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Review

A Critical Review on Improving the Fatigue Life and Corrosion Properties of Magnesium Alloys via the Technique of Adding Different Elements

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Abstract: Magnesium is the eighth-most abundant element in the world and its alloys have a widespread application in various industries such as electronic and transport (i.e., air, land, and sea) engineering, due to their significant mechanical properties, excellent machinability, high strength to weight ratios, and low cost. Although monolithic Mg metal is known as the lightest industrial metal (magnesium density is 30% less than the density of the aluminum, and this unique property increases the attractiveness of its usage in the transportation industry), one of the significant limitations of magnesium, which affects on its applications in various industries, is very high reactivity of this metal (magnesium with an electronegativity of 31.1 can give electrons to almost all metals and corrodes quickly). To overcome this problem, scholars are trying to produce magnesium (Mg) alloys that are more resistant to a variety of loads and environmental conditions. In this regard, Mg alloys include well-known materials such as aluminum (Al), Zinc (Zn), Manganese (Mn), Silicon (Si), and Copper (Cu), etc., and their amount directly affects the properties of final products. In the present review paper, the authors attempted to present the latest achievements, methods, and influential factors (finish-rolling, pore defects, pH value, microstructure, and manufacturing processes, etc.) on the fatigue life and corrosion resistance of most significant Mg alloys, including AM50, AM60, AZ31, AZ61, AZ80, AZ91, ZK60, and WE43, under various conditions. The summarized results and practical hints presented in this paper can be very useful to enhance the reliability and quality of Mg-made structures.

Keywords: magnesium alloys; fatigue life; corrosion resistance; characterization

1. Introduction

In today's world, various industries are moving towards the use of lightweight materials and new alloys with enhanced properties in order to achieve different goals, such

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as improving quality and increasing comfort and efficiency. The transportation industry is not separate from this category, and in various fields such as land transportation (from passenger vehicles to the transportation of goods by trolleys and trucks), sea, and air transportation seeks to reduce fuel consumption and as a result, reduce air pollution, decrease the production of harmful gases for the ozone layer, etc. In the meantime, marine engineering has not been far from this issue, and researchers have made many efforts in this direction. Some of the alloys that have been used as a suitable substitute for steels are various types of aluminum alloy series. However, in recent years, special attention has been paid to the applications of super-light magnesium alloys. However, due to mechanical and dynamic characteristics, it is necessary to strengthen this alloy compared to aluminum. In this regard, one of the important properties of the material that has received much attention from scientists is fatigue properties in low, high, and very high cycle regimes. In other words, industrial parts and machines are exposed to complex and repetitive dynamic loads for which there is no clear trend, such as loads caused by sea waves clashing on the hull of ships, the pile-foundation of offshore platforms, and marine structures. Various methods have been proposed to strengthen fatigue characteristics of magnesium alloys. Meanwhile, the most practical method is to make Mg alloys by adding different rare elements. Thus, in the present review paper, the effect of adding different elements on the fatigue properties of magnesium was discussed.

Magnesium is a chemical element with the symbol Mg and atomic number 12. This solid metal has a gray and shiny appearance that is very similar in appearance to the other five elements in the second group of the periodic table. It has been known that all elements of this group (alkaline earth elements) have the same electron configuration in the outer shell and a similar crystal structure. Moreover, magnesium is the eighth most abundant element in the world (about 2.1% of the Earth's crust is made up of magnesium) and the largest magnesite mining in 2017 were China, Russia, Brazil, and Turkey, respectively. Magnesium produced in the United States comes from three sources: seawater, brine, and minerals. Seawater is processed by companies in California, Delaware, Florida, and Texas to obtain magnesium. Brine is water that is even saltier than seawater. The most common magnesium production process used in China is the silicothermic reaction. In this process, the existing oxides are reduced at high temperatures in the presence of silicon. This process is usually executed using ferrosilicon. However, it can be performed in the presence of carbon at a temperature of 2300 °C [1]. However, in America, the story is a little different. In the United States, magnesium is extracted by utilizing a process called DOW. In this process, magnesium chloride obtained from brine or seawater is melted and electrolyzed [2]. Mg^{2+} cation is the second most abundant cation in sea water and is considered a huge source of magnesium. To obtain magnesium from water, calcium hydroxide is added to seawater to produce magnesium hydroxide precipitate:

$$\mathrm{MgCl_2} + \mathrm{Ca(OH)_2} \rightarrow \mathrm{Mg(OH)_2} + \mathrm{CaCl_2} \tag{1}$$

The pure Mg is a highly reactive metal, which is naturally found only in combination with other elements as a cation with a capacity of +2, such as Dolomite ($\mathrm{Mg}CO_3$), Carnallite ($\mathrm{KMg}Cl_3$), and Epsomite ($\mathrm{MgS}O_4$). Therefore, to achieve its purity it must be produced artificially. At present, this metal is mainly obtained by electrolysis of magnesium salts obtained from brine and is primarily used as an essential component in the production of aluminum-magnesium alloys. In fact, the importance of magnesium is due to its low density compared to aluminum, which in combination with this metal produces light and strong alloys. These alloys are known as magnalium. Most magnesium alloys are made from a combination of this metal (Mg) with others [3] such as Al, Zn, Mn, Si, Cu, Zr, and rare metals, which are divided to cast alloys (i.e., AZ63, AZ81, AZ91, AM50, AM60, ZK51, ZK61, ZE41, etc.) and wrought alloys (i.e., AZ31, AZ61, AZ80, ZK60, M1A, HK31, etc.).

Magnesium alloys have a hexagonal lattice structure that affects the fundamental properties of these alloys. Hexagonal lattice plastic deformation is more complex than cubic crystal metals such as aluminum, copper, and steel. Nowadays, thermomechanical processed Mg alloys are being used. Generally, the name of magnesium alloys is often indicated by two letters and two numbers. For example, AZ91 means a magnesium alloy with 9% aluminum and 1% zinc [4]. In recent years, global demand for magnesium has grown significantly, especially in the automotive and aluminum industries. Additionally, the expansion of steel and aluminum production industries in the Persian Gulf countries and the use of magnesium as a sulfurizing agent in the steel industry has led to increased demand for magnesium in this region. It is predicted that the demand for this metal in the world will reach over 5928.1 million US dollars in 2027, from 4115 million US dollars in 2019 [5]. In short, magnesium alloys in most sectors of industry and human life, including automotive (clutch and brakes, and housing), aerospace (helicopter rotor fittings, wheels, and gearbox), maritime (shore and offshore platforms), commercial (computer housings, hand tools, ladders, and textile machines), and other sectors, have had undeniable influence [6,7]. This element is used to create nodular graphite in cast iron [8]. Furthermore, it can also be used as a galvanic anode (sacrifice) in pipes, boats, and water heaters. Today, magnesium batteries are one of the investment items to produce rechargeable batteries. Due to its low density and desirable mechanical and electrical properties, magnesium is widely used in the manufacture of mobile phones, personal computers and tablets, cameras, and other electronic components. This element can also be used to create flashes in cameras.

Despite these many advantages, this element and its alloys have low corrosion resistance, fatigue properties, and creep strength. The presence of iron, nickel, copper, and cobalt strongly activates corrosion in magnesium alloys [9]. In greater amounts than usual alloys, these metals precipitate as intermetallic compounds, and the deposition sites act as active cathode sites. These sites regenerate water and cause magnesium loss. Obviously, by controlling the amount of these metals, corrosion resistance can be significantly improved. Moreover, adequate manganese can overcome the corrosive effects of iron in these alloys. The addition of a cathodic substance also removes atomic hydrogen from the metal structure. Evidence has shown that the tendency of magnesium to creep declines at high temperatures by adding scandium and gadolinium. In addition, flammability is greatly reduced by a small amount of calcium in the alloy. In addition to the issue of corrosion and creep, attention to resistance to high pressures and cyclic loads are also very important. In other words, magnesium alloys are subjected to multi-input complicated loading depending on the marine conditions, which must be able to withstand these loads at different depths [10,11]. The issue of fatigue failure is also a major challenge in the research of scientists and manufacturers of magnesium alloys because a large part of the applications of magnesium alloys are in moving parts, and it is possible to experience cyclic forces almost wherever there is movement. In this regard, numerous studies have shown that the main cause of failure of industrial parts during operation is the destructive phenomenon of fatigue [12–14]. The fatigue life of a component depends directly on various factors from production to maintenance, and not choosing the right type of material to produce the final product can reduce its service life. It seems that application of novel techniques such as artificial intelligence, genetic algorithms, and fuzzy decision-making methods can be useful to apply new Mg alloys with higher reliability and quality [15–17].

As mentioned, magnesium alloys have a wide range of applications in various sectors of life and industry. However, their structural flaws and shortcomings cannot be ignored. Efforts have been made to improve the quality and reliability of these alloys to deal with adverse conditions. For example, the dynamic marine atmospheric corrosion behavior of AZ31 has been studied [18]. They measured the corrosion rate of alloy after one year in an ocean environment. They also reported the max. depth of corrosion pits. Jiang et al. have studied corrosion behavior of EW75-Mg alloy in the research vessel KEXUE during the ocean voyage [19]. For this purpose, they performed various tests on samples in two directions of extrusion and perpendicular to the extrusion direction. Xie et al. have focused on the effects of different Ca contents on the corrosion behavior of AZ31 alloys based on marine applications [20]. Moreover, Yang et al. have investigated atmospheric corrosion behavior of AZ31 alloy after one year in a harsh marine environment [21]. They also measured and reported the corrosion rate and pit depth. In the current article with a detailed review of the latest research in this field, the most practical and reliable achievements and approaches used to improve the fatigue life and corrosion resistance of the major types of Mg alloys, including AM50, AM60, AZ31, AZ61, AZ80, AZ91, ZK60, and WE43, are presented.

2. A Brief Overview of the Mg Alloys Studied in this Study

Given the composition of Mg alloys, there are more than a dozen magnesium alloys. However, only a few of them have industrial and practical applications and the rest have limited or only laboratory applications. The compositions of Mg alloys discussed in the following are presented in Table 1 to provide better insight into the main elements of each alloy.

Table 1. Composition of main Mg alloys (weight percent).

