Chapter

Fatigue of Magnesium-Based Materials

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Abstract

Magnesium alloys and metal matrix composites (MMCs) are attractive materials for biomedical application. Magnesium has a module of elasticity that is close to that of human bones and it is biocompatible with the human body. Human body fluids make a corrosive environment to magnesium. In addition, different body parts are subjected to cyclic loading reaching a magnitude of about 80 MPa and an estimated total of 106 cycles per year. Therefore, understanding the fatigue behavior of magnesium alloys and magnesium metal matrix composites (MMCs) is an essential aspect especially when they are used as load bearing components. Magnesium has a hexagonal closed-packed (HCP) lattice structure with a c/a ratio of 1.623, and it does not have enough independent slip systems to sustain large plastic deformation. Therefore, magnesium deforms plastically by two different mechanisms: slipping and twinning. Twinning-detwinning deformation is manifested in the cyclic stress-strain response of wrought magnesium alloys when loaded along the working direction. A significant stress asymmetry is usually observed resulting in the development of high mean stress. Research on magnesium and its alloys is rapidly increasing. This chapter presents different aspects of fatigue, in general, and on magnesium in particular, including experimental method, damage models and fatigue life equation.

Keywords: fatigue, cyclic behavior, life estimation, Mg alloys, magnesium metal matrix composites

1. Introduction

Magnesium has a hexagonal closed-packed (HCP) lattice structure with a c/a ratio of 1.623. According to von Mises [1], the ductility of the material, which depends on the its ability to withstand general homogeneous strain that involves changes in the shape of the crystal, is possible when five independent slip systems are activated. This condition is not met in HCP metals such as magnesium, therefore, deform plastically by two mechanisms: slip and twinning. Slip and twin planes for HCP metals are illustrated in **Figures 1** and **2**. Among these systems, the basal slip (0001) and the $(10\bar{1}2)$ tension twin are easiest to be activated due to their low critical resolved shear stresses (CRSS).

The American Society of Testing and Materials (ASTM) [3] defines fatigue as “the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a

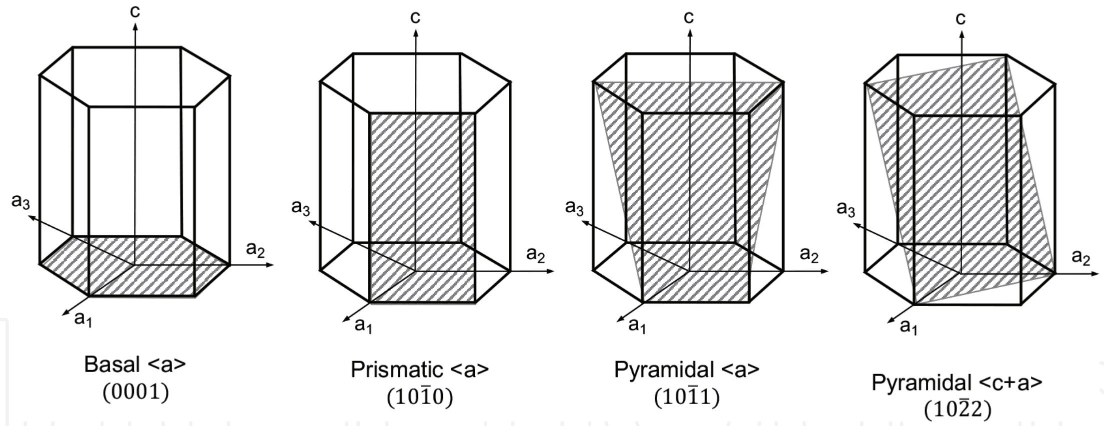

Figure 1.
Slip planes in HCP metals [2].

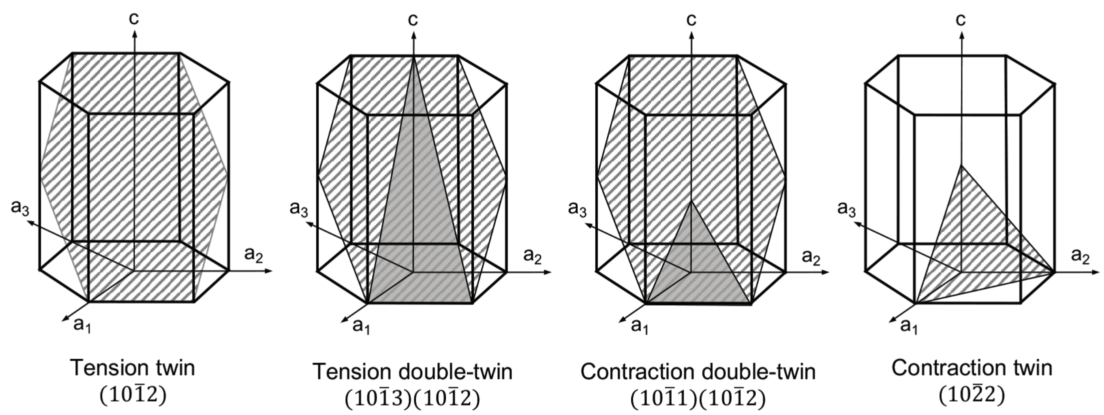

Figure 2.
Twin planes in HCP metals [2].

sufficient number of fluctuations". Fatigue failure can occur even if the generated stress is below the yield limit. Therefore, in a macro-scale viewpoint fatigue failure is similar to brittle fracture where no signs of severe plastic deformation such as necking are observed.

