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Magnesium alloys in the automotive industry: Alloying elements and their impact on material performance

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Abstract

This study aims to systematically review and evaluate the application of magnesium (Mg) within the automotive sector, with a focus on enhancing fuel efficiency and supporting environmental sustainability. The review emphasizes the latest advancements in cast magnesium alloys, wrought magnesium alloys, and functional magnesium materials, including the development of novel Mg-based materials. The environmental impact of utilizing magnesium in automotive components is also critically analyzed. Recent innovations, particularly in the fields of nanocomposites and alloying, have significantly enhanced the mechanical properties of magnesium alloys, such as increased strength and improved grain refinement, making them suitable for high-temperature applications. The findings suggest that the competitive pricing and enhanced properties of magnesium and its alloys are key drivers for their widespread adoption in automotive manufacturing. The paper provides a detailed discussion on the current trends in magnesium alloy applications, with particular focus on the role of alloying elements and strategies to address associated challenges. This comprehensive review outlines the recent technological advancements in magnesium materials and their relevance to modern engineering applications in the automotive industry.

Keywords: Magnesium alloy; Strength mechanism; Mg-Composite; Automotive applications

1. Introduction

The most important issue in our domain has always been how to make the best use of the limited resources that are at our disposal. Because of rising carbon dioxide (greenhouse gas emission) levels and global temperature, manufacturers around the world are becoming increasingly conscious of the need to take preventative measures to lower their carbon footprints [1]. The 'carbon neutrality' and 'emission peak' initiatives that China suggested in September 2020 have garnered interest from policymakers throughout the world. Magnesium (Mg) and magnesium alloys can be used extensively as a means to this end. When it comes to conserving weight and cutting down on greenhouse gas emissions, magnesium alloys are your best bet. In addition, Mg alloys have a high theoretical specific capacity for batteries, high specific strength and stiffness, superior damping performance, strong biocompatibility, a big hydrogen storage capacity, and so on and so forth [2]. As a result, magnesium and its alloys have found use in several industries throughout the globe, including those related to transportation, aircraft, and the three C's (computers, communications, and consumer electronics). In addition, there has been a rise in interest in using magnesium and magnesium alloys in the healthcare and energy industries. There are still many obstacles to be solved before magnesium alloys may be used in more applications. However, the fast degradation rate of Mg alloys and the narrow hydrogen charging and discharging window need to be solved in functional materials in order to expand the future application of Mg alloys beyond their current structural applications [3]. Cast magnesium alloys and deformed magnesium alloys are the most common types of magnesium alloys now in use, with casting manufacturing accounting for the vast majority [4]. Magnesium's strong chemical activity makes it susceptible to reactions with environmental chemicals that result in inclusion formation.

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Primary magnesium readily interacts with O_2 and N_2 to create nonmetallic inclusions like MgO and Mg_3N_2 during manufacturing and smelting processes [5]. Casting properties are diminished, and the magnesium alloy's mechanical characteristics are severely impacted, since nonmetallic inclusions appear mostly in the grain boundaries of the matrix structure. Therefore, the purpose of the current review is to analyze all of the facets related to magnesium and its alloys in order to have a deeper familiarity with this special metal. In this paper, we take a quick look at the alloying elements that are compatible with magnesium and then go deep into how each of those alloying elements affects the material's qualities. Magnesium alloys and composites are explained, including the many forms that can develop. Finally, the importance of magnesium and its alloys in structural applications is highlighted.

2. Phase Diagram

Material properties can be separate into structure independent properties and structure-dependent properties. Structure-independent properties are properties that are largely unaffected by microstructure. Denseness, electrical properties, thermal conductivity, specific heat. Such properties are resolved by chemical composition and atomic properties. On the other hand, all structure-sensitive properties are mechanical properties [6].

Metallurgists describe materials not only by their chemical composition but also by the phases present. For binary and ternary systems, this can be done relatively easily in the form of phase diagrams. Although state diagrams represent equilibrium states, they cannot provide information about the phases of the physical shape or distribution of phases that can occur in non-equilibrium processes.

They are particularly useful for microstructural interpretation and planning of heat treatments such as aging and thermo mechanical treatments. The most significant phase diagrams for the magnesium binary alloy system are displayed and explained on the following pages. Supplementary alloying elements are added to commercial alloys for a variety of reasons [7]. To change the Mg solid solubility of the primary alloying elements, to change the phase precipitation mode, or to create different intermetallic phases. Knowledge of the phase diagram and thermodynamic characteristics of these alloys is necessary in order to define the processing conditions for creating different Mg-based alloys and subsequent treatments to acquire the optimal mechanical properties. This is necessary in order to establish the processing conditions for making various Mg-based alloys. In addition, with the use of computational thermodynamic modeling, one may gain a better understanding of phase relations as well as phase stability under a set of provided conditions. The accurate description of the binary systems makes it possible to approach the phase equilibrium features of alloy formation and to keep track of specific alloys during heat treatment or solidification by calculating the phase distributions and compositions [8]. This is made possible thanks to the fact that the binary systems are described in such detail. Attempts have been made to calculate phase diagrams and obtain information relevant to alloy development to facilitate understanding and fill knowledge gaps. These are described below.

2.1. Magnesium Aluminum

Aluminum is one of the utmost essential alloying elements in magnesium. Some systems enclose up to 10 wt% Al. AZ, AE, AM, and AS. Fig 1 (a), shows the Mg-Al system. Al is one of the lean metals that are readily soluble in magnesium. Beyond the solubility limit, the brittle intermetallic $Mg_{17}Al_{12}$ separates. The solubility limit of aluminum at the eutectic temperature is 11.5 at% (12 mass %), dropping to about 1% at room temperature [9]. As a result, $Mg_{17}Al_{12}$ plays a leading role in determining properties Fig 1 (b). Commercial alloys based on Mg-Al contain other alloying additions of zinc, AZ91, AZ81, AZ63.

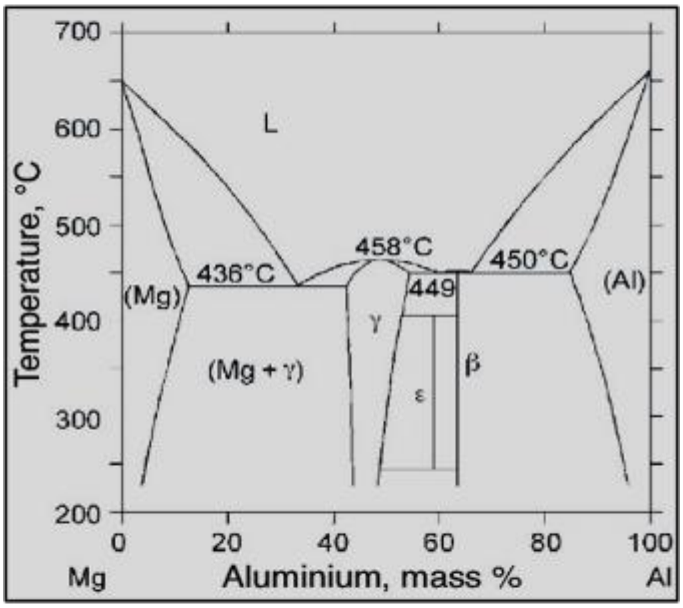

Figure 1 (a) Phase diagram of Mg-Al binary alloy [9]

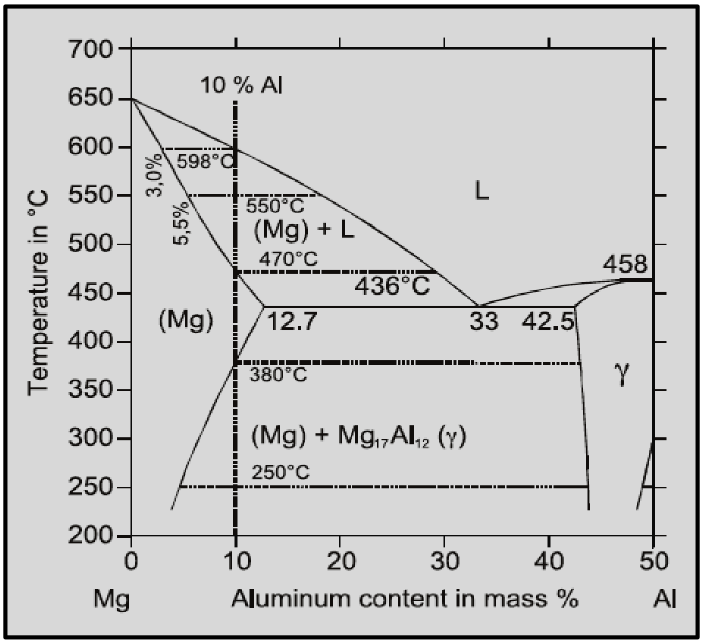

Figure 1 (b) Magnesium-rich section of Mg-Al system [9]

2.2. Magnesium Zinc

Zinc is an essential alloying element, although it hardly acts as a major alloying element (ZK, ZH, ZM, ZC, and ZE alloy series). The two-phase diagram Fig 2, shows 51.3 wt% eutectic. The mass solubility at the eutectic temperature is 6.2% [10].