Elements	Al	Mn	Zn	Si	Ce	Cu	Y	Re	Nd	Zr	Other	Mg
AM60 [22]	6.29	0.28	0.05	0.02	-	-	-	-	-	-	0.0026	Bal.
AM50 [23]	4.70	0.32	0.13	0.03	-	0.004	-	-	-	-	0.0094	Bal.
AZ31 [24]	3.1	0.54	1.05	0.1	-	-	-	-	-	-	0.045	Bal.
AZ61 [25]	6.0	0.34	0.67	0.01	-	0.002	-	-	-	-	0.002	Bal.
AZ80 [26]	8.24	0.20	0.67	0.012	-	-	-	-	-	-	0.0065	Bal.
AZ91 [27]	8.7	0.25	0.65	0.006	-	-	-	-	-	-	0.0045	Bal.
ZK60 [28]	0.001	0.005	5.693	0.008	0.027	0.002	-	-	0.062	0.860	0.008	Bal.
WE43 [29]	-	0.13	0.20	-	-	-	4.16	3.80	-	0.36	-	Bal.

3. Effect of Simultaneous Addition of Aluminum and Magnesium Elements (Mg-Al-Mn)

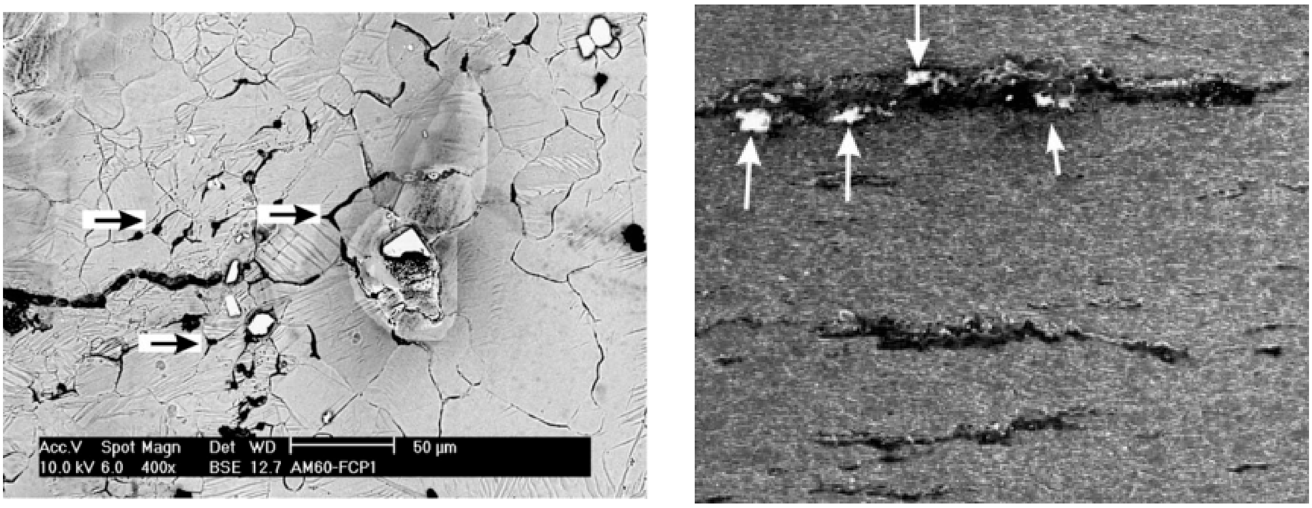
3.1. AM60

This alloy (AM60) has good strength, proper energy-absorbing properties, and great ductility and castability. The main chemical compositions of AM60 alloy are magnesium, aluminum, manganese, zinc, and silicon. The mechanical properties of AM60 magnesium alloy are given in Table 2.

Table 2. Mechanical properties of AM60 magnesium alloy [30].

Properties	Symbol	Unit	Value
Ultimate tensile strength	UTS	MPa	225–240
Yield stress	YS	MPa	130
Elastic modulus	E	GPa	45
Hardness (Brinell)	HB	—-	65

The first discussion about producing any new alloy and material is related to its proper structure and behavior in the face of environmental conditions. In general, improper microstructure and internal defects (microcrack and porosity) greatly reduce the life of the final product depending on the type of loads applied [31]. In summary, the most common methods of improving the quality of microstructure and grain size of AM60 magnesium alloy are thermal treatment [22] and mechanical processes such as the Severe Plastic Deformation (SPD) method [32]. One efficient technique to reduce the weight of automotive mechanical components is the use of AM60 high pressure casting, which is debatable due to internal porosity [33]. The fatigue crack propagation is correlated by the gradual transfer between Intergranular and Transgranular (cleavage) failure mechanisms at the crack tip, which is affected by the plastic zone size and Linear Elastic Fracture Mechanics (LEFM) [34,35]. Figure 1 presents the effect of microstructures on the formation and growth of fatigue cracks through Scanning Electron Microscopy (SEM) observations. In this regard, the presence of oxide inclusions in most metal materials, especially magnesium alloys, can be seen due to the high reactivity of this element, which can reduce the fatigue life of alloy [36].



(a) **(b)**

Figure 1. Influence of microstructure on advent and propagating microcrack "Reused with permission from Elsevier by License No. 5494601058390" [36]; (**a**) The crack tip of extruded AM60 at a high ΔK; (**b**) The macro-cracks near oxide and Al–Mn particles.

It should be noted that the shape and arrangement of the pores are also significant other factors affecting initial and propagation crack. Although it has been declared that surface roughness is not a considerable agent, it is better to do more research to prove this issue [37]. Kadiri et al. have stated that the fatigue crack propagation mechanism of AM60 alloy includes four main stages [38]: 1. incubation, 2. the small crack at the interface of the Al-rich eutectic/dendrite cell, 3. the small crack proceeds within the eutectic, and 4. the long crack formation stage. Figure 2 clearly shows the effects of the size and shape of the pores on the stress concentration and therefore the strain concentration. The larger the pore size, the higher the strain concentration zone [39].

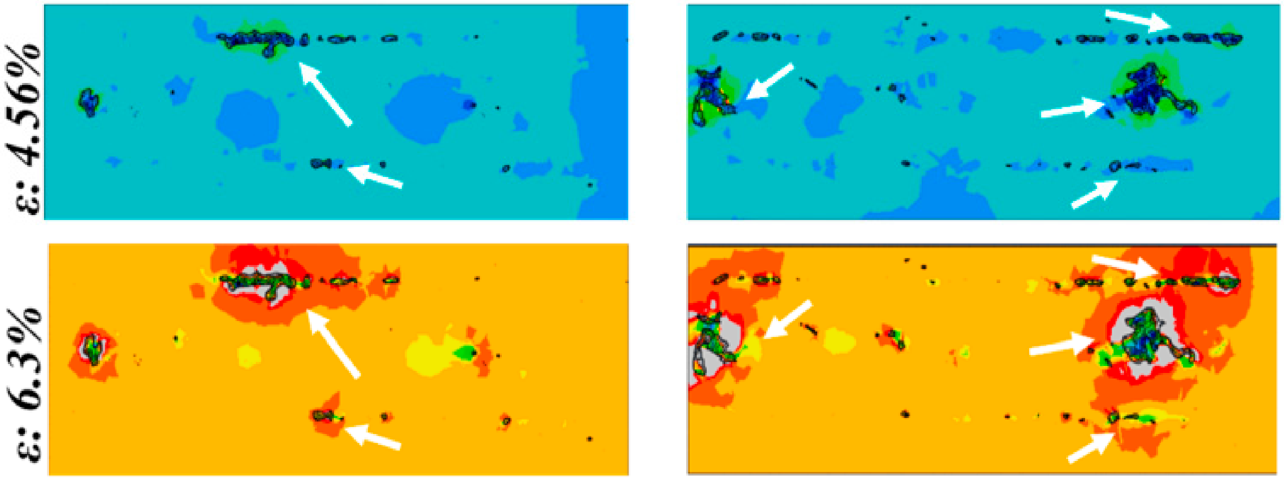


Figure 2. The effects of the pore size and shape on the strain concentration zone "Reused with permission from Elsevier by License No. 5494610474468" [39].

The high-pressure die-cast AM60 Mg alloy is prone to inverse surface macro-segregation under specific process conditions. Indeed, macro-segregation causes initial fatigue cracks on cast surfaces and decreases the alloy life due to the slip incompatibility of brittle intermetallic eutectic components in the macro-segregation regions [40]. One of the proposed techniques to improve the fatigue life and structural characteristics of the AM60 alloy is to use Equal Channel Angular Pressing (ECAP), which reduces grain size and dislocations. However, it should be noted that the effectiveness of this technique depends on the number of passes and the temperature used. For example, studies by Kulyasova et al. and Akbaripanah et al. have found that to gain a more proper microstructure and mechanical behavior, temperature and passes should be set at temperatures below 150 °C and the two passes, respectively (see Figure 3) [41,42]. Additionally, it is stated that only after two passes, UTS of Am60 increases up to 9 MPa. In addition to this progress, the most improvement in both HCF and LCF of the AM60 alloy was gained after two passes of ECAP. Moreover, High-Pressure Torsion (HPT) is also employed to enhance the microstructure, crystallographic texture, and hardness of AM60 magnesium alloy, while $\frac{1}{2}$ turn had better results compared to higher turns [43].

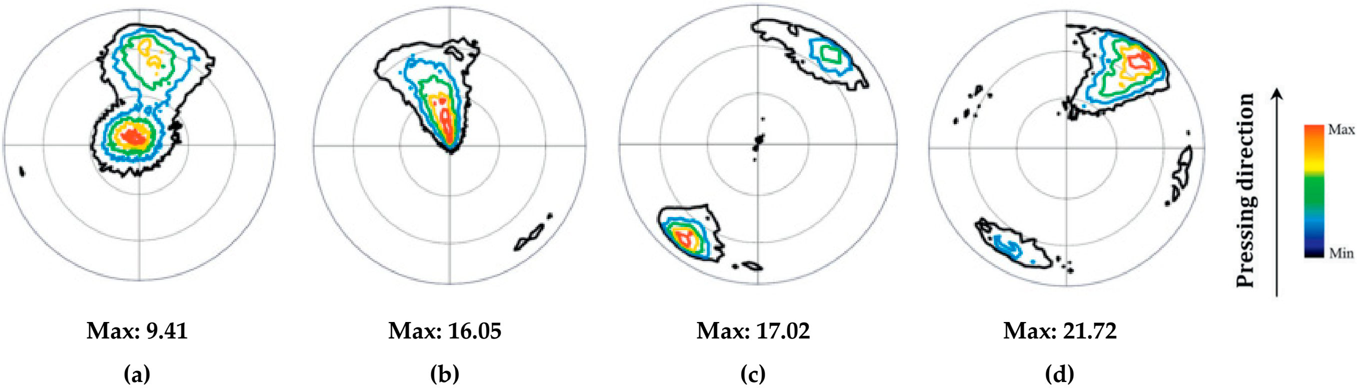


Figure 3. The influences of ECAP technique on texture evolution (pole figures) "Reused with permission from Elsevier by License No. 5494610777006" [42]; (**a**) Extruded; (**b**) 1 pass; (**c**) 2 passes; (**d**) 6 passes.

