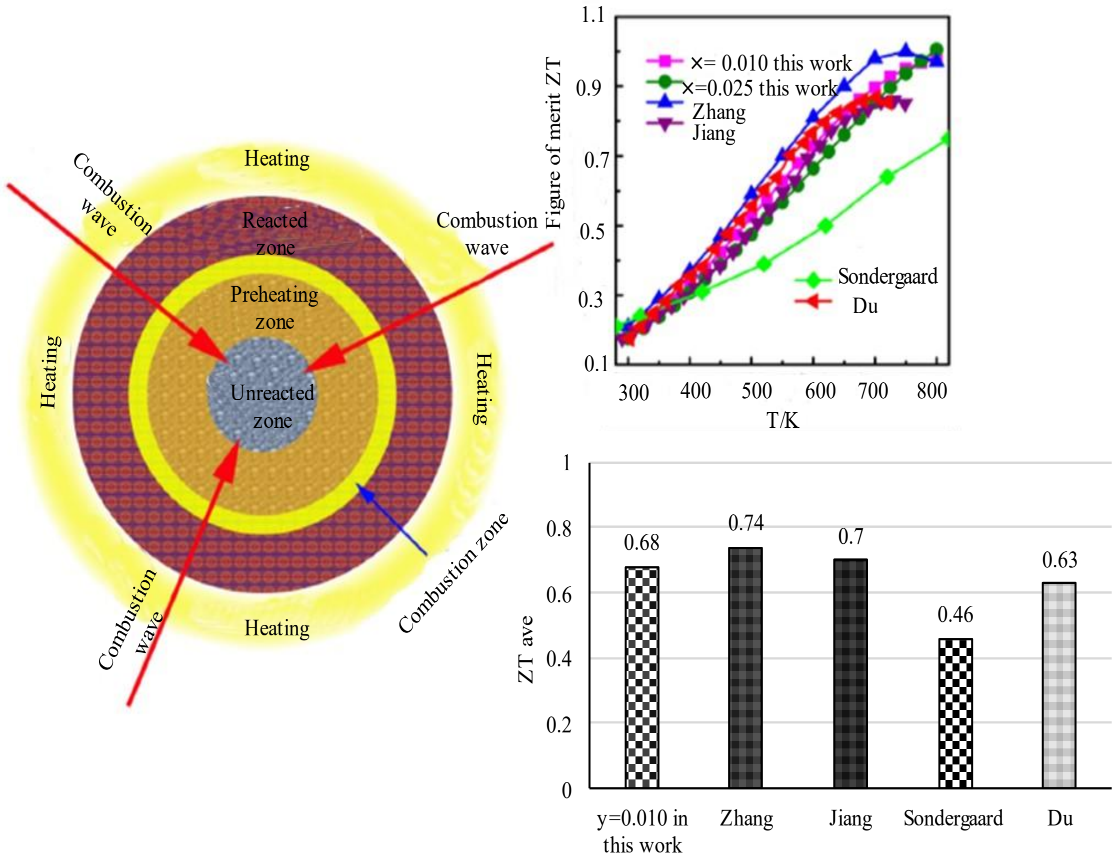
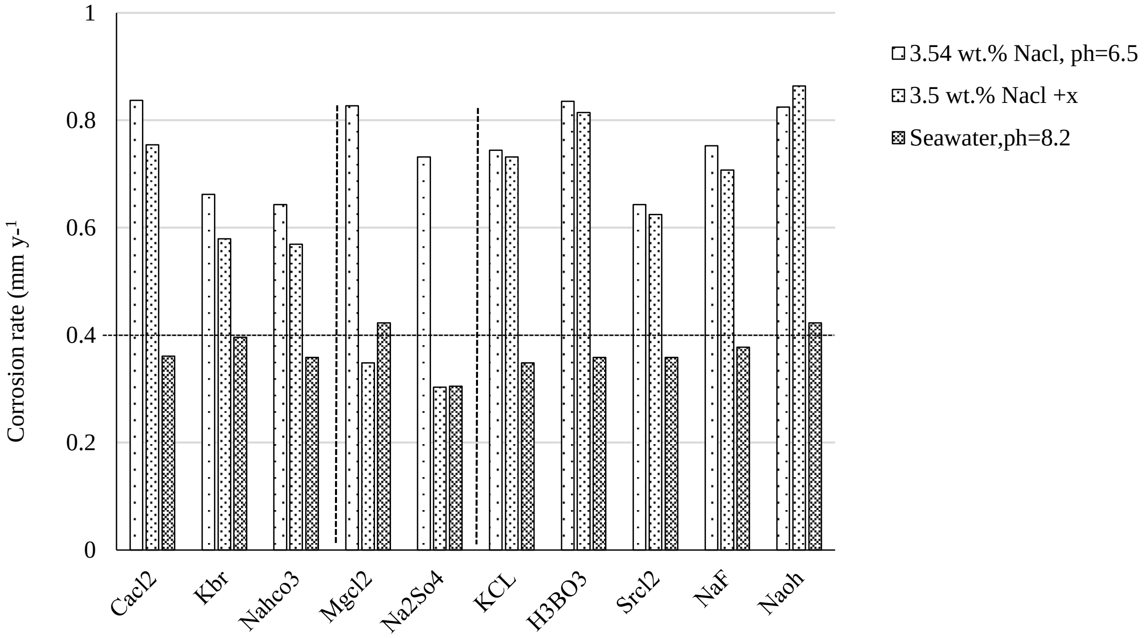