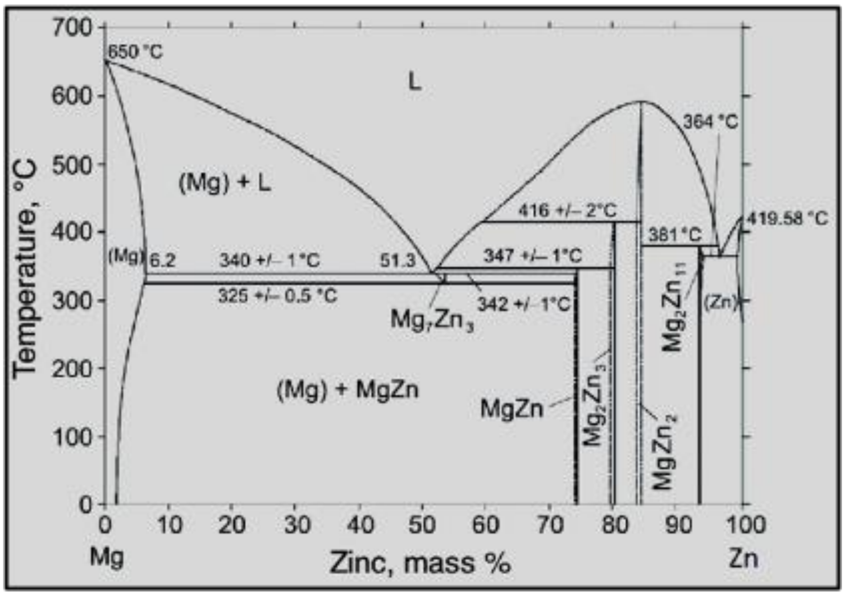

Figure 2 Phase diagram of Mg-Zn system [10]

2.3. Magnesium-Manganese

Manganese is an essential additive to various magnesium alloys. More recently, it has become important in the advancement of high-performance creep alloys. The Mg Mn phase diagram is incredible in several respects. By a peritectic reaction in which magnesium Fig 3, precipitates from L + a Mn at 653 °C. The solubility of Mn in solid magnesium is higher than in liquid (2.2 wt% vs 2.0 wt%). As the temperature decreases, the solubility reduction and manganese precipitation increases [11].

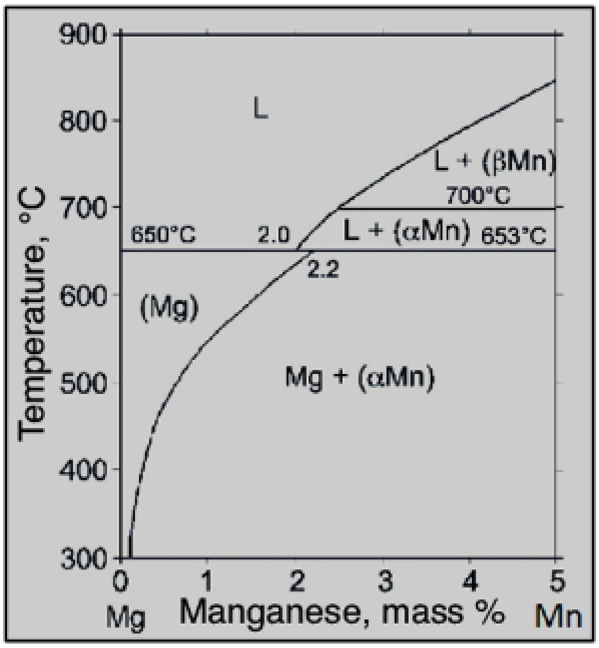

Figure 3 Magnesium-manganese phase diagram up to 5 mass % Mn [11]

2.4. Magnesium-Scandium

Scandium has recently been viewed as an alloying additive that can be used to superior creep properties. The Mg-Sc system Fig 4, shows a peritectic and a steep rise in melting point. The diagrams exposed were resolved by a combination of experiments and thermodynamic study. The previously approved diagram turned out to be flawed. The decrease in solubility suggests possible ageing, but MgSc formation very slowly and inconsistently. A vigorous ramification is detected only apart the extension of Mn [12].

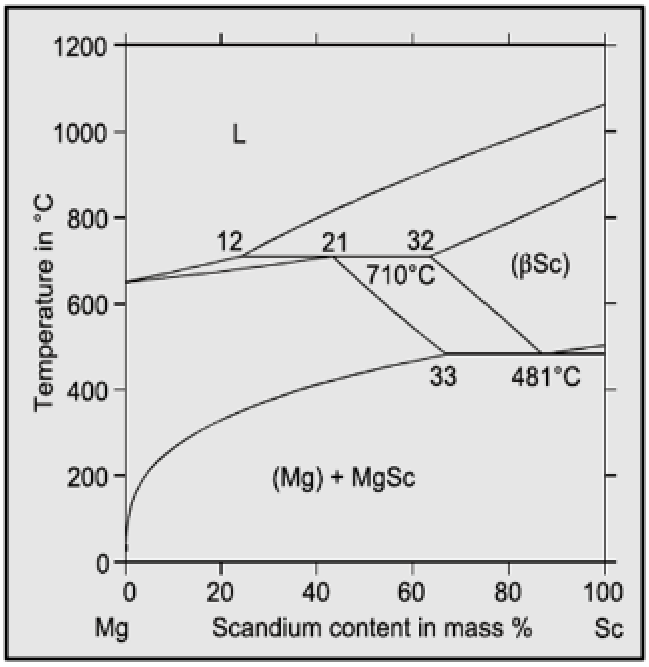

Figure 4 Mg-Sc phase diagram up to 50 mass % Sc [12]

3. Effect of adding alloying elements to magnesium

The magnesium in its as-cast form has low strength and a high rate of deterioration. As a result, the quality of the material can be improved by employing a suitable approach for alloying and processing. The reaction of chemically active magnesium with alloying chemicals results in the formation of intermetallic compounds. These intermetallic phases, which may be seen in magnesium alloys, have an effect on the microstructure, and as a result, they have an effect on the material characteristics. The alloying elements have a direct effect on the strengthening of the mechanical characteristics of the material through the processes of precipitation hardening, grain-refinement strengthening, and solid-solution strengthening. In order to make magnesium's matrix more robust, other elements with a high temperature-dependent solubility will need to be alloyed with it. Table 1, provides a concise overview of the most frequent alloying elements as well as the effects these elements have on magnesium alloy [13-18]. The effect of each of these alloying elements may be linked to the total number of alloying elements as well as the proportion of the element that makes up the alloy. One must take note of a certain significant facet in connection with the components that go into the alloying process.

Table 1 Some alloying elements and their effect on Mg [13-18]

Alloying element	**Influence on material properties of mg alloys**
Aluminum (al)	Increases hardness, strength and castability
Zinc (Zn)	Yield stress is enhanced and corrosion resistance is improved
Calcium (Ca)	Improves corrosion resistance, creep resistance and grain refinement
Manganese (Mn)	Improves salt water corrosion resistance
Scandium (Sc)	It is known that the addition of Sc to Al-based alloys is an effective way to increase their mechanical properties and an important role in the refinement of grains in pure aluminum

3.1. Aluminum

It has the greatest possible beneficial effect on magnesium. The addition of aluminum increases the strength of an alloy by 180 MPa. As a result, it is the Mg (magnesium) alloy component of choice. An alloy can be heat treated if it contains more than 6 wt. % aluminum. Al may be dissolved in Mg around 12 wt. %, although this value changes with temperature.