Environmental and humidity conditions are the serious factors that have a significant impact on reducing the fatigue life and corrosion resistance of AM60 magnesium alloy, which must be considered in design factors [44,45]. In brief, common and practical methods for assessing the corrosion rate of magnesium alloys include Mg ion release measurement, electrochemical methods, weight loss measurement, and hydrogen evolution measurement [46]. As shown in Figure 4, the pH value can have a considerable influence on the fatigue life of AM60 magnesium alloy. Evidence indicates that AM60 alloys in the face of higher pH have greater fatigue life than the lower values. This is due to the formation of stable magnesium hydroxide, which delays hydrogen diffusion and matrix dissolution [47]. In this regard, the anodizing process is recommended for AM60 magnesium alloy with the thickness of 5µm due to fewer internal defects compared to more thicknesses [48].

3.2. AM50

AM50 alloy such as AM60 has good strength, proper energy-absorbing properties, and great ductility and castability. This lightweight alloy is also widely used in high-tech industries, such as electronics, aerospace, and automotive. The main chemical compositions of AM50 alloy are magnesium, aluminum, manganese, zinc, and silicon. The mechanical properties of AM50 magnesium alloy are listed in Table 3.

Although the high fatigue strength and low density of AM50 magnesium alloy can be a proper reason to replace aluminum alloys, some shortcomings such as the tendency for corrosion and creep, reduction in fatigue life in the high-cycle state, and low Young's modulus should not be ignored [50]. Strain amplitude is an influential factor on cyclic stability, hardening, and softening, which its relationship with reversals follow Basquin and Coffin–Manson laws. Moreover, during the Low-Cycle Fatigue (LCF) state, dynamic-strain aging occurs at the total strain amplitude of 1.5 pct, and Transgranular cracks emerge at the surface and then are turned into Transgranular modes [51]. Shrinkage pores are the main sites for the formation of main cracks, in such a way that several cracks form near the shrinkage pores and then propagate, leading to fatigue cracking through the Al-rich eutectic [52]. A serious factor that should be considered about all materials is related to the sensitivity to stress concentration. For example, Marsavina et al. have investigated the effect of stress concentration induced by R-notch and V-notch on fatigue properties of AM50 magnesium alloys [23]. As shown in Figure 5, the fatigue strength has been reduced from 55.85 MPa by 25% and 61.2% for the R-notch and V-notch types, respectively, which indicates the relatively high sensitivity of this alloy to sharp notches [23].

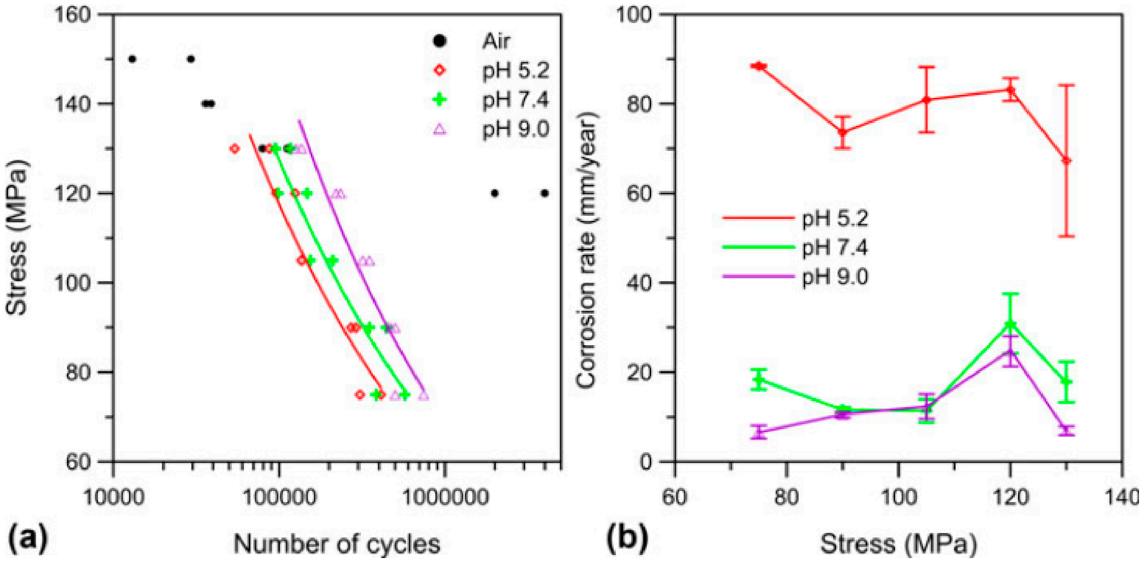


Figure 4. Effect of pH value on the material properties of AM60 magnesium alloy in Phosphate Buffered Saline (PBS) solutions, including (**a**) HCF region of S-N curve, and (**b**) corrosion rate [47].

Table 3. Mechanical properties of AM50 magnesium alloy [49].

Properties	Symbol	Unit	Value
Ultimate tensile strength	UTS	MPa	210–230
Yield stress	YS	MPa	125
Elastic modulus	E	GPa	45
Hardness (Brinell)	HB	—-	60

One proposed method to improve texture quality, mechanical properties, and fatigue characteristics is utilizing the hot rolling process [53]. In addition, researchers' studies and industrialists' experiences indicate that the fatigue properties of metals and alloys with higher tensile strength are better. As a result, there is a direct relationship between the ultimate tensile strength and the fatigue limit (about one half). Based on the results of this research, the best combination of strength and ductility was obtained with a roll speed of 5 m/min and a roll temperature of 200 °C. In addition, the texture and the yield stress depend on roll speed and temperature, respectively [53]. Increasing Ca value can improve formability due to decreasing r-value (the Lankford values extracted from a plastic strain of 10% of deformed samples) and increasing n-value (the strain hardening exponent values obtain from a strain interval from 5% to 15% of tensile tests) [54]. The compressive yield stress of Twin roll cast commercial AM50 magnesium alloy is about 70% of its tensile yield stress caused by the firm basal texture. In addition, the Rolling Direction (RD) has a higher fatigue toughness than the Transverse Direction (TD) due to 54% more tensile elongation [55]. Figure 6 presents the effect of temperature on the fatigue life of cast AM50 magnesium alloy, which has an inverse impact. Generally, at temperatures close to

100 degrees, cleavage fracture of Mg-dendrites and α-Mg grains occurs, while for higher temperatures, the small fatigue cracks cleave the Mg grains, which were smoothened due to the high temperature [56].

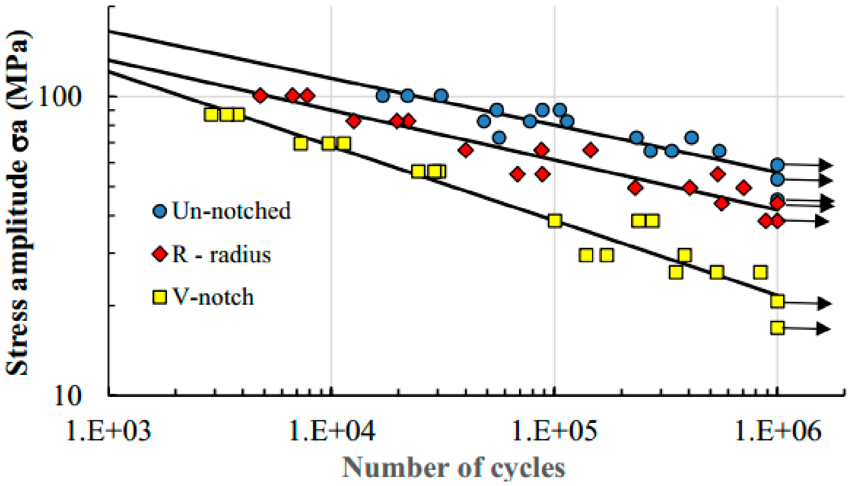
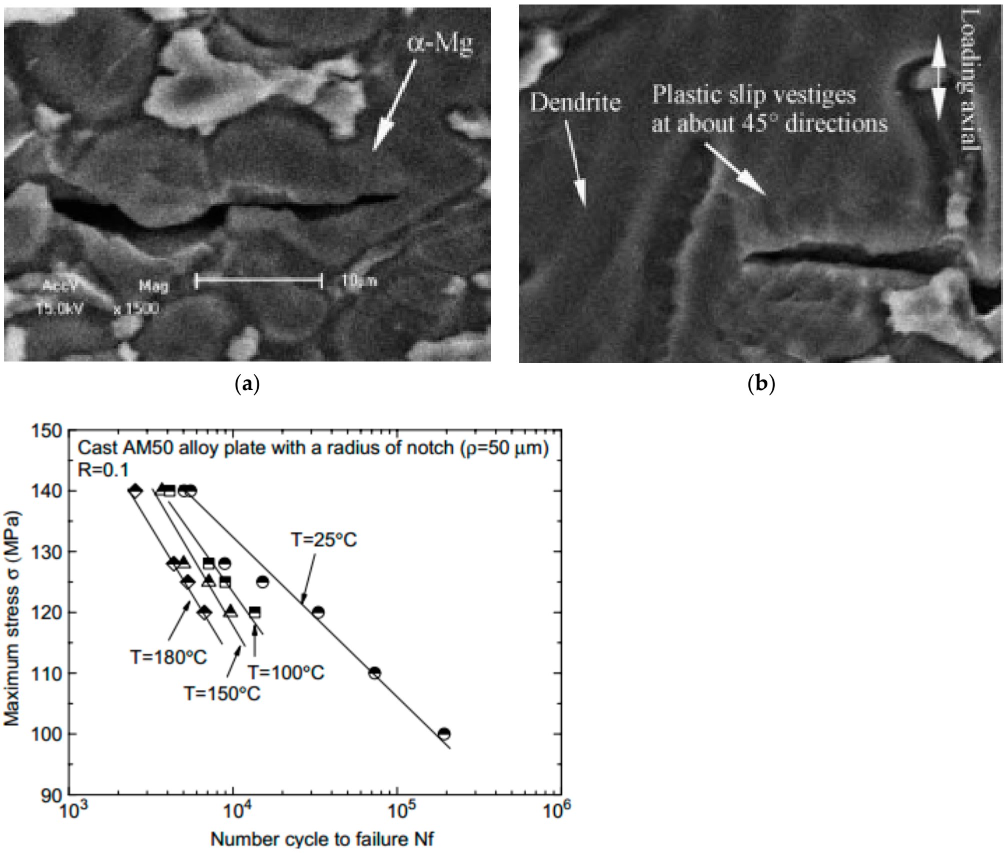


Figure 5. Comparison of S-N curve as HCF behavior of AM50 magnesium alloy considering different notch shapes "Reused with permission from Elsevier by License No. 5494611488014" [23].



