Review Article

Prospective of Magnesium and Alloy-based Composites for Lightweight Railway Rolling Stocks

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Abstract
Magnesium and its alloy have superior characteristics and matches to great potential in railway rolling stocks. The low density and high strength make it ideal for lightweight applications, exceptionally for car bodies and rolling stocks. In this study, a comprehensive review has been carried out on magnesium alloy towards its prospective in railroad vehicles, emphasizing fatigue damage, vibration, energy savings, and overcoming wear or friction loss. Furthermore, with better stiffness and strength, the weight reduction contributes to the better energy and fuel-saving for low-speed trains than bullet and high-speed trains. However, the potential application of magnesium and its alloy has a colossal study gap in the railway industry's processing, fabrication, and maintenance that needs further studies and research.

Keywords: Energy saving, Rolling stocks, Magnesium alloy, Lightweight

1 Introduction

The worldwide development and modernization in the railway industry made significant progress in constructing high-speed railway networks [1]. The high-speed railway network is expanding for the better connectivity between economic centers. Railway transportation maintains a sustainable transportation system, however, the extensive utilization of aluminium causes scarcity in resources [2]. Reducing the over-dependency on aluminium necessitates discovering alternative lightweight materials, such as carbon fiber reinforced polymer, magnesium, and other green materials for railway networks undoubtedly minimizes carbon dioxide emissions. In the automotive industry, lightweight metals, such as magnesium and magnesium alloys could replace high weight materials. According to the numerous studies carried out, reducing the weight of automobiles is one of the primary means by which their fuel utilization can be minimized between 0.1 L/(100 km × 100 kg) and 0.9 L/(100 km × 100 kg) [3]. The reduction in fuel requirement reduces overall carbon dioxide emissions. The magnesium or any metal extraction results in more significant carbon emissions, however, the environmental impacts can be compensated with fuel consumption and better life durability [4]. In a railway carriage, running gears and body structure accounts for the majority of 25% to 35% of the overall weight [5]. Reducing weight in the front of an automobile transforms the center of gravity toward the back, enhancing and providing better steering and cornering response. Furthermore, strategically incorporating magnesium into the roof and doors can lower the center of gravity, reducing rollover risks. However, the weight saving in the running gears attributes to security requirements. Therefore, it is essential to optimize the weight of the body structure to design a new lightweight carriage [6].

Magnesium has been commonly employed as a suitable material choice for numerous applications, such as communication, automobile, military, aviation, and railway industries [7]. Figure 1 illustrates the broad application of magnesium-based alloy for various sectors. The lightest structural metal attributes its

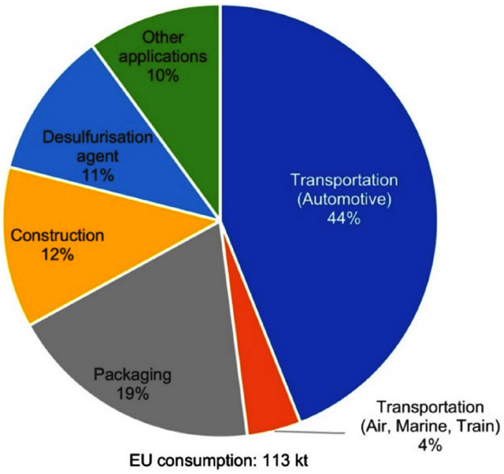

Figure 1: Wide application of magnesium alloys over various sectors [8].

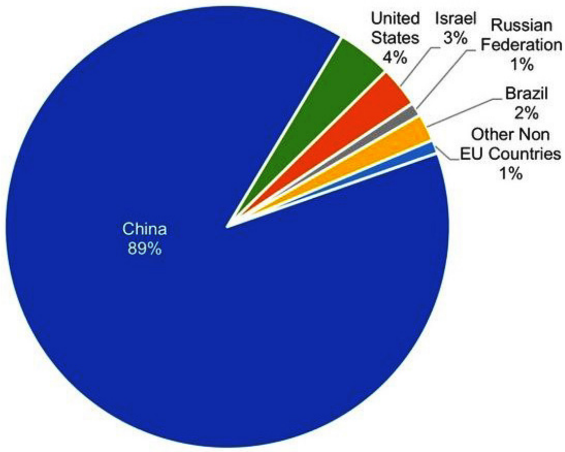

Figure 2: The global production of magnesium, in period 2012–2016 [8].