Alloys with a high concentration of Al have a lower solubility of aluminum at room temperature. The cathodic reaction accelerates corrosion when more than 3 wt. % of Al is present. When Al is added to Mg, the kinetics at the anode slow down below the solubility threshold. In alloys with a high concentration of -phases, Al increases susceptibility to stress corrosion cracking [14].

3.2. Zinc

Zinc is the most popular and efficient addition to magnesium alloys. Together with aluminum, it's utilized to increase durability. Zinc counteracts the corrosion-promoting effects of nickel and iron impurities in magnesium alloys by increasing their corrosion resistance. Zinc content in Mg must be less than 2.5wt. %. However, going from 1 to 3 wt. % Zinc is said to boost corrosion rates [15].

3.3. Calcium

The solubility of calcium in magnesium under equilibrium circumstances is 1.34 wt%. In particular, it enhances the thermal and mechanical stability of magnesium alloy. At high temperatures, the oxidation process in cast magnesium alloys is slowed by the addition of calcium. A little amount of calcium can improve the rollability of magnesium sheets, but anything more than 0.3 causes the sheet to split when welded. Adding calcium to magnesium is not biocompatible beyond 1 weight percent when used in medical purposes. In Mg alloys, the rate of corrosion is quite rapid after it approaches the solubility limit (about 1.34 wt%) [16].

3.4. Manganese

Due to its limited solubility (2.2 wt.%) in magnesium, manganese (Mn) addition to magnesium is minimized. However, the corrosion rate did not noticeably alter when Mn was added as a binary element to Mg alloys (up to 5 wt. Therefore, manganese is an alloy used with aluminum and others. Recent research has focused on how Mn may enclose Fe in Mg alloys without adding aluminum. Even without Al present, Mn can still play a significant role in the sequestration of Fe, thus this is encouraging. The annexation of manganese improves the saltwater corrosion protection of Mg-Al and Mg-Al-Zn alloys. Manganese is commonly mixed with supplementary alloying elements such as aluminum [17].

3.5. Scandium (Sc)

Magnesium alloy's mechanical qualities were enhanced by the addition of trace amounts of Sc, which allowed the alloy's magnesium grains to refine and precipitates containing Sc to develop. So, Sc is selected to improve the AZ61 alloy's mechanical characteristics even further. Sc has higher solid solubility in magnesium (15.9%) and lower density (3 gcm^3) than other rare earth elements like Ce, Nd, Y, and Gd in magnesium alloy, so adding Sc in AZ61 alloy can not only improve the mechanical properties, but also maintain the low density of magnesium alloy [18].

4. Classification of Magnesium alloys

Saving energy and lowering carbon dioxide emissions by using lighter construction materials has been a top priority for many nations. The 'Energy-saving and new energy vehicle technology plan' published by China, for instance, calls for a 10% weight reduction in cars by 2020, a 20% reduction by 2025, and a 35% reduction by 2035 compared to that in 2015 [19]. Due to their low density among metallic structural materials, Mg alloys provide a possible answer when applied as a structural material. This means that research on structural Mg alloys is still very much in the spotlight [20].

Technology finds many uses for the nonferrous alloys of titanium, aluminum, and magnesium. Their exceptional characteristics make them excellent replacements for steel in a variety of structural contexts. Magnesium and its alloys are the lightest of the structural metals mentioned here (Ti, Al, and Mg) [21]. The development of new technologies has led to a growth in the application of Mg alloys (magnesium alloys) in the construction and medical fields. The compatibility of Mg and its alloys with other technical materials is to be investigated in the context of alloy production [22].

Cast magnesium alloys (Mg alloys) and wrought magnesium alloys (Mg alloys) are two types of Mg alloys that are processed differently and are used for different purposes in engineering and R&D, respectively. Cast alloys can include magnesium alloys made with a die or another casting method. Recently, cast alloys have found widespread use in the manufacturing and commercial sectors. However, cast magnesium alloys have been used mostly in fields that need only modest mechanical properties [23]. Magnesium alloys are worked when they are processed further through operations such as extrusion, forging, pressing, rolling, SPD (severe plastic deformation), and ECAP (equal channel angular pressing). Grain refining is not the only method for reducing grain size in the microstructure; plastic deformation and severe plastic deformation (SPD) are also useful [24]. Wrought Mg alloys have better mechanical characteristics than cast Mg alloys. The key reasons for this are the material's uniform microstructural composition and its well-defined grain refinement without pores. Some magnesium Mg- Al, Mg-Zn, Mg-Zn-Ca, Mg-Zn-Mn, Mg-Zn-RE alloys are discussed are as follows-

4.1. Mg-Al Based alloys

At 437 °C (eutectic temperature), there is a high solubility of aluminum in magnesium (12.7 wt.%). Solid-solution strengthening occurs when Al dissolves Mg matrix, forming the α-Mg and $\gamma - Mg_{17}Al_{12}$ phases. Mg-Al-based alloys have great castability but poor mechanical characteristics. It has a high corrosion resistance that increases with aluminum content. Common 1 wt. % additives to Mg-Al-based extrusion alloys include zinc and manganese (Mn) [25]. Biodegradable materials research has focused mostly on the AZ31, AZ61, AZ81, AZ91 59, and AM60 family Mg-Al-based based alloys. The aluminum and zinc in AZ61 are denoted by the letters A and Z, respectively. Each alloying element's percentage composition is indicated in numerical sequence below each occurrence (6% Al and 1% zinc). Alloys of Mg, including AM30, AM40, AM50, and AM60, contain Al, Mn, however Al makes up a larger percentage of these metals. Since AM alloys lack Zn-containing eutectic ternary phases, they are more easily extrudable and have superior mechanical characteristics [26]. Zinc is added to Mg alloys to reinforce the solute, while Mn increases anti-corrosion characteristics by eliminating trace amounts of Fe. By forming a stable Al_2Ca phase with a melting temperature as high as 1352 K [27], calcium (Ca) enhances the strength and creep of Mg-Al alloys. The addition of 1.7 wt.% Ca to an extruded Mg-2.32Al alloy significantly reduced grain size. This resulted in an increase of 186 MPa for the UTS, 143 MPa for the YS, and 8.9% for the elongation. The optical pictures in Fig. 5, provide strong evidence for this, demonstrating the existence of a sharply fractured Al_2Ca phase [28]. This is how improved mechanical qualities may be achieved.

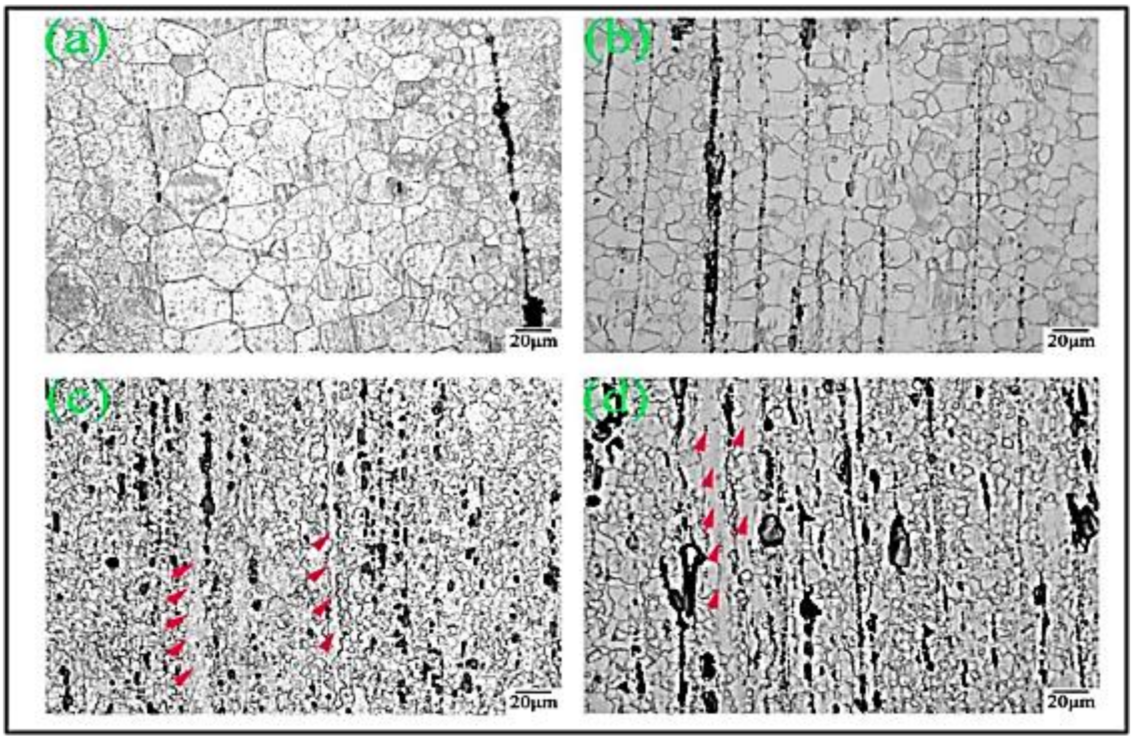

Figure 5 Optical images of the as-extruded alloys: (a) Mg-0.61Al-0.46Ca; (b) Mg-1.34Al-1.03Ca; (c) Mg- 2.32Al-1.70Ca; (d) Mg-3.74Al-2.52Ca [28]