Cyclic loading is very common. It can occurs because of operational condition such as increase and decrease of loads or due to the motion of loaded parts. Cyclic loads can be classified into constant and random loads. Constant load can be represented by an amplitude and a mean. A cycle in a constant amplitude loading is clearly defined. However, the definition of a cycle in random loading case is not as clear as in constant amplitude loading. Therefore, a count method is required to quantify the number of cycles in random loading situation. Applied cyclic loading can either be uniaxial or multiaxial. In a constant multiaxial cyclic loading, amplitudes, means, phases and frequencies of the applied loads can be different. Of course, multiaxial loading can involve random loads.

The classifications explained before were merely based on mechanical loads such as forces, moments and torques. However, fatigue damage might result from the application of cyclic thermal loads. In addition, fatigue damage process can get complex due to interactions between applied cyclic loads, mechanical or thermal, and other damaging phenomenon such as creep. Effect of environmental attacks, residual stress, coating, surface finish, geometrical irregularities have significant impact on fatigue damage process and fatigue life.

There are two approaches to study fatigue of materials: initiation and propagation of cracks. Fatigue initiation approach is concerned about relation between the applied cyclic loads and the initiation of small cracks that generally do not exceed

1 mm in size. On the other hand, fatigue propagation approach is concerned about the relation between the applied cyclic loads and the growth of an existing crack to a size that causes catastrophic failure.

The initiation approach, which is commonly referred to as *fatigue*, is classified based on the damaging variable. There are three methods to analyzing fatigue: stress-, strain- and energy-based. If a damage model, stress-, strain- or energy-based, is calculated on specific planes the used method is further classified as *critical plane* method. Stress-based methods use stresses, normal and/or shear, to quantify fatigue damage. Similarly, strain-based method use strains, normal and/or shear, to quantify fatigue damage. Lastly, energy-based methods use strain energy density to quantify fatigue damage.

All fatigue models require monotonic and/or cyclic properties of materials. Strain and energy-based cyclic properties can be obtained by performing series of tests under strain-controlled loading condition. On the other hand, stress-based cyclic tests properties can be obtained by performing series of tests under stress-controlled loading condition. The well-known stress-life and strain-life curves can be obtained from these tests.

2. Characterization of fatigue behavior

A common classification in fatigue initiation analysis is based on fatigue life [4]. The term "low cycle fatigue, LCF" refers to fatigue failure that occurs between 10^3 and 10^5 cycles. On the other hand, the term "high cycle fatigue, HCF" refers to fatigue failure that occurs between 10^5 and 10^7 cycles. The last class is called "very high cycle fatigue, VHCF" that refers to fatigue failure that occurs after 10^7 cycles. Because it is easier to control the stress at low load levels than strain, HCF and VHCF tests are usually performed under stress-controlled condition. However, strain-controlled tests can be performed with wide strain levels that cover lives less than 10^3 and up to 10^7 cycles. Because strain-controlled tests are usually performed at high strain levels and significant plasticity resulting in low number of cycles to failure, heating of the sample due to internal friction becomes a concern. Therefore, tests that are expected to last for few hundred or thousand cycles shall be performed with frequencies that shall not exceed few Hertz, if not less 1 Hz. Yet, a common practice in strain-controlled testing is to switch the control mode to stress when a test exceeds 10^4 cycles. This allows for increasing the frequency to reduce the time required to finish the test. On the contrary, HCF and VHCF tests are usually performed with frequencies higher than 20 Hz.

2.1 High cycle fatigue

The high cycle fatigue behavior of materials can be characterized for a mode of stress, i.e., normal or shear, by performing stress-controlled experiments. ASTM standard for conducting force controlled constant amplitude axial fatigue tests of metallic materials [5] can be followed in tests performed using cyclic axial machine. Similarly, the standard by International Organization for Standardization [6] can be followed in tests performed using four-point rotating bending machine. Unlike cyclic axial or rotating bending tests that are usually performed on solid specimens, cyclic torsion test is usually performed on tubular specimen because shear stress across tubular specimens that satisfy thin-walled tube condition can be assumed constant. Of course, a machine with dynamic torsional load cell is required to perform cyclic torsional experiment. There is no particular standard for performing cyclic torsional tests, however, the ASTM standard for strain-controlled axial-torsional fatigue testing with thin-walled tubular specimens [7] can be used.