potential in designing and developing lightweight railway carriages for the high-speed railway network. In addition, it would be an ideal sustainable choice with better heat resistance, damping characteristics, and energy-saving [9]. Magnesium-based alloys and composites were introduced in 2003 and applied to numerous interior components in railway carriage interiors. Shinkansen in Japan were the first designed magnesium train carriage with the new design observed to be 5 tons of weight reduction [10]

The global magnesium alloy market is widely expanding. It is estimated that the market is projected to reach USD 3.2 to 3.4 billion by 2027 in the near future at an annual growth of 12.3% [11], [12]. Magnesium alloy has excellent potential for broad application to minimize fuel consumption and greenhouse gas emissions for the transportation industry. However, the European Commission reported that magnesium and alloy elements had been categorized as critical resources since 2011 [13] and have economic importance and supply risk for the European Union. China is the leading magnesium producer with more than 90% compared to other nations, as shown in Figure 2 [14]. It shows that China's global influence in magnesium production makes it a leading producer compared to other countries. As the recent report published by Reporter link agency [15], magnesium alloy market is expanding rapidly, and the industries of the developed nation have a growing demand. The United States demand will be growing over to 11%, followed by Europe. It is remarked that Germany will have a predominant role in the magnesium alloy market up to US$64.2 Million within the next four to five years. It is expected that the demand for magnesium alloy will incline in Asian nations. It is forecasted that Japan's alloy market size will reach a market value of US$94.8 Million [12]. It is perceived that several macro-economic factors and influential geographic factors will play a significant role in the coming years.

The demand for highly durable lightweight materials, which could withstand corrosion, wear, and resistance with better durability, is rising. Numerous advances were carried out in the railway and transportation industry, from operational efficiency to combustion systems. Lightweight materials were widely applied across transportation industries. It is identified that one-third of emissions is released from transportation [16]. The studies pointed out that the emissions can be significantly minimized by reducing the total weight of automobiles [17]. The material selection needs to meet specific characteristics, such as lightweight, strong, and better wear and tear resistance in the long run and high-speed application. This review article provides an insight towards magnesium application-based prospectus in rolling stocks and other essential components in the railway industry.

2 Suitability of Magnesium in the Railway Industry

The railway industry is rapidly growing and becoming one of the most attractive business options currently available. It is observed that magnesium has the ideal physical and mechanical attributes to make it a perfect option for designing a lightweight body for a high-speed rail network. The magnesium alloy exhibits the better thermal conductivity and melting point during the comprehensive studies on various materials, such as plastics and other composites [18]. In addition, the magnesium-based alloys also demonstrated excellent mechanical characteristics, such as yield strength, tensile strength, and elongation to fracture than that of aluminium alloys, which have been currently employed in high-speed railway applications [19]. Table 1 describes the suitable characteristics of the various magnesium-based alloy. The overall attributes of magnesium alloy can be further enhanced to exceptional by combining magnesium with titanium alloy and carbon fiber reinforced polymer. Along with these necessary characteristics, the magnesium alloy has better damping characteristics and can limit vibrations, providing the better riding comfort for passengers. Koo and his research team [20] conducted a study on different material for designing railroad box-type car body, and found that the magnesium and aluminium based alloy provides the better durability.

Damping is another crucial factor in limiting noise or vibrations without employing additional dampers. Magnesium alloy inherits favorable damping characteristics compared to other commonly used materials in designing railway cars [21]. The magnesium exhibits high solubility with other alloying elements, such as nickel, copper, and silicon, enhancing damping characteristics [21]. Figure 3 exhibits the steel, aluminium, and magnesium alloy performance comparison. As it inherits excellent damping characteristics, magnesium and alloys could minimize the vibrations and maintain superior passenger riding comfort. In addition, magnesium alloy is comparatively ideal durable than plastics. Magnesium alloy has better energy absorption capability to withstand cracking stress and strain [23].