After going through thermomechanical procedures, the AZ31 alloy that contained calcium performed better than the AZ31 alloy that did not contain calcium. The calcium-containing AZ31 alloy had higher ductility and finer grains than the calcium-free AZ31 alloy. In addition, Kwak et al.'s examinations of hot compressive behavior on extruded 0.5 wt.% Ca-AZ31 alloy revealed that Ca refined the grains and generated a more homogenous structure [29]. These findings were based on the fact that Ca produced a more homogeneous structure. This is because, at higher temperatures, the dispersion of the Al_2Ca phase in the matrix promotes dynamic recrystallization and hinders the coarsening of the grains [30] different heat treatments were tested to see how they affected the microstructure and mechanical characteristics of Mg-6Zn-1Al-0.3Mn. Microstructure of Mg-6Zn-1Al-0.3Mn magnesium alloy after various solution treatments is shown in Fig 6. When comparing the microstructure before and after solution treatment, it is clear that the dendritic patterns vanished. There are still several undissolved MgZn phases in the matrix and a few particles are scattered in the grain interior or grain borders after a single-stage solid solution treatment procedure at 335 C for 9 hours (Fig. 6 a and 6 b). More MgZn phase dissolves into the matrix after the two-stage solution procedure of 335 C 9 4 h + 385 C 9 4 h, with just a few undissolved particles interspersed (Fig. 6 c, d). The MgZn phase in the matrix is virtually totally dissolved after a solution treatment process of 335 C 9 4 h + 385 C 9 8 h, although grain develops significantly (Fig. 6 e, f).

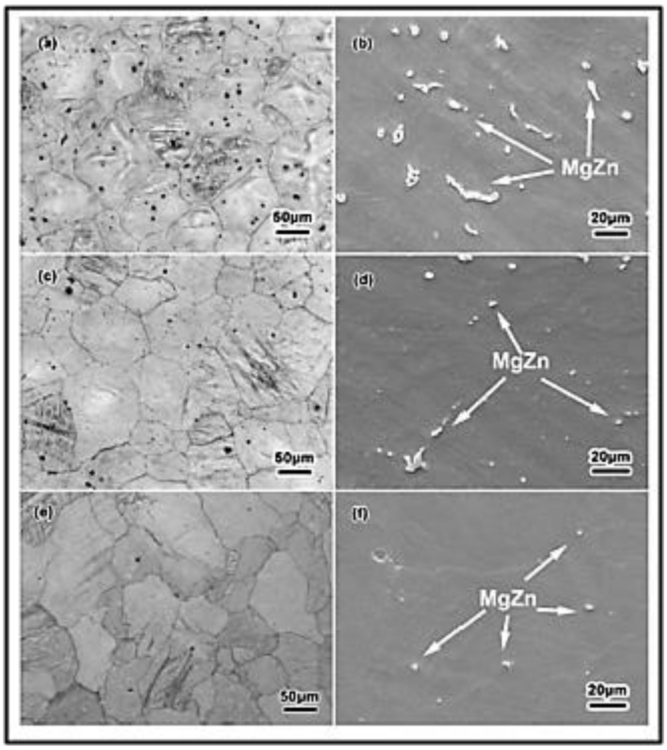

Figure 6 Optical images (a, c and e) and SEM images (b, d and f) of different solution treatments: (a)(b) 335°C x 8 h; (c)(d) 335°C x 4 h + 385°C x 4 h; (e)(f) 335°C x 4 h + 385°C x 8 h. [30]

4.2. Mg-Zn Based alloys

In addition to aluminum, zinc (Zn) is often used since it is an effective alloying element. Zinc, in contrast to aluminum, is biocompatible since it is a naturally occurring element. Therefore, it is also put to use in biomedicine. In Mg-Zn alloys, it makes up the bulk of the other alloying elements. Mg-Zn alloys consist mostly of α-Mg matrix and γ-MgZn phases, both of which have atomic number. Zinc is most soluble in magnesium at the eutectic temperature of 340°C (6.2 wt.%), however its solubility drops dramatically to around 2.6 weight percent at 150°C. Yield strength (YS) of Mg-Zn alloy improves with increasing zinc content, while maximum ultimate tensile strength (UTS) (216.8 MPa) and elongation (15.8%) are achieved only at 4 wt. % of zinc. Alloying elements such as calcium, zirconium, yttrium, strontium, silicon, and manganese can improve the mechanical characteristics of Mg- Zn based alloys [31-32].

4.3. *Mg-Zn-Ca alloys*

The researchers have demonstrated an interest in Mg-Zn-Ca alloys due to the cost effectiveness of these materials as well as the exceptional mechanical qualities they possess. Additionally, calcium functions well as a grain refiner in magnesium-based alloys. The drawback of calcium is that the solubility of calcium in magnesium alloys is limited 1.34 wt. %, which causes the mechanical qualities of magnesium alloys to degrade when the calcium concentration is increased above 1% [33]. At room temperature, the hot extruded condition of the alloy composed of magnesium, zinc, and calcium showed outstanding mechanical characteristics. This is because processed grains and a weaker basal texture contributed to the problem. The material had an elongation of 44%, a YTS of 105 MPa, and a UTS of 205 MPa [34]. It is interesting to note that when the temperature at which the alloy was extruded was raised, the ductility of the metal rise but its strength declined.

4.4. Mg-Ca-RE Alloys

Magnesium granules are smoothed out by calcium. It also improves magnesium alloys' tensile characteristics and corrosion resistance. Therefore, the mechanical qualities of magnesium alloys can be improved by adding rare earth elements [35]. The addition of yttrium to magnesium alloys resulted in a unique Mg- 1Ca-1Y alloy with increased elongation (up to 15.9%) and decreased corrosion resistance. The addition of yttrium to Mg-Ca-Y-Zr alloy greatly improved its strength. The material's tensile properties improved, with the yield strength rising to 120 MPa, the ultimate tensile strength reaching 191 MPa, and the elongation reaching 8.3% [36].

4.5. Mg Zn-Mn alloys

Mg-Zn-Mn alloys are strong and ductile, and they also have a good corrosion resistance. In its extruded form, the Mg-5.99Zn-1.76Ca-0.35Mn alloy has remarkable mechanical characteristics, including a yield strength of 289 MPa and an elongation of 16% [37]. The tensile yield strength of Mg-Zn-Ca alloy was improved by 50 MPa 108 after 0.3% Mn was added to the mix. Extruded wrought Mg-2 Zn alloy has its ductility and yield strength improved by the addition of around 2 wt.% manganese. In the course of heat deformation, the fine Mn precipitates polished the grains and enhanced the slip resistance of the base plane. The addition of manganese to magnesium greatly improved both its ductility and strength. Its tensile strength and elongation were similarly improved to 204.3 MPa and 38.8%, respectively [38]. When Mn was added to an extruded Mg-6 Zn alloy, it increased the material's strength and age-hardening response. Mg-Zn-Mn and Mg-Zn-Mn-Si alloys exhibit yield tensile strengths (YTS) in the 200-240 MPa range [39]. The one-step aging method increased their strength by 80 MPa. Using a two-stage aging process, the YTS of these alloys was further enhanced. The first stage of the therapy was performed at temperatures between 70°C and 90°C, while the second stage was conducted at temperatures between 160°C and 180°C .This increased the YTS to a pressure of 338-350 MPa. Although peak-aged Mg-Zn-Mn-based alloys have exceptional strength, their widespread implementation has been hampered by their poor ductility [40].