(**a**) (**b**)

(**c**)

Figure 6. Effects of different temperatures on fatigue characteristics of AM50 magnesium alloy "Reused with permission from Elsevier by License No. 5494620116925" [56]. (**a**) SEM image of fatigue crack tip at σ_{max} = 128 MPa, T = 150 °C 8C, N = 4109; (**b**) SEM image of plastic slip vestiges near crack tip at σ_{max} = 125 MPa, T = 150 °C 8C, N = 5819; (**c**) S–N curves of cast AM50 magnesium alloy in different temperatures.

4. Effect of Simultaneous Addition of Aluminum and Zinc Elements (Mg-Al-Zn)

Zinc is a rare but essential element for the human body. It is reported that the addition of 1–6 wt% of Zn to pure magnesium can change static properties, such as yield stress and ultimate tensile strength. In this regard, Zhang et al. have stated that the maximum UTS is obtained when zinc is kept up to 4% by the weight [57]. Nevertheless, in a review article published in 2022, Istrate et al. have showed that the relationship between the percentage of zinc added to magnesium and the change in yield stress and ultimate tensile strength is not direct and linear [58]. For example, the yield stress in magnesium alloy with 7% zinc is lower than the yield stress in magnesium alloy with 5% zinc. Moreover, they investigated the corrosion properties of this alloy in different environments as anodic, cathodic, or compound reactions. In this way, they focused on biocorrosion, and the practical target for that was dental implants. In addition, they compared the corrosion rate in magnesium alloys with different percentages of calcium. However, much research has not been completed in the field of fatigue behavior of this alloy (i.e., Mg-Ca), so it is avoided to deal with it separately. The focus of this section is dedicated to adding different percentages of aluminum and zinc elements to pure Mg.

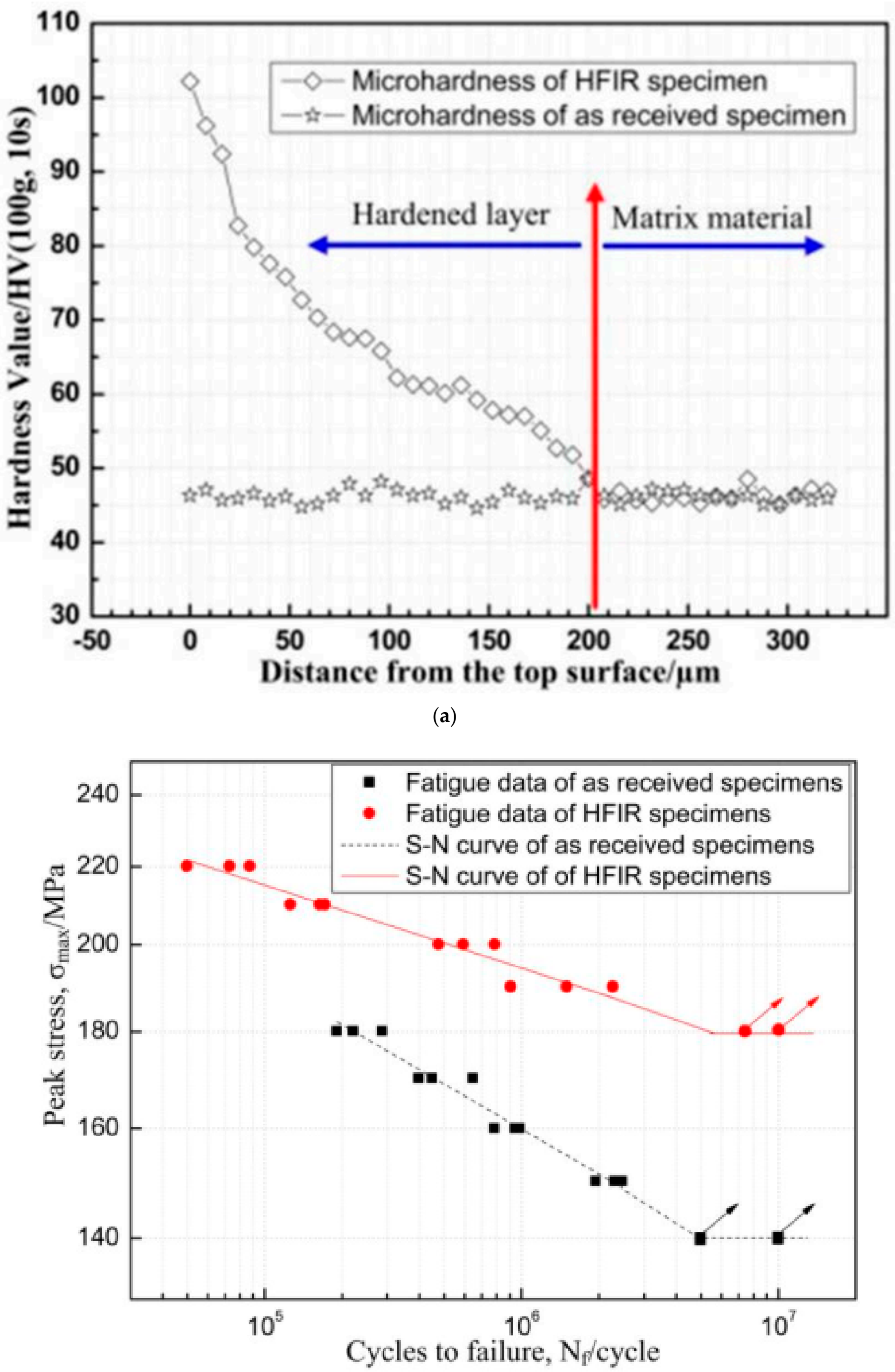
4.1. AZ31

AZ31 alloys have proper machinability and light weight, and while they are prone to corrosion, they are anodized to avoid this phenomenon. The main chemical compositions of AZ31 alloy are magnesium, aluminum, zinc, manganese, and silicon. The mechanical properties of AZ31 magnesium alloy are given in Table 4.

Table 4. Mechanical properties of AZ31 magnesium alloy [59].

Properties	Symbol	Unit	Value
Ultimate tensile strength	UTS	MPa	260
Yield stress	YS	MPa	200
Elastic modulus	E	GPa	44.8
Hardness (Brinell)	HB	—-	49

Looking at recent research, it can be seen that recent studies have gone toward exploring the effects of microstructure on AZ31 magnesium alloy behavior and how they can modify their structure to promote the performance of AZ31magnesium alloy. Nakai et al. have found that twinning and detwinning play main roles on the AZ31 magnesium alloy [60]. They stated that twinning occurs under both types of microstructures, including texture and random orientation, if the compressive stress is greater than the compressive yield strength, while detwinning occurs only in the texture structure if tensile stress is less than the tensile yield strength. Fatigue Crack Growth (FCG) is accelerated due to the appearance of tensile twins made by the compression side of $R = -1$. In other words, as was mentioned when the maximum compressive stress exceeds the compressive yield strength, the velocity of fatigue crack growth is also increased [61]. Additionally, cyclic hardening is increased during fatigue caused by the increase in the dislocation density. Moreover, the increase in the total strain amplitude can cause twinning effects to be prevalent, leading to saving more energy at higher total strain amplitudes [62]. The High-Frequency Impacting and Rolling (HFIR) process showed significant results in increasing microhardness and fatigue life of AZ31 magnesium alloy so that it could increase the fatigue life by 28.6%, as demonstrated in Figure 7 [63].



(**a**)

(**b**)

Figure 7. The impacts of HFIR on the material properties of AZ31 magnesium alloy "Reused with permission from Elsevier by License No. 5494620245825" [64]. (**a**) The cross-sectional microhardness of as-received and HFIR samples; (**b**) S-N curves of as-received and HFIR samples.

Anes et al. have found that the stress scale factor can be a useful method to estimate the fatigue life of AZ31 B-F, and they proposed a threshold model for assessing safe or unsafe states under proportional loading conditions (Figure 8) [24]. Moreover, Equation (1) was used to calculate the safety factor of the AZ31B-F magnesium alloy based on the proportional loadings, where λ is stress amplitude ratio and σ_a is the normal stress amplitude.

A summary of achievements and approaches related to the AZ31 magnesium alloys are presented in Table 5.

$$n = \frac{96.29 - 67.9 \times \lambda}{\sigma_a} \quad (2)$$

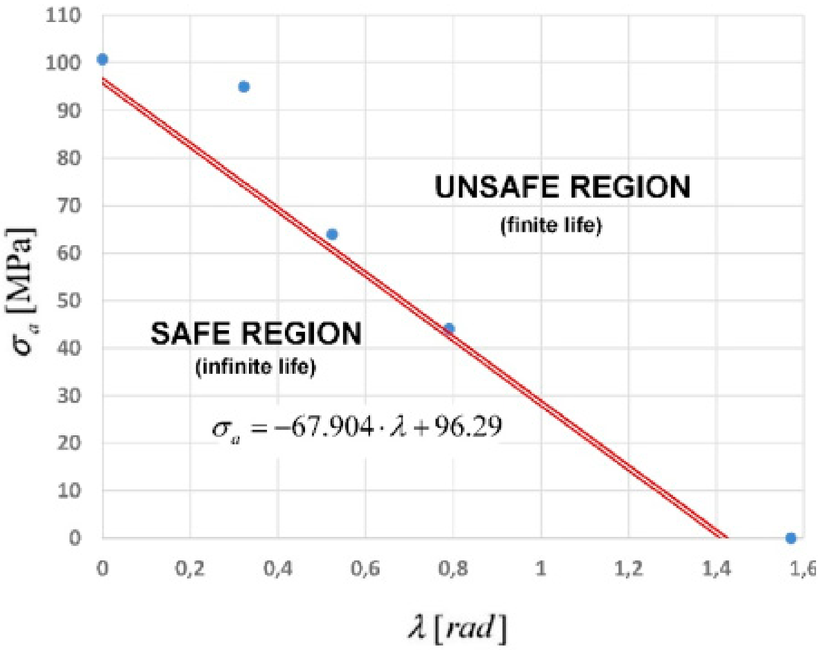


Figure 8. The threshold model to identify the safe region of AZ31B-F magnesium alloy based on the proportional loading conditions [24].

Table 5. The summary of novel research on the AZ31 magnesium alloys.