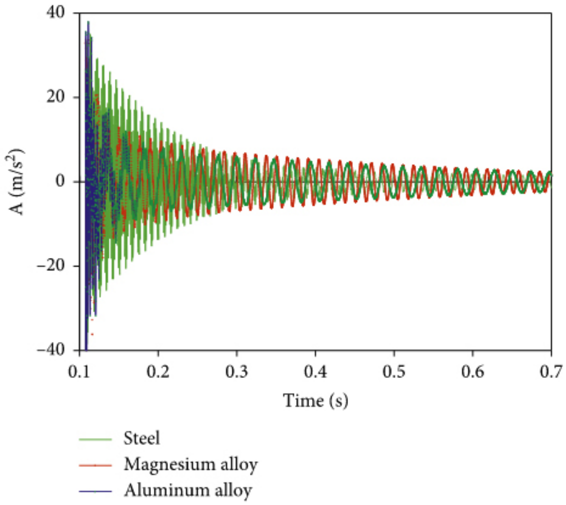

Figure 3: Vibration amplitudes of magnesium alloy, aluminium alloy, and steel [22].

Table 1: Characteristics of various alloys towards various engineering applications [23]

Alloys	Specific Strength (MPa/(g/cm^3))	E (GPa)	εf (%)	YS (MPa)	UTS (MPa)	λ (W/(M·K))	Tm (°C)
Magnesium							
AZ91	154	45	8	160	280	72	596
ZW61	232	45	16	250	420	80	620
KBM10	201	45	23	250	360	88	610
AZ80	183	45	10	210	330	78	610
AZ31	170	44	12	180	300	85	630
ZK60	188	43	10	280	340	72	615
AM60	154	45	8	160	280	72	596
Composites							
CFRP 700	1000	131–200	NA	NA	NA	800–700	300
GFRP	166	9.2–25	NA	NA	NA	200–1000	300
TI- ALLOY (Ti-6Al-4V)	250	110	20	650	1100	15	1500
Polycarbonate (PC)	85	6.7	3	NA	104	0.2	160

NA: not available. Tm: melting point/initial fusion temperature; Specific strength = UST/ρ; λ: heat conductivity; UTS: ultimate tensile strength; E: Young's elastic module; YS: 0.2% proof yield tensile strength; εf: elongation-to-fracture; Tg: glass transition temperature.

The combination of alloying elements by blending with magnesium enhances the damping characteristics. Furthermore, proper annealing and aging mechanisms could additionally boost the damping characteristics. The magnesium alloys designed with specific structures, such as honeycomb further enhance adsorption of vibrations. The magnesium-based honeycomb structure can be incorporated into various components of high-speed railways, such as instrument panels, a wall side structure, floor and body roof structure [24].

Magnesium alloy has comparatively low cutting resistance compared to other available metals. As a result, magnesium alloy has the lowest heat fusion value compared to other materials. In addition, it supports high pressure casting with its flexibility to cast complex structures and thinner walls [25]. Compared to aluminium, magnesium has low latent heat for solidification, saving both energy and cost savings for mold casting. Furthermore, the magnesium alloy has numerous cost-saving benefits in recycling, forming, casting, and melting.

3 Magnesium Based Applications in the Railway Industry

Couplers are one of the significant components of high-speed railways as it is crucial for railway safety [26]. Due to the high-speed transition and rapid breaking result in vigorous vibrations and stress on the rail cars, so the couplers must be able to meet the safety standards [27]. Couplers play a critical role as it is necessitated to handle extreme stress and strain caused by emergency braking leads to derailment in the locomotive [28]. However, the current couplers made of 74 kg weight are hugely inconvenient for operations [29]. The ultralight high-strength magnesium couplers can be more convenient in a high-speed railway network. The magnesium-based couplers maintained high strength and were fabricated through superplastic multistep forging-extrusion. The multistep forging technology produces a homogeneous microstructure with fine grain that prevents couplers' deformities. The practical stress analysis was carried out on the mold forming process, and it was noticed that the magnesium-based couplers were fabricated with better strength and were lightweight.

Lightweight and comfortable railway locomotive transportations require lightweight wheels that