4.6. Mg–Al–Zn alloys with minor Sc:

A small amount of Sc can refine the as-cast Mg-Al-Zn alloy particles and change the state and distribution of the $Mg_{17}Al_{12}$ phase. The microstructure of as-cast Mg-9Al-1Zn-0.3Sc alloy is mainly composed of an α-Mg matrix, $Mg_{17}Al_{12}$ phase, and $Mg_5 Al_4$ Sc intermetallics [41]. Adding 0.3% Sc increases the strength at high temperatures, but slightly reduces the elongation of the as-extruded Mg-9Al-1Zn alloy. Addition of 0.3% Sc increases the room temperature tensile strength from 303 MPa to 341 MPa. Over the test range from room temperature to 200 °C, the elongation increased from 12.7% to 38.2% for alloy but increased from 11.5% to 31.0% for alloy [42]. The effect of Sc addition on the microstructure and mechanical properties of as-cast Al-Mg alloy was studied. The results showed that when the Sc content exceeded 0.4 wt%, a pronounced grain refinement effect was observed, transforming the typical dendritic microstructure into fine equiaxed grains. It is found that Sc significantly increases both the hardness and strength of the tested Al-Mg alloys, but significantly reduces the ductility. When the Sc content reached 0.2 wt%, 0.4 wt%, and 0.6 wt%, the tensile strength of the Al-Mg alloy increased by 4%, 30%, and 40%, respectively. Yield strength increased by 18%, 78%, and 111%, respectively. However, elongation decreased by 12%, 33%, and 44%, respectively. The addition of Sc slightly increases hardness. The properties of the Al-Mg-Sc alloy appear to reflect a superposition of the properties of the Al-Sc and Al-Mg alloys. The formation of Al_3Sc precipitates does not seem to be affected by the presence of Mg [43]. Magnesium increases the strength and work-hardening exponent of Al-Sc-based alloys in direct proportion to the amount of Mg present in the solution.

4.7. Mg-Graphene

Magnesium (Mg) is the earth's lightest structural metal and it has enormous reserves. Because of these characteristics, it is a promising engineering material that has the potential to increase energy efficiency and system performance in the automotive and electronic industries. On the other hand, the low strength and ductility of magnesium and magnesium alloys are the primary reasons for their restricted application. A wide range of magnesium matrix composites have been generated by selecting different types of reinforcement and processing techniques [44]. This has been done in an effort to improve the mechanical characteristics of the composites. The results of these studies have shown a novel approach to addressing the inherent drawbacks of magnesium and alloys of magnesium. However, traditional composites often make a trade-off between strength and ductility, which significantly hinders the prospective capacity of magnesium matrix composites to serve a larger variety of technical applications [45]. According to studies [46], Mg and its alloys that have been strengthened using nanosized reinforcements have improved their mechanical characteristics without suffering a major loss in their ductility.

Graphene, a two-dimensional material composed of six-membered rings of hybridized carbon atoms, has unique mechanical, thermal, and electrical properties. It has a modulus of 1 TPa and a breaking strength of 125 GPa. One way to exploit its surprising properties for mechanical applications is to transform graphene into various material matrices. Graphene has a wide range of applications in electronics and polymer reinforcement. Graphemes have also been used in other fields such as metal-graphene composites. Also, graphene is very lightweight. The density of graphene is estimated to be ($1.06g/cm^3$) these extraordinary properties make it the perfect reinforcement for metal matrix composites.

Recently, studies of graphene-based magnesium composites have been reported [47], but they have received less attention compared to graphene-based aluminum composites. A potential problem is the main difficulty of uniformly distributing graphene in the metal matrix and the possibility of interfacial chemical reactions between graphene and the metal matrix. Most research has focused on magnesium matrix composites with uniformly dispersed reinforcements that provide increased stiffness and strength. Che et al. [48] prepared graphene nanoplate-reinforced Mg composites by a combination of liquid sonication and solid stirring and obtained dramatically improved properties. Rashad et al. [49] fabricated magnesium-reinforced metal matrix composites using graphene nanoplates (GNPs) by powder metallurgy processing. The modulus, yield strength, and elongation at break of extruded magnesium composite nanocomposites reinforced with only 0.3 wt% GNS increased by 131%, 49.5%, and 74.2%, respectively, over unreinforced pure magnesium matrix. [50]. Graphene can be used as multilayer graphene known as graphene nanosheets (GNPs). GNPs have several advantages over CNTs due to their two-dimensional morphology. Since the mechanical strength of GNPs is comparable more to that of CNTs.

However, in order to successfully produce magnesium matrix nanocomposites with superior mechanical characteristics, the first challenge that must be overcome is the limited wettability that exists between the ceramic nanoparticles and the molten magnesium matrix [51]. It is exceedingly challenging to scatter nanoparticles in metal melt, particularly magnesium melt. This is due to the fact that magnesium melt is more prone to combustion in comparison to other metal melts, which makes the process of melting alloys more hazardous. This indicates that the process of creating magnesium matrix nanocomposite is an extremely difficult task. For the purpose of making magnesium matrix composites with nano-sized particles, researchers have investigated casting methods that use either liquid- or solid-based procedures [52]. In addition, as a result of the unique size effect of nanoparticles, there is a distinct 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 [53]. This is due to the fact that nanoparticles have a smaller surface area than larger particles, so they are more easily crushed. In addition, the relationship between the aforementioned microstructure and the mechanism of the magnesium matrix nanocomposite that is responsible for its strengthening and toughening has been investigated in a number of published works [54]. In Table 2, we see a compilation of the mechanical characteristics of Mg graphene composite during the previous three years.

Table 2 The mechanical properties Mg graphene composite at room temperature in 2019–2022 [55-63]

Mg-GPN composite (wt%)	Process	UTS (MPa)	TYS (MPa)	EL (%)	Ref.
Mg/0.3 wt% GNPs	Semi-powder metallurgy	198	147	3.11	[55]
Mg/1.25 wt% GNPs	Hot pressed sintering	209	182	10	[56]
Mg/0.1 wt% GNPs	high energy ball mill	197	130	7.5	[67]
Mg-1Al-1Sn-0.18GNPs	powder metallurgy	201	185	13.1	[58]
Mg-1Al-0.6 GNPs	powder metallurgy	216	169	13.0	[59]
Mg-1Al-0.18GNPs	high energy ball mill	210	164	14.5	[60]
AZ31-1.5 wt% GNP	powder metallurgy	232	188	13.1	[61]
AZ31-1.5GNP	Stir-casting method	211	168	9.1	[62]
AZ31-3GNP	Stir-casting method	229	196	7.8	[63]

5. Applications of Mg alloys and composite

Due to its exceptional features as the lightest structural metal, including low density, biocompatibility, and poor resistance to corrosion, magnesium is employed in a wide variety of applications. It's used in aeronautical engineering, the automobile industry, and electrical appliances. Communication, computing, hydrogen storage, and consumer uses are also expanded.

5.1. Aerospace Applications

The only components of aeronautical vehicles that make use of magnesium are the engine, the transmission systems, and the landing gears. Magnesium is cast into these components. Magnesium has a wide range of applications in the helicopter sector, particularly in the manufacturing of gearboxes and other non-structural components. Despite the fact that magnesium has a low density, structural applications made of magnesium are not favored by the manufacturers of Airbus and Boeing. This is owing to the fact that magnesium has a poor resistance to corrosion.

5.2. Automobile Applications

The transition to lighter automobiles is one of the most important steps that can be taken to reduce fuel consumption. Due to magnesium's low density, there is a tremendous amount of potential for its use in the automotive industry. This has emerged as an extremely important topic of discussion among scholars all around the globe. But magnesium has a low electrochemical potential, which is the primary reason why magnesium is susceptible to galvanic corrosion. This makes magnesium a very vulnerable element. This galvanic corrosion has been one of the primary factors that has limited the usage of magnesium in the automotive industry. There are several logistical challenges associated with using magnesium in the structural applications of vehicles. The issue of corrosion does not exist in the earlier designs made of steel or aluminum, hence they are not suited for use with magnesium. If you use the same design for Mg, there is a risk that the items may fail owing to galvanic corrosion. As a result, magnesium has discovered the vast majority of its uses in the interiors of automobiles, which are not susceptible to corrosion. Magnesium is used in the production of a variety of automotive components all over the globe, including instrument panels, dashboards, steering wheels, and components of steering wheel columns. Mg is used in the production of the transfer cases of four-wheel drive vehicles in North America. This falls under the category of power trains. Certain regions in Europe are responsible for the production of engine blocks using the newly developed creep resistant magnesium alloys.