Author	Year	Method	Results
Jamali et al. [64]	2022	- Analysis of the deformation and crack initiation mechanisms - Fully-reversed, strain controlled cyclic deformation along the rolling direction after 50 cycles	1- Distinct deformation bands were found in more than one out of four grains due to tensile twins or pyramidal slip. 2- Cracking has occurred in large grains caused by Transgranular cracks parallel to the pyramidal slip bands or twin boundaries.
Kim et al. [65]	2022	- LCF properties of AZ31 sheets with different thicknesses - Twin-roll casting and subsequent hot rolling and fully reversed strain-controlled fatigue tests	1- Tensile yield strength and texture intensity increase by decrease in the thickness of the sheet. 2- In-plane isotropic fatigue properties. 3- Total strain energy density is a proper fatigue damage parameter for predicting fatigue life.
Guo et al. [66]	2021	- Fatigue performance evaluation based on self-heating	1- A new fatigue limit assessment method has been proposed based on the statistical analysis of self-heating data.
Yamada et al. [67]	2021	- Equal-Channel Angular Pressing (ECAP)	1- The efficiency of ECAP on fatigue life depends on the value of stress amplitude. 2- Strength is more efficient than ductility to improve fatigue life.
Nischler et al. [68]	2021	- Fatigue behavior of hot-bent	1- A novel uniaxial hot-bent specimen. 2- The texture was changed. 3- Increase in the Schmid factor. 4- Observations of Macroscopic bands of twinned grains due to tension twins even in compression tests of the hot-bent specimens.

Table 5. *Cont.*

Author	Year	Method	Results
Guo et al. [69]	2020	- Infrared thermography - Utilizing data processing method to compensate the temperature rise of the fixture	1- AZ31 magnesium alloy had undergone cyclic hardening during fatigue phenomenon. 2- A special thermal model has been proposed that can estimate the fatigue limit.
Lei et al. [70]	2021	- The uniaxial ratcheting-fatigue interaction - The influences of stress level and stress rate	1- The compressive ratcheting will occur in the whole-life cycles. 2- The effect of stress rate on the whole-life ratcheting depended on the mechanism that controls the plastic deformation. 3- Reduction in the fatigue life occurs during the asymmetric stress-controlled cyclic deformation by the ratcheting deformation.
Yang et al. [71]	2018	- The relationship between microstructure and tensile behaviors	1- Twinning−detwinning was the main deformation mechanism. 2- Decrease in the average grain size after fatigue test.
Meng et al. [72]	2019	- The effect of precompression along the extrusion direction	1- Decrease in the tensile yield strength rapidly after applying precompression. Moreover, the ultimate tensile strength is increased with the rise of precompression deformation.
Srivatsan et al. [73]	2012	- Effects of nanoparticles of aluminum oxide and micron size nickel particles	1- The elastic modulus, yield strength, and ductility were increased.
Wang et al. [74]	2012	- The effects of zirconate and phosphate chemical liquids	1- This method can reduce the stress-intensity factor and the fatigue crack growth rate. 2- The zirconate liquid was more effective than phosphate liquid.

Another way to prevent corrosion of AZ31 magnesium alloy, except for anodizing, is to use the top coating. Shaha et al. have studied the influence of the Cold Spray (CS) process (AA7075 powder) and Electrostatic Painting (EP) on the corrosion resistance of AZ31 B Cast Mg Alloys in presence of 3.5% NaCl solution. From Figure 9, a combination of the cold spray and electrostatic painting (CS + EP) improves the fatigue life of the sample, under load of 80 MPa, up to 10^7 cycles [75].

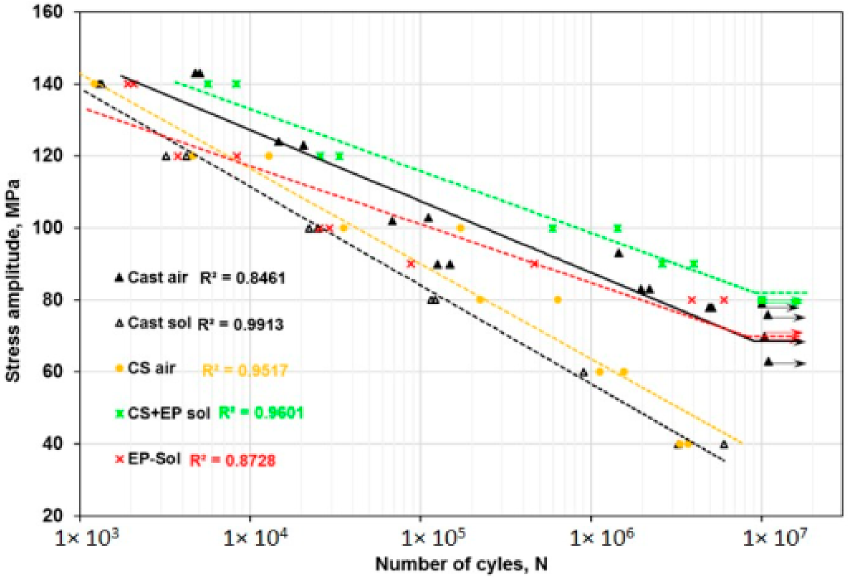


Figure 9. Effects of coating process on the corrosion resistance of AZ31 magnesium alloy [75].

4.2. AZ61

AZ61 alloys have excellent machinability and lightweight castability, while they are like AZ31 alloys, prone to corrosion, which are anodized to avoid this phenomenon. The main chemical compositions of AZ61 alloy are magnesium, aluminum, zinc, manganese, and silicon. The mechanical properties of AZ61 magnesium alloy are presented in Table 6.

Table 6. Mechanical properties of AZ61 magnesium alloy [76].

Properties	Symbol	Unit	Value
Ultimate tensile strength	UTS	MPa	310
Yield stress	YS	MPa	230
Elastic modulus	E	GPa	44.8
Hardness (Brinell)	HB	—-	60

This alloy is used in the automotive industry, especially in load-bearing constituents, due to its considerable strength and light weight. However, it is very important to study the behavior of this alloy under cyclic loading. In a study performed on wrought AZ61 magnesium alloy, it was reported that cracks appear at the surface and slip bands [77,78]. In these alloys, Mn content must be controlled, otherwise, for a high Mn content state, Al–Mn intermetallic inclusions may be formed, leading to the decrease in fatigue strength [79]. There are several types of surface treatment methods to improve the quality and fatigue life of magnesium alloys. An examination was completed on surface treatments of barrel processing, micro-peening, and shot peening to identify the superior method. As illustrated in Figure 10, shot peening was found to reduce the fatigue life of AZ61 magnesium alloy by up to 30% due to high surface defects and roughness, while barrel processing and micro-peening improved the life by up to 15% [80].

Uematsu et al. have found that Fatigue Crack Propagation (FCP) rate is primarily affected by the level of humidity and hydrogen embrittlement, whereas the anodic dissolution is at the second stage [81]. It should be considered that hydrogen diffusion itself depends on the stress intensity factor range (ΔK) and humidity. The effect of coatings can be beneficial or detrimental on AZ61 magnesium alloy, depending on their reaction with substrate. This fact can be deduced from the results of a study executed by Huang et al. [82]. Figure 11 shows Ni-Cu coated samples have lower Low-Cycle Fatigue (LCF) resistance than Cu or with alkaline states followed by acidic Cu due to the induced high residual tensile stress [82]. A summary of achievements and approaches related to the AZ61 magnesium alloys are presented in Table 7.

Table 7. The summary of novel research on the AZ61 magnesium alloys.

Author	Year	Method	Results
Huang et al. [83]	2021	- Effects of different values of micro-silicon carbide (m-SiC) particles on the mechanical and fatigue properties - The homogenization heat treatment	1- m-SiC particles led to improve Yield Strength (YS) and Ultimate Tensile Strength (UTS). 2- The increase in m-SiC particles makes the fatigue strength decrease.
Jain et al. [84]	2017	- Study of fatigue behavior using Nano indentation - Aged and solution treated conditions	1- Cyclic hardening occurred in the aged case. 2- Slip lines and twins appeared in the solution treated case.
Kakiuchi et al. [25]	2015	- The effect of hydrogen on Fatigue Crack Propagation (FCP)	1- The hydrogen increased FCP rates compared to air condition. 2- The acceleration of the FCP can be related to hydrogen embrittlement and diffusion.

Table 7. *Cont.*

Author	Year	Method	Results
Němcová et al. [85]	2014	- Impact of Plasma Electrolytic Oxidation (PEO) on the fatigue life	1- Reduction in fatigue life by 38% and 56% in the presence of air and NaCl, respectively.
Hwang et al. [86]	2013	- Samples reinforced with Silicon Carbide particles (SiCp)	1- Higher tensile strength and hardness. 2- The smaller grain size.
Bhuiyan and Mutoh [87]	2011	- Conversion coated and painted AZ61 magnesium alloy - Various corrosive environments	1- The remarkable effect of the coating and painting layer to enhance corrosion in counter with high humidity and NaCl environments.
Kakiuchi et al. [88]	2011	- Effect of film elastic modulus on fatigue life	1- Diamond-Like Carbon (DLC) film improved the fatigue strength. 2- Cracks originated near the boundary of DLC film and base metal.
Jordon et al. [89]	2011	- Effects of twinning, slip, and inclusions - MultiStage Fatigue (MSF) model	1- The extrusion direction of AZ61 magnesium alloy had higher yield strength, Taylor factor, and fatigue life than the extrusion transverse direction because the extrusion transverse direction has the low Critical Resolved Shear Stress (CRSS) for basal slip activation. 2- The particle size is more important than the anisotropy to evaluate the number cycles.
Zeng et al. [90]	2009	- The impacts of the artificial ageing heat treatment and loading frequency on Fatigue Crack Propagation (FCP)	1- Reducing the loading frequency caused to increase the FCP rate. 2- The FCP velocity is facilitated by the artificial aging heat treatment.

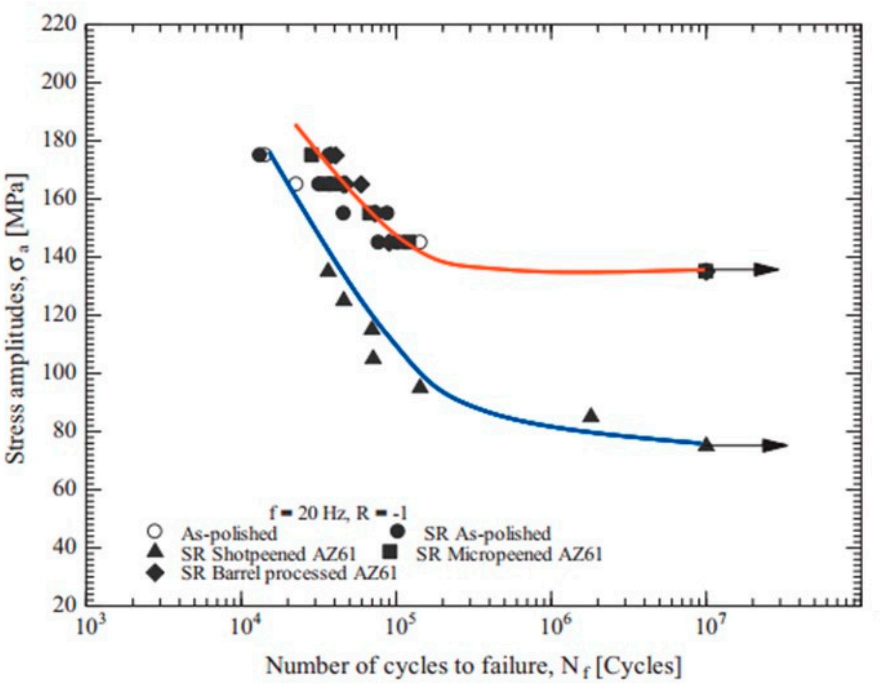


Figure 10. S–N curve of mechanical surface stress relieving treated AZ61 specimen "Reused with permission from Elsevier by License No. 5494631235674" [80].