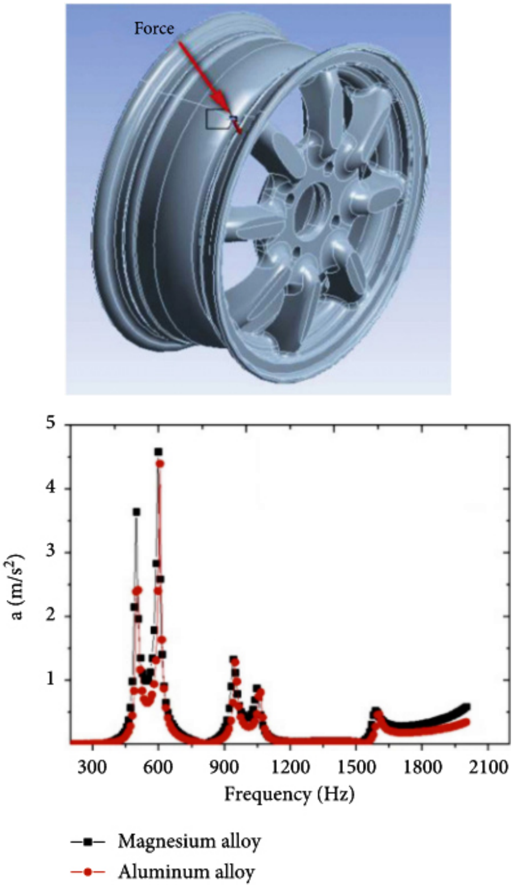

Figure 4: Magnesium alloy-based wheel Dynamic Impact Performance Analysis [24].

withstand stress and strain [24]. In addition, the magnesium alloy could able to reduce the vibrations. The analysis identified that structural and material damping combined with deformation analysis showed that magnesium alloy-based wheels were better than aluminium. In the studies, it is observed that magnesium-based alloy would reduce the weight by around 32.3% compared with aluminium alloy wheels. Figure 4 shows the testing performance using magnesium and aluminium alloy. The magnesium alloy-based wheels exhibited the better performance and would provide the better riding comfort. Compared with aluminium alloy wheels, the magnesium alloy wheel reduces the acceleration by around 13.9% and velocity around 11.8%. In addition, magnesium alloy observed a high damping ratio, minimizing vibrations compared to aluminium alloys.

Magnesium alloy-based honeycomb structures were embodied as thermal and sound insulators. Numerous materials, such as aluminium alloy, glass, resins, paper, etc., have been widely employed as honeycomb structures. Magnesium alloy with honeycomb structure with superior strength and lightweight suits for better thermal adsorption and superior strength [30]. The magnesium alloy-based honeycomb structure module is used in the train engine and other buffers option for better airflow and thermal management [31]. Extrusion is one of the most commonly employed processing techniques. The magnesium alloy is composed of heavy rare earth metals. After extrusions, the combination of rare earth metals could enhance the ultimate tensile strength between 400 and 550 MPa [32]. However, high density and expenses associated with rare earth metals limit its suitability towards lightweight industrial applications. It has been reported that the reciprocating extrusion technique enhanced the ultimate tensile strength of AZ90 alloy with excellent formability and stability [32]. In addition, the slow-speed extrusions with low temperatures have demonstrated excellent tensile strength characteristics.

4 Alloy Processing Techniques

No element is perfect, and every element has its drawbacks. Similarly, magnesium also inherits its drawbacks, such as rapid oxidation when exposed to an atmospheric and aqueous environment and poor corrosion resistance. In order to overcome these drawbacks and to enhance its characteristics, it is essential to be alloyed with other elements [33]. Various alloy processing techniques have been developed for magnesium metal matrix composites. Temperature process techniques have been mainly categorized as 1) Liquid processing, 2) Vapour processing, and 3) Solid-state processing [33].

The solid-state processing techniques were mainly classified as diffusion bonding and powder metallurgy. The magnesium and other metallic composites were prepared using mechanical techniques under temperature-sensitive treatment in powder metallurgy. The main drawback is that it is expensive and unsuitable for bulk production [34]. In contrast, diffusion bonding is another solid-state processing technique where matrix production forms reinforcement and foils as fibers. The fibers were manufactured at a particular order, pressed at a higher temperature, and finally laminated to multilayer with excellent shear strength. It has limitations to manufacture large complex parts [35]. Vapor processing techniques are mainly classified as physical vapor deposition and chemical vapor deposition. The process involves thin film deposition by condensation of vaporized metal oxides to the surface of magnesium. The process is time-consuming, and it does not have any mechanical interface as it is a purely chemical process. This technique provides a better surface coating, which could resist corrosion.