5.3. Potential applications of magnesium matrix composite reinforced by nanoparticles

Nanoparticle-reinforced magnesium matrix composites are now only accessible on a very limited scale. New magnesium matrix nanocomposites are being considered as potential candidates in aerospace, automotive, electronics, and biomedical sectors to replace conventional magnesium alloys and composites due to their light weight, excellent dimensional stability, and mechanical integrity. In the vehicle sector, cutting weight by 10% would result in a 7% reduction in fuel usage. The replacement of conventional car materials with magnesium and its composites would result in a weight savings of 22-70%. There are a number of AZ and AM alloys that have been used as sheets or other vehicle components because to their high strength and ductility at room temperature. The engine blocks made from magnesium matrix nanocomposites can withstand high temperatures and be employed in high-temperature applications.

6. Conclusion

As the significance of magnesium and its alloys grew, more and more scientists and researchers throughout the globe began working on their study and advancement. The extensive review of magnesium and its alloys covers a wide range of topics. Recognizing magnesium's significance as an element is crucial. It's uncommon to come across materials with desirable characteristics like as high strength-to-weight ratio, low density. Magnesium's favorable mechanical qualities make it a desirable material for use in construction, transportation, and medicine. Magnesium's decreased density provides enough opportunity to investigate new technical disciplines, particularly the automotive industry, in light of the current trend toward lighter components. Because of its unique mechanical qualities and wide variety of possible uses, magnesium is really a one-of-a-kind metal.

There is no element which is perfect. Magnesium has its own set of limitations, the most significant of which being its exceedingly poor resistance to corrosion. Magnesium has low corrosion resistance qualities because it oxidizes quickly under wet or air circumstances. Magnesium has to be alloyed with other elements to improve its material characteristics. The pros and cons of different alloying elements have been extensively discussed. Some of the most influential alloying elements and their effects on mechanical properties have been summarized below. It should be kept in mind that very few elements are compatible with magnesium, therefore careful research of different elements is required before alloying them with magnesium.

Magnesium often combines with other elements to make alloys. Alloys have been explored, and their wide categorization has been covered. Depending on how many other elements are combined with magnesium, several alloys may be created. Alloys using magnesium include Mg-Ca, Mg-Al, Mg-Zn, Mg-RE, Mg-Li, etc. Alloys may be cast alloys or extruded alloys depending on whether or not they undergo any additional operations during production, such as extrusion. The literature on the many kinds of magnesium alloys and their properties has been compiled and analyzed at depth. It should be observed that the mechanical characteristics of the extruded Mg alloys, such as yield strength, ultimate tensile strength, or elongation, are superior to those of the cast Mg alloys. This is because after the secondary procedure, the alloys' grains are refined and they have a uniform microstructure.

There are two primary categories of magnesium alloy composites. To maintain the lightweight features of magnesium alloys, it is common practice to include nanoparticles (SiC, GNPs, B_4 C, Al $_2O_3$, etc.) or long and short fibers (glass fiber, carbon fiber, etc.) into the alloy's composition. Composite materials that are suitable for the intended application have been produced by integrally joining two or more materials using welding, diffusion, and bonding different materials using magnesium alloys. Magnesium matrix composites are expected to provide a new method to improve the strength and modulus of magnesium alloys. Functional magnesium materials show great potential and are becoming hotspots for breakthroughs and packages of magnesium and magnesium alloys. Among them, hydrogen storage Mg substances, battery Mg substances, bio-Mg substances, etc. have made speedy development andhave already shown their aggressive benefits over conventional substances. Consequently, functional magnesium materials are expected to end up an crucial growth point within the discipline of recent magnesium materials.

Compliance with ethical standards

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Disclosure of 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.

Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

References

[1] Sihang You, Yuanding Huang, Karl Ulrich Kainer, Norbert Hort, Recent research and developments on wrought magnesium alloys, Journal of Magnesium and Alloys, Volume 5, Issue 3, 2017,Pages 239-253, ISSN 2213-9567, https://doi.org/10.1016/j.jma.2017.09.001.

[2] Jiangfeng Song, Jia She, Daolun Chen, Fusheng Pan, Latest research advances on magnesium and magnesium alloys worldwide, Journal of Magnesium and Alloys, Volume 8, Issue 1, 2020, Pages 1-41, ISSN 2213-9567, https://doi.org/10.1016/j.jma.2020.02.003.

[3] Tiancai Xu, Yan Yang, Xiaodong Peng, Jiangfeng Song, Fusheng Pan, Overview of advancement and development trend on magnesium alloy, Journal of Magnesium and Alloys, Volume 7, Issue 3, 2019, Pages 536-544, ISSN 2213-9567, https://doi.org/10.1016/j.jma.2019.08.001.

[4] S. Jayasathyakawin, M. Ravichandran, N. Baskar, C. Anand Chairman, R. Balasundaram, Mechanical properties and applications of Magnesium alloy – Review, Materials Today: Proceedings, Volume 27, Part 2, 2020, Pages 909-913, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2020.01.255.

[5] Ye Jin Kim, Young Min Kim, Jun Ho Bae, Soo-Hyun Joo, Sung Hyuk Park, Microstructural characteristics and low-cycle fatigue properties of AZ91 and AZ91–Ca–Y alloys extruded at different temperatures, Journal of Magnesium and Alloys, Volume 11, Issue 3, 2023, Pages 892-902, ISSN 2213-9567, https://doi.org/10.1016/j.jma.2021.12.015.

[6] Zheng, Y.; Zhang, Y.; Liu, Y.; Tian, Y.; Zheng, X.; Chen, L. Research Progress on Microstructure Evolution and Strengthening-Toughening Mechanism of Mg Alloys by Extrusion. Materials 2023, 16, 3791. https://doi.org/10.3390/ma16103791

[7] Ye TIAN, Hong-jun HU, Hui ZHAO, Wei ZHANG, Peng-cheng LIANG, Bin JIANG, Ding-fei ZHANG, An extrusion−shear−expanding process for manufacturing AZ31 magnesium alloy tube, Transactions of Nonferrous Metals Society of China, Volume 32, Issue 8, 2022, Pages 2569-2577, ISSN 1003-6326, https://doi.org/10.1016/S1003-6326(22)65966-1.

[8] Prasad, C. D., Soni, P. K., Eswaran, A., Deshmukh, K., Shrivastava, R., & Tiwari, A. (2024). Studies on Wear and Microstructure assessment of WC-Co Reinforced Iron Based HVOF Coating. Results in Surfaces and Interfaces, 100237.

[9] Yan Yang, Xiaoming Xiong, Jing Chen, Xiaodong Peng, Daolun Chen, Fusheng Pan, Research advances in magnesium and magnesium alloys worldwide in 2020, Journal of Magnesium and Alloys, Volume 9, Issue 3, 2021, Pages 705-747, ISSN 2213-9567,https://doi.org/10.1016/j.jma.2021.04.001.

[10] Wang, S.; Chai, Y.; Jiang, B.; Yang, L.; Zhang, Y.; He, Y.; Liang, L. Effects of Zn Addition on the Microstructure, Tensile Properties and Formability of As-Extruded Mg-1Sn-0.5Ca Alloy. Metals 2023, 13, 493. https://doi.org/10.3390/met13030493

[11] Jianmin Yu, Zhimin Zhang, Ping Xu, Yingze Meng, Mo Meng, Beibei Dong, Huiling Liu, Deformation behavior and microstructure evolution of rare earth magnesium alloy during rotary extrusion, Materials Letters, Volume 265, 2020, 127384, ISSN 0167-577X, https://doi.org/10.1016/j.matlet.2020.127384.