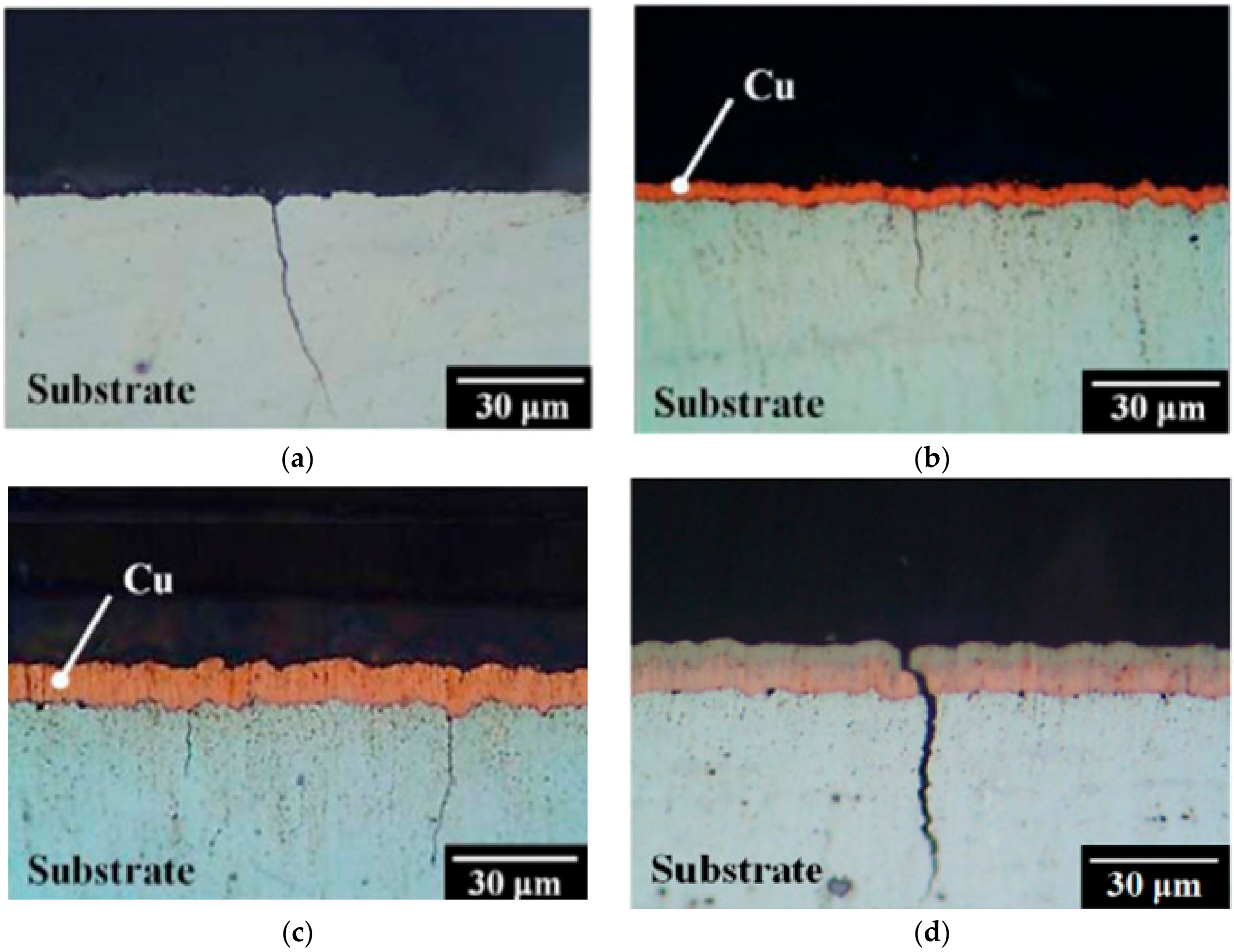


Figure 11. LCF fracture behavior of Mg alloy after (**a**) uncoated AZ61 specimen, (**b**) alkaline Cu-, (**c**) alkaline followed by acidic Cu-, and (**d**) Ni-Cu "Reused with permission from Elsevier by License No. 5494631394332" [82].

4.3. AZ80

AZ80 alloys have excellent machinability, lightweight castability, while they are like other AZ alloys, prone to corrosion, which are anodized to avoid this phenomenon. The main chemical compositions of this alloy are magnesium, aluminum, zinc, manganese, and silicon. The mechanical properties of AZ80 magnesium alloy are listed in Table 8.

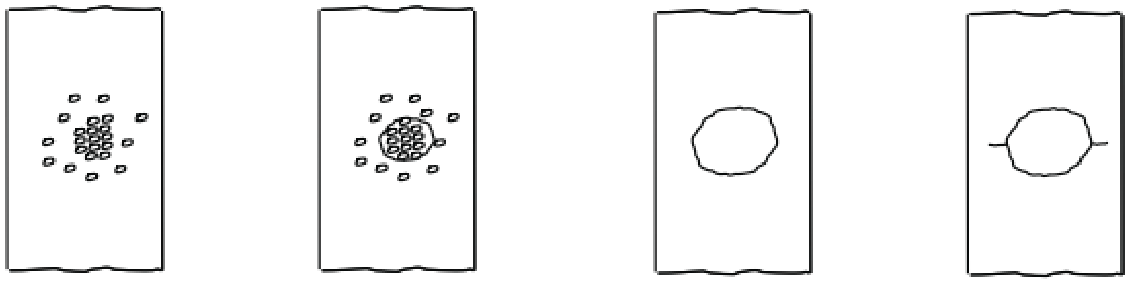
Table 8. Mechanical properties of AZ80 magnesium alloy [91].

Properties	Symbol	Unit	Value
Ultimate tensile strength	UTS	MPa	380
Yield stress	YS	MPa	275
Elastic modulus	E	GPa	44.8
Hardness (Brinell)	HB	—	82

Like other research that has been carried out on previous alloys, scholars have made efforts to explore a better understanding of AZ80 magnesium alloy behavior under diverse conditions, to provide practical solutions for improving the quality and fatigue life of these alloys. A fairly comprehensive study has been conducted by Xiong and Jiang to examine the effects of orientations on the fatigue crack growth and fatigue life of rolled AZ80 magnesium alloy [92]. The results showed the cyclic hardening behavior under fully reversed strain-controlled loading conditions for all specimens considering different orientations, including

90° (RD, rolled direction), 60° (ND60), 30° (ND30), and 0° (ND, normal direction). In addition, twinning–detwinning and dislocation slips are the main factors of cyclic plastic deformation in high and low strain amplitudes, respectively. Additionally, the ND samples had the lowest fatigue life compared to other types, while ND30 and ND60 samples showed the same behavior and more than RD samples. The Equal Channel Angular Pressing (ECAP) with two passes causes the highest yield strength, ultimate strength, and fatigue life, while more passes caused to a decrease in fatigue life, though the grain size increases. Moreover, the ECAP enhances the ductility and crack growth resistance of AZ80 magnesium alloy [93]. Experimental observations have shown that both lower frequency and bigger stress ratio increase fatigue crack propagation [94]. The influence of Shot Peening (SP) treatment on the fatigue life of notched samples showed that the optimum shot peening mode (high Almen intensities) boosted the fatigue life by about 60% (45 to 110 MPa) [95]. In addition, Zhang et al. have reported that the high roughness and surface defects due to shot peening treatment had little impact on the notched fatigue strength of the AZ80. One of the known weaknesses of AZ alloys is their sensitivity to adverse and corrosive environments.

The documentation indicates that the fatigue life of AZ80-T5 magnesium alloy is reduced by about 78% under 5% NaCl environment, due to the formation of corrosion pits on the sample surface and then rapid propagation of the initial cracks, even at low stress amplitudes (corrosion pit formation is depicted schematically in Figure 12) [26]. A summary of achievements and approaches related to the AZ80 magnesium alloys are presented in Table 9.



Nucleation of multiple corrosion pits

Coalescence of corrosion pits in dense region

Coalesced pit growth to critical size

Nucleation of fatigue crack from the critical pit

Figure 12. Schematic of the corrosion pit formation and crack growth of AZ80-T5 under 5% NaCl environment "Reused with permission from Elsevier by License No. 5494640105339" [26].

Table 9. The summary of novel research on the AZ80 magnesium alloys.

Author	Year	Method	Results
Gryguć et al. [96]	2021	- Different forging temperatures	1- Strain Energy Density (SED) was a proper fatigue damage parameter because was less sensitive to the changes of yield strength due to texture-induced anisotropy in the forging process.
Zhao et al. [97]	2021	- The effects of precipitates and aging treatments on low-cycle fatigue	1- Aging treatments improved the hardness by about 20%. 2- The T5 (direct-aging treatment) treatment was more effective than T6 (solution + aging treatment) in terms of compression and tension yield strength.

Table 9. *Cont.*

Author	Year	Method	Results
Gryguć et al. [98]	2020	- Consideration of multiaxial and proportional loading	1- The non-proportionality in multiaxial loading is destructive for the fatigue life, while the impact of proportionality is just on the shear response. 2- Along the plane of maximum normal stress, the pure axial cracking behavior is dominated by transverse cracks.
Zhao et al. [99]	2020	- Disc and rim samples of the extruded AZ80 automotive wheel - Strain controlled fatigue tests	1- Rim samples have slightly better mechanical properties compared to the disc samples. 2- Increasing the strain amplitude caused to rise the activation of twinning and detwinning.
Gryguć et al. [100]	2018	- The effects of microstructure/texture and thermo-mechanical history	1- Strain energy density is an appropriate parameter to predict the fatigue damage. 2- The cast-forged and extruded-forged showed an increase in fatigue life.
Huo et al. [101]	2017	- Effects of cyclic torsion and low-temperature annealing	1- The tensile and compressive yield stresses rose with the increase in grain refinement. 2- The cyclic torsion and low-temperature annealing enhanced fatigue strength by 70% (70 to 120 MPa).
Zhang and Lindemann [102]	2005	- The effect of roller burnishing	1- The optimum condition could enhance fatigue life by 110%.