Liquid processing is another widely utilized technique, disintegrated melt deposition, stir and squeeze casting. The melt processing is mainly carried out by two techniques by continuous feeding or molten bath. The disintegrated melt deposition is a combination of the spray and dispersion process. Two gas jets simultaneously passed for the manufacture of molten metal, the molten metal finally passed to hot extrusion for end-stage production [36]. Stir casting is another commonly employed processing technique in the liquid state, especially for composite fabrication, which entails the matrix metal is thermally activated to the liquidus temperature followed by the introduction of reinforcement particles and uniformly distributed into the molten matrix with the help of ultrasonic and mechanical stirring to overcome reinforcement phase and poor wettability [37]. The molten metal is cooled down to room temperature to yield the final product. Squeeze casting is another commonly employed technique in alloying, and it is one of the old and traditional techniques introduced for alloying in 1800. In this technique, the reinforcement placed in the molding cast and molten magnesium alloy is poured and solidified at high pressure. The process produced high volume percentage fractions followed by slow cooling to procure the solidification.

The alloying of magnesium with rare earth has numerous advantages, such as better weldability, corrosion resistance, workability, castability and strength. In the studies, it is observed that alloying with aluminium enhanced the corrosion resistivity by 1 to 9%, commonly known as Magnesium – Aluminium alloys. The alloying with aluminium enhances the microhardness and decreases the grain size [38]. The other common metal employed for alloying is zinc, and the zinc alloying enhances the tensile strength characteristics. The optimal addition of zinc for alloying with magnesium is 1%. The addition above 1% of zinc results in declination of weldability characteristics and causes hot shortness [39]. There are alloying with rare metals, such as La, Nd, Pr. However, now 15 elements can be blended as alloying substrates at the higher elevated temperatures, enhancing the suitability of magnesium-based alloying for the transportation and logistics industry.

To enhance the characteristics of magnesium alloys, it is essential to enhance the cleanliness and quality of magnesium melt. It helps 1) to effectively control the amount of gases dissolved, 2) to control the trace metals and 3) to remove the melt inclusion. Alloys with defective and varied chemical compositions will result in low homogeneity, which finally declines the final quality of magnesium alloys. Both surface and mechanical characteristics will get seriously affected [40]. It has been proved that certain compound traces, such as nickel, iron, copper and cobalt are severely harmful to magnesium alloys [41]. The most common impurity of magnesium alloy is traces of iron. The high immersion of stainless steel contains nickel, leading to nickel contamination. Similarly, cobalt contamination mainly results from toxic paint sources [41]. It is essential to eliminate these elements to procure high-quality magnesium alloys. It is essential to provide the proper hydrogen concentration; the higher hydrogen concentration in the alloying process would lead to the pore formation after the solidification. Inclusion is magnesium alloy would further result in declining mechanical characteristics, resulting in a high chance of corrosion [42]. The prominent magnesium melt is intermetallic and nonmetallic inclusions. The intermetallic inclusions are precipitated when ferrous metallic is separated. Whereas on the other hand, the nonmetallic inclusions entail both oxides and nitrides. These inclusions results in negative drawbacks, such as poor tensile strength and corrosion resistance. In addition, the choice of right manufacturing techniques plays a crucial role in the quality of alloys. It is critical that suitable processing technique is selected to attain the desired quality of the product without compromising the mechanical and physical attributes.

5 Energy-saving and Environmental Aspects Magnesium Alloy

As discussed above, the magnesium alloy is comparatively lighter than other available composites. The magnesium alloy-based train body was estimated to be 22% lighter than the aluminium body without compromising strength and stiffness. Recent studies assessed that magnesium alloy-based train body weights 7.8 t, whereas the train car manufactured by aluminium was about 10 t [43]. As the magnesium alloy replaces interior lining components, the overall weight of the railway carriage will be further minimized compared to that of a train designed with aluminium and other alloys. The total weight reduction is noticed in the range of 8.6 to 12.6%. Furthermore, the researchers carried out an in-depth investigation on energy-saving perspectives at different running stages. It was noticeable that magnesium alloy-based design exhibits the better energy saving than trains designed with aluminium [44].

Carbon dioxide emission is one of the potentially severe threats to humankind and the environment. New regulations were frame worked to minimize the emissions and toxic effects. It is necessary to implement sustainable production with better durability and energy saving. Utilizing lightweight magnesium alloy in the locomotive and transportation industry saves energy and reduces carbon dioxide and toxic gas emissions. From the studies and analysis, it is noticed that the reduction of body weight in automobiles reduces the fuel requirement due to less poisonous gas emissions [45]. Yi [46] carried out the life cycle assessment studies on a comparative analysis of magnesium and aluminium alloy. It is noticed that magnesium-based alloy proved to reduce carbon dioxide emission as wells as less human toxicity on the entire life span.