[12] Tao Wang, Lun Yang, Zhaofeng Tang, Lei Wu, Huanyuan Yan, Chao Liu, Yunzhu Ma, Wensheng Liu, Zhaoji Yu, Microstructure, mechanical properties and deformation mechanism of powder metallurgy AZ31 magnesium alloy during rolling, Materials Science and Engineering: A, Volume 844, 2022, 143042, ISSN 0921-5093, https://doi.org/10.1016/j.msea.2022.143042.

[13] Hui-Hu Lu, Li Lu, Wang-Gang Zhang, Zhen-Guang Liu, Wei Liang, Improvement of stretch formability and weakening the basal texture of Mg alloy by corrugated wide limit alignment and annealing process, Journal of Materials Research and Technology, Volume 17, 2022, Pages 2495-2504, ISSN 2238-7854, https://doi.org/10.1016/j.jmrt.2022.02.015.

[14] Zheng, Y.; Zhang, Y.; Liu, Y.; Tian, Y.; Zheng, X.; Chen, L. Research Progress on Microstructure Evolution and Strengthening-Toughening Mechanism of Mg Alloys by Extrusion. Materials 2023, 16, 3791. https://doi.org/10.3390/ma16103791

[15] Yuwei Song, Kezhen Yuan, Xian Li, Yang Qiao, Microstructure and properties of biomedical Mg-Zn-Ca alloy at different extrusion temperatures, Materials Today Communications, Volume 35, 2023, 105578, ISSN 2352-4928, https://doi.org/10.1016/j.mtcomm.2023.105578.

[16] Hucheng Pan, Rui Kang, Jingren Li, Hongbo Xie, Zhuoran Zeng, Qiuyan Huang, Changlin Yang, Yuping Ren, Gaowu Qin, Mechanistic investigation of a low-alloy Mg–Ca-based extrusion alloy with high strength–ductility synergy, Acta Materialia, Volume 186, 2020, Pages 278-290, ISSN 1359-6454, https://doi.org/10.1016/j.actamat.2020.01.017.

[17] Zhiyuan Jia, Qinyang Zhao, Yong Zhang, Yiku Xu, Yongnan Chen, Xiaotong Deng, Fengying Zhang, Lin Wang, Dizi Guo, Hot and cold rolling of a novel near-α titanium alloy: Mechanical properties and underlying deformation mechanism, Materials Science and Engineering: A, Volume 863, 2023, 144543, ISSN 0921-5093, https://doi.org/10.1016/j.msea.2022.144543.

[18] Tiwari, A., Kumar, N., & Banerjee, M. K. (2024). Applications of genetic algorithm in prediction of the best achievable combination of hardness and tensile strength for graphene reinforced magnesium alloy (AZ61) matrix composite. Results in Control and Optimization, 14, 100334.

[19] Dae Hyun Cho, Thomas Avey, Kyoung Hyup Nam, David Dean, Alan A. Luo, In vitro and in vivo assessment of squeeze-cast Mg-Zn-Ca-Mn alloys for biomedical applications, Acta Biomaterialia, Volume 150, 2022, Pages 442-455, ISSN 1742-7061, https://doi.org/10.1016/j.actbio.2022.07.040.

[20] Ziyue Jiao, Shaoyuan Lyu, Liang Wang, Chen You, Minfang Chen, Improving the mechanical properties and corrosion resistance of biodegradable Mg–Zn–Ca–Mn alloy bone screw through structural optimization, Journal of Materials Research and Technology, Volume 21, 2022, Pages 1442-1453, ISSN 2238-7854, https://doi.org/10.1016/j.jmrt.2022.10.004.

[21] B. NAMI, S.M. MIRESMAEILI, F. JAMSHIDI, I. KHOUBROU, Effect of Ca addition on microstructure and impression creep behavior of cast AZ61 magnesium alloy, Transactions of Nonferrous Metals Society of China, Volume 29, Issue 10, 2019, Pages 2056-2065, ISSN 1003-6326, https://doi.org/10.1016/S1003-6326(19)65112-5.

[22] Shao-zhen ZHU, Tian-jiao LUO, Ting-an ZHANG, Yun-teng LIU, Yuan-sheng YANG, Effects of extrusion and heat treatments on microstructure and mechanical properties of Mg–8Zn–1Al–0.5Cu–0.5Mn alloy, Transactions of Nonferrous Metals Society of China, Volume 27, Issue 1, 2017, Pages 73-81, ISSN 1003-6326, https://doi.org/10.1016/S1003-6326(17)60008-6.

[23] Tiwari, A. (2024). Prediction model for hardness and tensile strength of graphene reinforced AZ 61 alloy based composite using Metaheuristic Algorithm. Global Journal of Engineering and Technology Advances, 20(03), 042-052.

[24] Tiwari, A. (2015). To study and fabrication of air cushion vehicle. INTERNATIONAL JOURNAL of RESEARCH–GRANTHAALAYAH, 3, 70-84.

[25] Tiwari, E. A. (2015). Design and fabrication of desiccant wheel dehumidifier. International Journal of Advanced Research in Mechanical Engineering & Technology (IJARMET), 1(1), 7-16.

[26] Tiwari, A. (2015). Design and Fabrication of Double Acting Winch Type Elevator. International Journal of Mechanical Engineering and Robotics Research, 4(1), 41.

[27] Su, S.; Zhou, J.; Tang, S.; Yu, H.; Su, Q.; Zhang, S. Synthesis of Nanocrystalline AZ91 Magnesium Alloy Dispersed with 15 vol.% Submicron SiC Particles by Mechanical Milling. Materials 2019, 12, 901. https://doi.org/10.3390/ma12060901

[28] Qiong Xu, Yuhua Li, Hongyan Ding, Aibin Ma, Jinghua Jiang, Guobin Chen, Yegao Chen, Microstructure and mechanical properties of SiCp/AZ91 composites processed by a combined processing method of equal channel angular pressing and rolling, Journal of Materials Research and Technology, Volume 15, 2021, Pages 5244-5251, ISSN 2238-7854, https://doi.org/10.1016/j.jmrt.2021.11.005.

[29] Xiaojun Wang, Weiqing Liu, Xiaoshi Hu, Kun Wu, Microstructural modification and strength enhancement by SiC nanoparticles in AZ31 magnesium alloy during hot rolling, Materials Science and Engineering: A, Volume 715, 2018, Pages 49-61, ISSN 0921-5093, https://doi.org/10.1016/j.msea.2017.12.075.

[30] Tiwari, A. (2015). Design and Fabrication of Automatic Blackboard Duster. International Journal of Emerging Technology and Innovative Engineering, ISSN, 2394-6598.

[31] Kumar, E. S., & Tiwari, E. A. (2015). A work study on minimize the defect in aluminium casting. Int. J. Emerg. Technol. Eng. Res, 3(1), 32-38.

[32] Prajapati, S., Yadaf, P., Tiwari, A., & Kumar, A. (2017). Design and Fabrication Of Go-Kart For Achieve High Speed Without Differential Mechanism. Int. J. Eng. Sci. Res. Technol., 6(7), 340-365.

[33] Swarnkar, H., Jain, R., Tiwari, A., & Vasnani, H. (2024). Phase change material application in solar cooking for performance enhancement through storage of thermal energy: A future demand.

[34] Sharma, A., Tiwari, A., & Vasnani, H. (2020). Optimization of various process parameters for Co2 laser machining of carbon fiber reinforced polymer (CFRP). Int J Sci Technol Res, 9, 466-472.

[35] Kumar Sharma, L., Tiwari, A., & Vasnani, H. (2020). Optimization Of Tig Welding Parameters And Their Effect On Aluminium 5052 Plate. International journal of scientific & technology research, 9(3).Li Zhang, Kun Su, Kun-kun Deng, Kai-bo Nie, Cui-ju Wang, Wei Liang, Hot tensile behavior and deformation mechanism of Mg–5Al–2Ca alloy influenced by SiC particles, Mechanics of Materials, Volume 150, 2020, 103599, ISSN 0167-6636, https://doi.org/10.1016/j.mechmat.2020.103599.

[36] Harshita Swarnkar, Ritu Jain, Amit Tiwari, Graphene Coating and its Effect on Performance of Box Type Solar Cooker: An Experimental Investigation, Recent Patents on Mechanical Engineering; Volume 17, Issue , Year 2024, e22127976326095. DOI: 10.2174/0122127976326095240904221146

[37] Chang Hai, Wang Cuiju, Deng Kunkun, Nie Kaibo, Su Kun, Liao Ling, Wang Hongxia, Tong Libo, Effects of SiCp Content on the Microstructure and Mechanical Properties of SiCp/Mg-5Al-2Ca Composites, Rare Metal Materials and Engineering, Volume 47, Issue 5, 2018, Pages 1377-1384, ISSN 1875-5372, https://doi.org/10.1016/S1875-5372(18)30138-3.