4.4. AZ91

AZ91 alloys are the lightest type among the AZ group and have excellent corrosion resistance, strength, and castability. The main chemical compositions of AZ91 alloys are magnesium, aluminum, zinc, manganese, and silicon. The mechanical properties of AZ91 magnesium alloy are shown in Table 10.

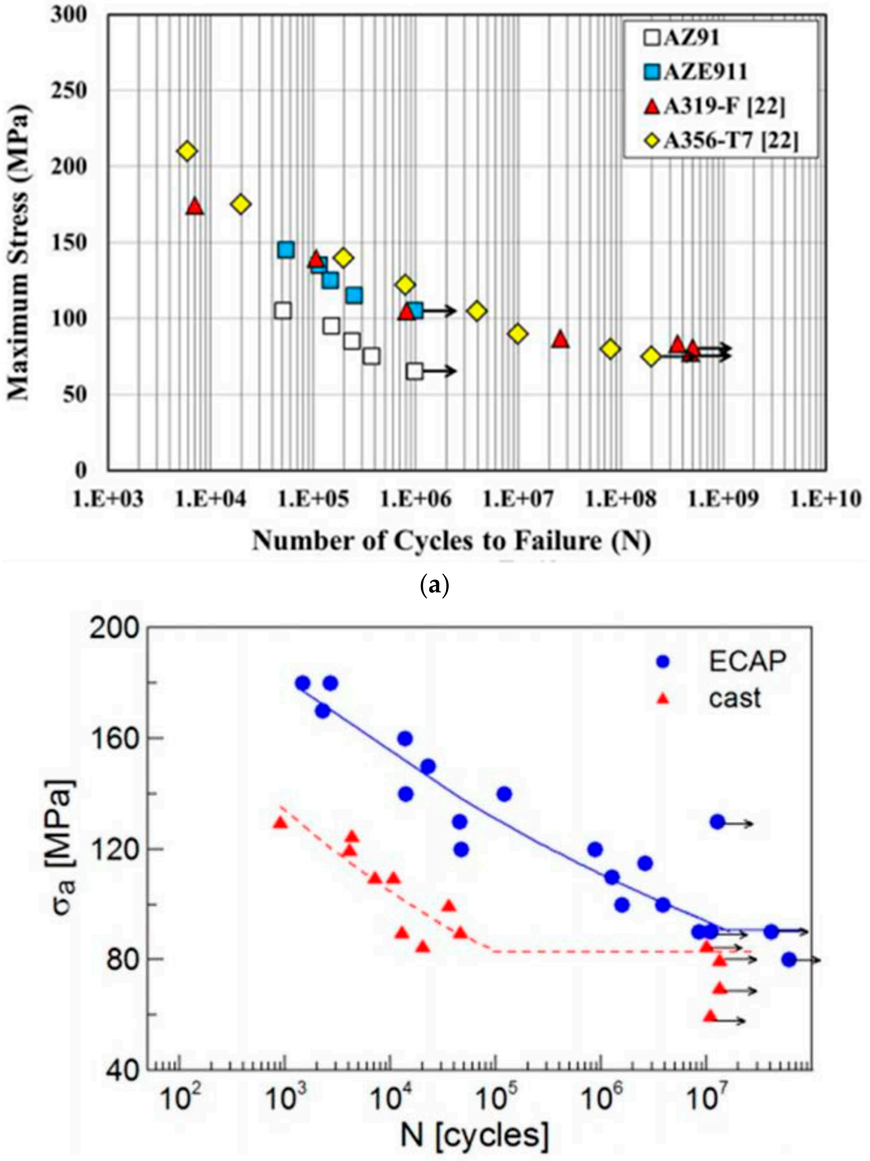
Table 10. Mechanical properties of AZ91 magnesium alloy [103].

Properties	Symbol	Unit	Value
Ultimate tensile strength	UTS	MPa	240–250
Yield stress	YS	MPa	160
Elastic modulus	E	GPa	45
Hardness (Brinell)	HB	—-	63

Addition or modification of the secondary elements' content is an active part of the Research and Development (R&D) process to present former Mg alloys with superior mechanical behavior and quality. For example, Rare-Earth Elements (REE) are the secondary elements that can be added to the AZ91 magnesium alloys (1 wt% RE) to turn into AZE911. This change can increase fatigue life by about 40%, while this amount of RE did not have a significant effect on hardness and ultimate tensile strength, as illustrated in Figure 13a [104]. The use of alumina fiber (Saffil) can be useful to increase the elastic modulus, yield strength, fatigue strength, and fatigue crack initiation resistance due to the rise of the volume fraction of fiber [105]. The artificial cooling method is another useful mechanical treatment to increase tensile and compressive strength and fatigue life due to grain size reduction and increase in $Mg_{17}Al_{12}$ amounts [106]. In addition, Severe Plastic Deformation (SPD) is one of the methods that has shown good results in some magnesium alloys. Fintová and Kunz have reported that using Equal Channel Angular Pressing (ECAP) have a significant effect on the ductility, yield, and tensile strength of AZ91 magnesium alloys [107]. In this regard, fatigue life increased due to ECAP (6 passes and T = 300 °C) in LCF regime. However, this method did not have a significant impact on lifetime in the HCF regime, as shown in Figure 13b. In addition to the mechanical properties of alloys that have been influenced by the type of coating, the process of applying coatings also has a serious impact (e.g., cold-sprayed NiCrAl coating performed better than plasma-sprayed NiCrAl coatings in terms of hardness, wear resistance, and corrosion resistance [108]). A summary of achievements and approaches related to the AZ91 magnesium alloys are presented in Table 11.

Table 11. The summary of novel research on the AZ91 magnesium alloys.

Author	Year	Method	Results
Ahmadian and SallakhNiknezhad [109]	2021	- Effect of shot peening treatment on corrosion properties	1- Improvement of corrosion resistance.
Fintová et al. [27]	2021	- Mechanisms of the fatigue crack initiation	1- Slip markings were crack initiation sites. 2- There was a direct relation between the size and number of slip stress amplitude.
Anandan and Ramulu [110]	2020	- Effects of surface conditions on fatigue life under various machining conditions	1- The higher feed rate of machining (1 µm) caused higher surface roughness and to create voids on the surface. 2- The feed rate of 0.1 mm/rev showed the highest fatigue life.
Azadi et al. [111]	2014	- Thermo-mechanical fatigue (TMF) - Low-Cycle Fatigue (LCF) at different temperatures	1- Cyclic hardening behavior occurred. 2- The higher temperature caused the alloy to have a brittle fracture. 3- LCF at high temperature had higher lifetime than LCF at the room temperature.
Lin et al. [112]	2013	- Uniaxial LCF failure behavior of hot-rolled AZ91	1- The fatigue life increased by increasing and decreasing the stress ratio and the peak stress, respectively. 2- A modified Basquin model is presented to evaluate fatigue life of AZ91 alloys.
Chen et al. [113]	2013	- Uniaxial asymmetric stress-controlled cyclic loading	1- Cracks started from the surface. 2- The fatigue life increased by increasing and decreasing the stress ratio and the peak stress, respectively. 3- The stress ratio and peak stress affected twinning deformation mechanism and the stress intensity factor range.
Korzynski et al. [114]	2011	- Influence of turning and dynamic bearing ball peening on the surface condition and fatigue life	1- The fatigue strength improvement due to compressive stress and surface hardening by ball peening.
Ishihara et al. [115]	2010	- Effects of defect-sizes in the diecast AZ91 magnesium alloy	1- Defects inside diecast AZ were the origin of crack initiate. 2- Distributions of the sizes and densities for defects in diecast AZ were presented.
Murugan et al. [116]	2009	- Impact of transverse load on the HCF behavior of low-pressure cast AZ91	1- Pores were places for emerging cracks. 2- The fatigue life of the transversely loaded low-pressure cast AZ91 samples were higher than the gravity cast samples.



(a)

(b)

Figure 13. Effectiveness of various methods (REE and ECAP) to improve the fatigue life of AZ91 magnesium alloys "Reused with permission from Elsevier by License No. 5494640246452" [104]. (**a**) Effects of REE on fatigue life; (**b**) Effect of ECAP on fatigue life.

5. Effect of Simultaneous Addition of Zinc and Zirconium Elements (Mg-Zn-Zr)

ZK60 alloys have proper machinability and light weight, and while they are prone to corrosion, they are anodized to avoid this destructive phenomenon. The main chemical compositions of ZK60 alloy are magnesium, zinc, and zirconium. The mechanical properties of ZK60 magnesium alloy are given in Table 12.

Table 12. Mechanical properties of ZK60 magnesium alloy [117].

Properties	Symbol	Unit	Value
Ultimate tensile strength	UTS	MPa	365
Yield stress	YS	MPa	305
Elastic modulus	E	GPa	44.8
Hardness (Brinell)	HB	—-	88

The presence of Cerium (Ce) is one of the main differences of ZK60 magnesium alloys from previous ones. The effect of Ce value on ZK60 magnesium alloys characteristics has been investigated [118]. It was found that this element causes more fine crystal grains and increases tensile strength, while elongation increases first, and when Ce value exceeded 0.94%, decreased. As mentioned earlier, SPD processes such as Multiaxial Isothermal Forging (MIF) affects significantly toward improving fatigue life in both low-cycle and high-cycle states [119]. Investigating the behavior of ZK60 magnesium alloy under fatigue loading greatly helps to predict and reduce the possibility of sudden failure. Xiong and Jiang have claimed that at tension mode and strain less than 3.0%, the fatigue phenomenon occurs, including crack initiation, small crack growth, and final failure [120]. Albinmousa et al. have tried to identify comprehensively the fatigue cracks behavior of V-notched ZK60 magnesium samples using X-ray tomography (Figure 14), and to provide a relationship between the number of cycles and the crack surface area, which was a power relationship [121]. ZK60 magnesium alloys under adverse environmental conditions are prone to rapid failure, such as AZ alloys. A summary of achievements and approaches related to the ZK60 magnesium alloys are presented in Table 13.