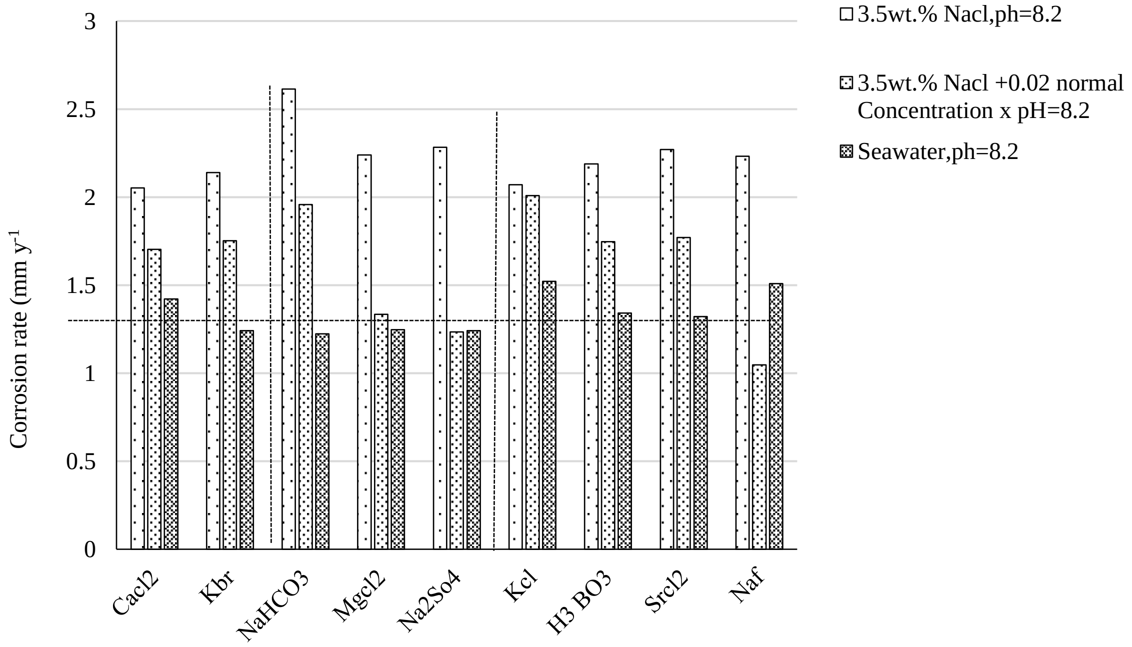
Figure 3. Mg 2 (Si 0.5 Sn 0.5) 1-x Sb x compounds prepared by thermal explosion (TE) combined with plasma activated sintering (PAS) exhibit superior peak ZT peak and average ZT ave [60–61].

C. Wang et al. [68] achieved a high corrosion inhibition efficiency for commercial purity Mg with the addition of sodium 2,5-pyridinedicarbolxylate, 3-methylsalicylate and fumarate into 0.5 wt% neutral NaCl solution. Its corrosion efficiency increases with increasing concentration of inhibitors. They concluded that strong iron complexing agents are effective corrosion inhibitors to impede the micro-galvanic corrosion of Mg with a high amount of Fe impurities [69]. (Figure 4).



(a)

Figure 4. (a): Comparison of corrosion rate for each pure Mg specimen in different solutions evaluated from average hydrogen volume: (a) addition of various concentrations of X [62–65].



(b)

Figure 4. (b): Comparison of corrosion rate for each pure Mg specimen in different solutions evaluated from average hydrogen volume: (b) addition of 0.02 normal concentration X [66–67].

DISCUSSION

The amount of magnesium utilized in the automobile sector is anticipated to expand by at least 300% during the next eight to ten years. Increasing the amount of Mg alloy per car will contribute to obtaining global goals for reducing greenhouse gases. Recent developments in processing Mg alloys have increased the potential usage of Mg alloys in the automotive industry. Currently available magnesium alloy vehicle parts are typically produced using the above-mentioned casting procedures. Long-term mechanical assembly and welding can be used to combine magnesium alloys; however, further research on the forming processes of magnesium alloys is required to increase the use of magnesium in the automobile sector. When magnesium alloys are used in place of other materials, automobile components can have their weight reduced by 22% to 70%. Magnesium alloy components provide superior energy-absorbing properties, ductility, and strength-to-density ratios. Magnesium alloys' drawbacks include their high molten reactivity, immunity to galvanic corrosion, fire hazard, poor fatigue, poor creep. It is crucial that the magnesium alloy parts are designed with proper drainage in mind to avoid the buildup of corrosive materials like moisture or water. Mg alloys' resistance to corrosion is decreased by Fe, Ni, and Cu.

CONCLUSION

With the continuous advancement of nanotechnology and the urgent need for light weighting, the research and appli- cation fields of magnesium matrix composites reinforced by nanoparticles will be also expanded. The nanoparticles are mostly added into the magnesium using external addition method. It is an important de- sign idea for preparing magnesium matrix nanocomposites with higher performance and more new functions through in situ method. Based on the theory of liquid- solid phase transition and in-situ synthesis technology, it is expected to synthesize magnesium matrix nanocomposites containing dispersed fine nanoparticles with controllable concentration. There are still challenges in terms of compactness, interface bonding, and abrasion resistance in the magnesium matrix nano composite configuration using advanced characterization methods. The design and optimization of the existing magnesium matrix nanocomposite configuration as well as the effect of local reinforcement content and the structural parameters on the strengthening and toughening mechanism are important research directions for magnesium matrix composites.

Declaration of Competing 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.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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