[38] Chang, H., Hu, X., Wang, X. et al. Aging behavior of the extruded SiCp-reinforced AZ91 Mg alloy composite. Journal of Materials Research 34, 335–343 (2019). https://doi.org/10.1557/jmr.2018.427

[39] Xiaofeng Ding, Fuqiang Zhao, Yuanhua Shuang, Lifeng Ma, Zhibing Chu, Chunjiang Zhao, Characterization of hot deformation behavior of as-extruded AZ31 alloy through kinetic analysis and processing maps, Journal of Materials Processing Technology, Volume 276, 2020, 116325, ISSN 0924-0136, https://doi.org/10.1016/j.jmatprotec.2019.116325.

[40] Kumar, Y., Tiwari, A., Vasnani, H., & Kumar, N. (2018). Investigation of mechanical behavior of Al 6063 & SiC composite materials. International Journal of Advanced Technology and Engineering Exploration, 5(47), 376-384.

[41] Tiwari, A., Vasnani, H., Kumar, N., & Labana, M. (2017). A Review on Waste Heat Recovery and Reused of Exhaust Gases from Diesel Engines. International Journal of Advance Reaserch in Science and Engineeing, Volume, (08).

[42] Israr, M., Tiwari, A., Labana, M., & Gangele, A. (2015). Performance analysis and fabrication on a turbocharger in two stroke single cylinder petrol engine. Int. J. Eng. Technol. Innov, 2(2), 14-21.

[43] Israr, M., Tiwari, A., & Gangele, A. (2014). Implementation and application of nanotechnology in industrial sector. Int. J. of Multidisciplinary and Scientific Emerging Research, 3(2).

[44] Tiwari, A., Kumar, N., & Banerjee, M. K. (2024). Ageing Characteristics of Stir Cast AZ 61 Alloy with Minor Additions. Recent Patents on Engineering, 18(6), 67-82.

[45] Swarnkar, H., Jain, R., & Tiwari, A. (2024). Comparative Energy and Exergy Performance of Box-Type Solar Cookers Using Various Pot Materials. International Journal of Machine Systems and Manufacturing Technology, 2(01), 9-15.

[46] S.S. Nene, S. Zellner, B. Mondal, M. Komarasamy, R.S. Mishra, R.E. Brennan, K.C. Cho, Friction stir processing of newly-designed Mg-5Al-3.5Ca-1Mn (AXM541) alloy: Microstructure evolution and mechanical properties, Materials Science and Engineering: A, Volume 729, 2018, Pages 294-299, ISSN 0921-5093, https://doi.org/10.1016/j.msea.2018.05.073.

[47] Liping Zhong, Yongjian Wang, Yuchen Dou, On the improved tensile strength and ductility of Mg--Sn--Zn--Mn alloy processed by aging prior to extrusion, Journal of Magnesium and Alloys, Volume 7, Issue 4, 2019, Pages 637-647, ISSN 2213-9567, https://doi.org/10.1016/j.jma.2019.07.007.

[48] Tiwari, A., Vasnani, H., Jain, R., Swarnkar, H., Tanwar, H., & Srivastava, S. (2024). Fabrication of low-cost metal polishing machine for preparation of microstructure samples of lightweight alloy and composite material. Global Journal of Engineering and Technology Advances, 19(3), 112-123.

[49] Gabra, M. H., Jain, R. K., & Tiwari, A. (2017). Energy efficient cupola furnace via hybridization with a biomass gasifier. Int. J. Emerg. Technol. Eng. Res, 5, 54-62.

[50] Sachin, B., Rao, C. M., Prasad, C. D., Tiwari, A., Ravikiran, Raghavendra, T., ... & Madhusudhana, R. (2024). Interactive design and development of an intelligent vision-driven 3D printed precision sorting mechanism for silk cocoons. International Journal on Interactive Design and Manufacturing (IJIDeM), 1-10.

[51] Chopra, A., Jain, T. K., Saxena, N., & Tiwari, A. (2023). Predictive Analytics of a Community Survey Data by Artificial Neural Network-A Subset of Machine Learning. Indian Journal of Science and Technology, 16(34), 2778-2788.

[52] Tiwari, A., Kumar, N., & Banerjee, M. K. (2023). Effect of Hot Rolling on Microstructure and Mechanical Properties of Stir Cast AZ 61 Alloy with Minor Additions. Indian Journal of Science and Technology, 16(24), 1810-1822.

[53] Tiwari, A., Vasnani, H., & Labana, M. (2017). The process for manufacturing of ball bearing and effect of material in bearing life. Int. J. Adv. Res. Sci. Eng, 6, 235-252.

[54] 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; 02(01):24-32.

[55] Pravin Sharma, Vivek Patel, Adarsh Kr Singh, Amit Tiwari. Phase Transformation of Manganese Steel: A Role of Alloying Elements. Trends in Mechanical Engineering & Technology. 2024; 14(2): 15–20p

[56] Sachin, B., Rao, C.M., Prasad, C.D. et al. Interactive design and development of an intelligent vision-driven 3D printed precision sorting mechanism for silk cocoons. Int J Interact Des Manuf (2024). https://doi.org/10.1007/s12008-024-02086-5

[57] Chen Xu, Jianfeng Wang, Shanshan Liu, Zhong Wang, Kenan Ru, Shichuang Sun, Yufeng Sun, Effect of quenching temperature on microstructure and mechanical properties of Mg-35 wt%Sc alloy, Journal of Alloys and Compounds, Volume 943, 2023, 169165, ISSN 0925-8388, https://doi.org/10.1016/j.jallcom.2023.169165.

[58] Hucheng Pan, Yuping Ren, He Fu, Hong Zhao, Liqing Wang, Xiangying Meng, Gaowu Qin, Recent developments in rare-earth free wrought magnesium alloys having high strength: A review, Journal of Alloys and Compounds, Volume 663, 2016, Pages 321-331, ISSN 0925-8388, https://doi.org/10.1016/j.jallcom.2015.12.057.

[59] Yahia Ali, Dong Qiu, Bin Jiang, Fusheng Pan, Ming-Xing Zhang, Current research progress in grain refinement of cast magnesium alloys: A review article, Journal of Alloys and Compounds, Volume 619, 2015, Pages 639-651, ISSN 0925-8388, https://doi.org/10.1016/j.jallcom.2014.09.061.

[60] Monis Luqman, Yahia Ali, Moustafa Mahmoud Y. Zaghloul, Faheem A. Sheikh, Vincent Chan, Abdalla Abdal-hay, Grain refinement mechanism and its effect on mechanical properties and biodegradation behaviors of Zn alloys – A review, Journal of Materials Research and Technology, Volume 24, 2023, Pages 7338-7365, ISSN 2238-7854, https://doi.org/10.1016/j.jmrt.2023.04.219.

[61] Soo-Min Baek, Jeong-Ki Kim, Du-Won Min, Sung Soo Park, Remarkably slow corrosion rate of high-purity Mg microalloyed with 0.05wt% Sc, Journal of Magnesium and Alloys, Volume 11, Issue 3, 2023, Pages 991-997, ISSN 2213-9567,https://doi.org/10.1016/j.jma.2022.08.003.

[62] Yanfu Chai, Bin Jiang, Jiangfeng Song, Bo Liu, Guangsheng Huang, Dingfei Zhang, Fusheng Pan, Effects of Zn and Ca addition on microstructure and mechanical properties of as-extruded Mg-1.0Sn alloy sheet, Materials Science and Engineering: A, Volume 746, 2019, Pages 82-93, ISSN 0921-5093, https://doi.org/10.1016/j.msea.2019.01.028.

[63] Li-ping ZHONG, Yong-jian WANG, Microstructure evolution and optimum parameters analysis for hot working of new type Mg–8Sn–2Zn–0.5Cu alloy, Transactions of Nonferrous Metals Society of China, Volume 29, Issue 11, 2019, Pages 2290-2299, ISSN 1003-6326, https://doi.org/10.1016/S1003-6326(19)65135-6.