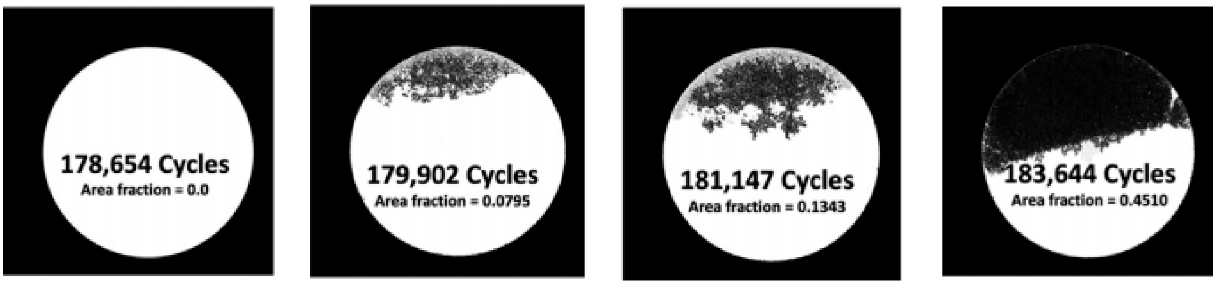


Figure 14. Area fraction of projected crack surface by utilizing X-ray tomography for sample HCF-ZK60-V20 "Reused with permission from Elsevier by License No. 5494640591175" [121].

Table 13. The summary of novel research on the ZK60 magnesium alloys.

Author	Year	Method	Results
Xiong et al. [122]	2022	- Influence of pre-corrosion on fatigue life of modified ZK60 magnesium alloy	1- A total strain energy model was proposed to predict fatigue life of modified ZK60. 2- β parameter was proposed to express the correlation between fatigue life and the cyclic deformation mechanism. 3- When twinning-detwinning dominated cyclic deformation, the fatigue life decreases by increasing the β parameter.
Xiong and Yu [123]	2022	- Effects of surface treatment methods	1- Residual dislocation-retwining, dislocation slip, residual twins-dislocation slip interaction, and dislocation slip are the main reasons of the ratcheting deformation under various loading conditions.
Liu et al. [124]	2021	- Impacts of different loading environments on fatigue life	1- Various loading environments significantly affect fatigue life and the failure mode.
Meng et al. [125]	2020	- Effects of phase difference and stress ratio	1- The mechanism is wavy-slip for various phase and conditions.
Morri et al. [126]	2020	- Influence of plasma electrolytic oxidation	1- The plasma electrolytic oxidation caused to reduce fatigue strength by about 15%.
Albinmousa [127]	2021	- Notch effect on ZK60 Magnesium alloys	1- The Strain Energy Density (SDE) approach is a practical and reliable method to evaluate fatigue life. 2- It is stated that the notch geometry affects fatigue life.

Table 13. *Cont.*

Author	Year	Method	Results
Pahlevanpour et al. [128]	2019	- The anisotropic fatigue behavior of extrusion (ED) and radial (RD) directions	1- ED had higher fatigue strength than RD due to lower plastic strain energy.
Pahlevanpour et al. [129]	2018	- Effects of different directions of ZK60 extrusion	1- Twin lamellae and profuse twinned grains dominated extrusion direction (ED). 2- Slip bands dominated the radial direction (RD). 3- The quasi-static behaviors were dissimilar for various directions, while the cyclic behavior in LCF regime was dependent on direction.
Karparvarfard et al. [130]	2019	- Influences of cast and cast-forging on ZK60 magnesium alloys	1- Cast-forged samples had higher fatigue strength. 2- The Persistent Slip Bands (PSB) and intermetallic were the main places of crack initiation at high cycle fatigue state.
Chang et al. [131]	2016	- Impact of thin film metallic glass	1- The W-TFMG coating enhances fatigue life by approximately 4 times. 2- The Z-TFMG coating is enhanced fatigue life by about $>$ 250 times.
Dong et al. [132]	2014	- The aging effects on cyclic deformation and fatigue life	1- The aging process had significant impacts on the strain, fracture stress, and the stress–strain response under both monotonic compression and tension mode. 2- The aging process had slight effects on fatigue life and cyclic deformation.
Yu et al. [133]	2012	- Cyclic deformation and LCF properties	1- Under high strain amplitudes, the main reason for crack initiation is due to the twinning–detwinning process. 2- Under low strain amplitudes, dislocation slips or interaction between dislocation slips and residual twins has an important role in crack initiation.

6. Effect of Simultaneous Addition of Yttrium and Rare Earth Elements (Mg-W-REE)

WE43 alloys have proper corrosion resistance, high strength, and mechanical properties. The main chemical compositions of WE43 alloy are magnesium, gadolinium, and yttrium. The mechanical properties of WE43 magnesium alloy are shown in Table 14.

Table 14. Mechanical properties of WE43 magnesium alloy [134].

Properties	Symbol	Unit	Value
Ultimate tensile strength	UTS	MPa	274
Yield stress	YS	MPa	215
Elastic modulus	E	GPa	44.2
Hardness (Brinell)	HB	—-	85–105

WE43 magnesium alloys, compared to the previous alloys, have not been properly studied in terms of structural and functional aspects under different loading and environmental conditions. Experimental studies have shown that the direct-chill casting method to produce WE43 magnesium alloys has good effects on reducing the average grain size and improving the mechanical properties such as hardness, yield strength, etc. [135]. Moreover, various heat and mechanical treatments have been performed to improve the quality of the alloys and metals. The effects of T5 (aged for 48 h at 204 °C) and T6 (underaged and peak-aged) on WE43 magnesium alloys have been investigated and it was found that T5 aging process had a much higher effect than T6 aging process on the fatigue life of WE43 magnesium alloy. In addition, average short crack growth rates were independent of conditions [136,137]. From Figure 15, the increase in the environmental temperature can be a destructive factor in reducing the life of WE43-T5 magnesium alloy. However, the Transverse Direction (TD) has shown higher fatigue strength than the Rolling Direction (RD) and greater resistance to increasing temperature. Furthermore, pre-strain in the compression state had a higher impact on fatigue life, while in the tension state, fatigue just slightly increased at low stress amplitudes [138]. Gu et al. have stated that the cause of cracking in WE43 alloys is related to micropores [29]. In addition, the cyclic loading, surrounding environment, alloying elements, and microstructures are major factors affecting the fatigue life of WE43 magnesium alloys.

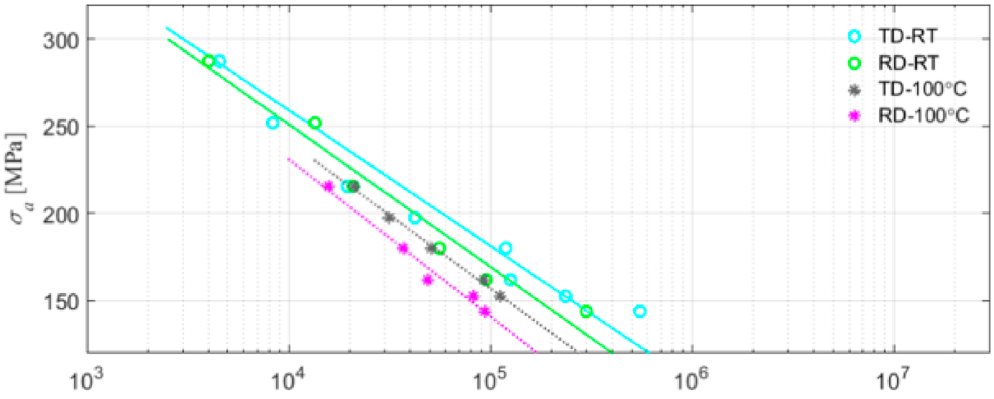


Figure 15. S-N curves for samples of WE43-T5 along rolling (RD) and transverse (TD) directions at different temperatures, including room and 100 °C "Reused with permission from Elsevier by License No. 5494640717153" [138].

7. Future Recommendations

This section is dedicated to the direction of future work, which the authors addressed based on their experience, capabilities and knowledge, available equipment, and above-mentioned literature review. Therefore, these suggestions are only for research purposes and there are no claims on them, and other researchers can contact the corresponding author to have cooperation in any of the following areas. Several articles have been devoted to extracting the fatigue properties of magnesium alloys, but it is rare to find a document that has reported the fatigue strength under different loading conditions (i.e., tension-tension, tension-free, tension-compression, free-compression, compression-compression, bending, torsion, and combination modes such as multiaxial loading), so one of the future research directions is to investigate the effect of loading type on the fatigue strength of different categories of magnesium alloy. In addition, in medical applications such as dental implants, it has been shown that the addition of calcium is very effective to improve biocorrosion properties, but from the fatigue viewpoint, attention has not been paid to this alloy, which can be added at the end of the previous research direction. Moreover, identifying the mechanisms of fatigue crack growth in different classification of Mg alloy and depending on their texture due to two properties improvement operations, including heat treatment and severe plastic deformation, should be investigated. In addition, magnesium is an alloy with high reactivity, so it oxidizes quickly, and the effects of the form and arrangement of pores caused by oxidation on the mechanism of crack growth, crack growth rate, and fatigue should be considered. Finally, the techniques presented to reduce the crack growth rate, such as laser shock pinning, ultrasound peening, rolling, and punching, etc., should be examined in different classifications of magnesium alloy and the effectiveness of each of them should be determined optimally. Finally, the authors try to apply different machine learning techniques to predict the mechanical, metallurgical, material, and fatigue properties of magnesium alloys.

8. Conclusions

As has been mentioned in detail, there are diverse types of magnesium alloys depending on the composition of the elements such as aluminum, zinc, manganese, silicon, copper, rare metals, etc. In the present paper, more than 95% of the most novel and practical studies related to magnesium alloys consist of AM50, AM60, AZ31, AZ60, AZ80, AZ91, ZK60, and WE43 were reviewed to stand out their outcomes and guide prospective research in this segment. In summary, the most important points can be stated as following:

- Corrosion is a serious and common issue having been considered for most magnesium alloys. Despite much research, a complete and accurate understanding of these alloys' behavior subject to adverse environmental conditions has not yet been provided, and the proposed solutions and methods have worked for a specific alloy or condition.
- Contrary to many studies on fatigue life and crack behavior of aluminum alloys and steels under various loading conditions, the investigation of these concepts for Mg alloys have not been comprehensively and accurately explained, and most of mentioned works have repeated the similar procedure or presented approaches for a limited range of Mg alloys.
- The use of numerical and modeling methods in recent research is rarely seen, though these methods can help increase the speed of research and provide a more reliable explanation under different working conditions.
- A series of the methods and techniques proposed to improve the fatigue life and other mechanical properties should be carefully considered depending on the type of alloy, and one setting or approach cannot be used for all kinds of Mg alloys.
- Despite the development of artificial intelligence and a variety of optimization methods, the lack of these methods can be clearly realized in the discussion of production and prediction of Mg alloys' characteristics in the presence of different amounts of elements and environmental and working conditions.

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