However, the usage of magnesium has certain limitations due to its low corrosion resistance. Especially, when the magnesium gets in contact with the saltwater, it gets aggressively vulnerable to corrosion [47]. Therefore, it is necessary to utilize alloying, surface treatment, and coating to prevent corrosion vulnerability. Along with alloying, the layer acts as a superior barrier to impede the contact of aggressive ion species with magnesium [48]. It is noticed from the studies that pure magnesium has meager standard equilibrium potential as compared with other structural metals, thus there are high chances of suffering in both galvanic and generalized corrosion when coupled with more noble metals [49]. Numerous techniques have been identified to protect the magnesium alloy from corrosion.

Compared to traditional processes, such as coating deposition and electrochemical machining, advanced techniques act as a coating layer, in addition, it enhances the mechanical and morphology characteristics. Sequential complex processing with protective coating inherits excellent anticorrosion characteristics than single-layer coating. Nevertheless, the commercial-scale production of magnesium-based railway carriage still has numerous constraints. There are further in-depth investigations on various dimensions, such as corrosion, durability, prerequisites for mass production, and joining between hybrid materials. In the economic aspects, the costs associated with magnesium alloy are the expensive choice for 1.3–1.5 times compared to aluminium alloys and other available light metal alloys [50]. However, technological advances will accelerate magnesium production to be cost-effective process in the near future.

6 Outlook and Future Prospectus

The magnesium and magnesium-based alloy has gained worldwide attention. The modified magnesium alloy with inherited microstructures that enhance the mechanical and physical characteristics develops new alloys, and there is a significant research gap in production technology. In addition, the protection and corrosion of magnesium alloys constitute a significant concern. Magnesium-based alloy processing and production technologies have made significant progress in the recent years. Recently, cast technology has been upgraded to manufacture large-scale ingots and magnesium alloy with the superior mechanical attributes was developed. The commercial-scale production with high-quality Mg-Gd-Y-Zn-Mn alloy ingots was manufactured through semi-continuous casting. The production of Mg-9Gd-4Y-1Zn-0.8Mn alloy with superior strength incorporated as support beam profile incorporated in rail and locomotive transportation provides better mechanical attributes, uniform composition, and excellent surface quality [51].

Although research and investigations on magnesium alloy were widely investigated, many problems and drawbacks still need to be resolved. Especially, the load-bearing structure and mechanical characteristics of magnesium alloys need to be further enhanced to replace steel or aluminium-based alloys. For example, the plasticity and ultimate tensile strength of superior strength of magnesium-based alloy could be further enhanced to be more than 600 MPa and 7–10%, respectively [43]. In addition, the elastic modulus of magnesium-based alloys could be further enhanced to meet up the standard of aluminium alloy [52]. Another characteristic, such as corrosion resistance of magnesium-based alloy, needs to be further enhanced for better durability and life span. High-strength magnesium alloys would make significant contributions to the transportation and automobile industry. However, there is a serious research and development gap in various stages of production, fabrication, processing, post-treatment, maintenance, and replacement of magnesium alloy.

The fundamental research and studies on magnesium and its alloys will be further deepened and strengthened. The comprehensive data, such as activity coefficient, thermal conductivity, diffusion coefficient are limited. The primary research on various precipitates and their precipitation mechanisms inherits various phase relationships is also scary and the development of joining and sustainable welding technology for magnesium alloys is still challenging. It is expected that these challenges could be resolved within the next five to ten years to meet up industrial demand.

7 Conclusions

The high-speed rail network has numerous challenges. It is necessary to design lightweight structures without compromising safety for rapid development and advancement in high-speed technology worldwide. Magnesium alloy has been successfully incorporated into railway and other transportation industries from small-scale key components to large-scale commercial applications. Incorporating magnesium alloy in railway boogies enhances the locomotive industry's efficacy, maneuverability, and safety. Magnesium alloy has attractive mechanical attributes to makes it an ideal candidate for locomotive applications. It inherits superior strength, excellent damping capacity, bulk availability, cost-effective and lightweight, makes the perfect choice for a high-speed railway network, and expands its suitability for the broad transportation market.

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