The stress-life ($S - N$) curve, which is also known as the Wöhler curve, is usually used to represent the relation between applied stress amplitude, σ_a or τ_a and fatigue life N_f in a log-log scale. A typical $S - N$ curve shows a linear curve in the finite life region as shown in **Figure 3**.

Understanding that a linear curve in a log-log scale indicates that the relation between the stress amplitude and fatigue life is of a power-type, Basquin [8] was the first to model this curve as

$$\sigma_a = \sigma'_f \left(2N_f\right)^b \tag{1}$$

where σ'_f is the axial fatigue strength coefficient and b is the axial fatigue strength exponent.

Some materials such as steel and magnesium alloys show a distinct plateau commonly called the "fatigue limit". This limit is usually observed between 10^6 and 10^7 cycles. Tests that exceed 10^7 cycles are usually stopped and are called run-out. This limit used to be called the "endurance limit" that is a stress amplitude below which no failure will occur. However, it has been shown if the testing is continued specimens eventually fail. Therefore, it is recently accepted that endurance limit

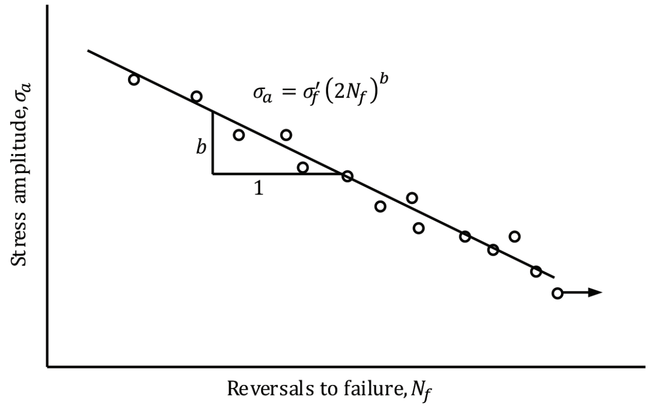

Figure 3.
A typical stress life curve.

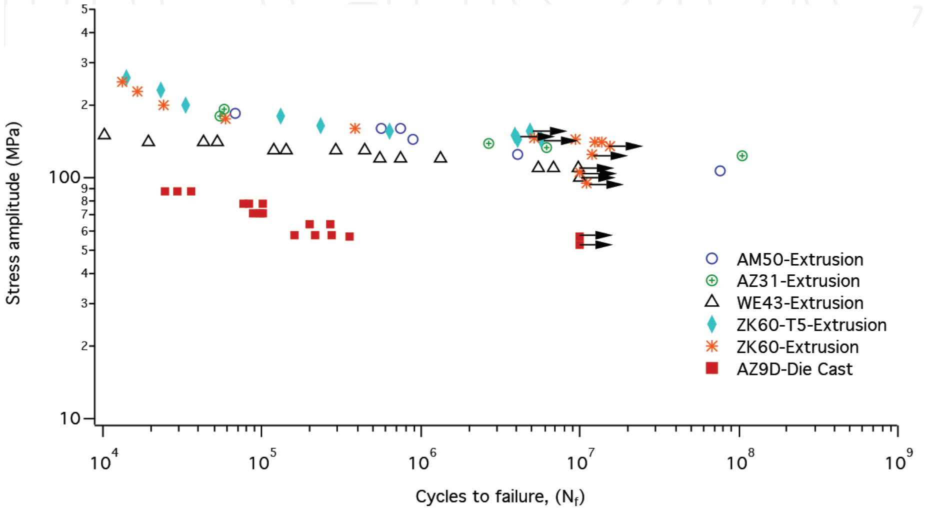

Figure 4.
Stress life curve for different Mg-alloys [9–13].

does not exist. Run-out tests are usually marked with an arrow symbol. Stress-life curves for six different magnesium alloys are presented in **Figure 4**. This figure clearly shows the difference between die-cast and extruded alloys with the former having less fatigue strength due to the existence of pores and cavity resulting from the casting process.

2.2 Low cycle fatigue

Similar to the HCF, the low cycle fatigue (LCF) behavior of materials can be characterized for a mode of strain, i.e., normal or shear, by performing strain-controlled experiments. ASTM standard for conducting strain controlled fatigue tests of materials [14] can be followed in tests performed using cyclic axial machine. While controlling the strain, using strain measurement device such as an extensometer, the load signal is also acquired. This allows calculating both the stress and strain that can be represented for a given cycle by a hysteresis loop as shown in **Figure 5**.

Wrought alloys that are produced by extrusion, rolling or forging processes develop strong texture. This texture is characterized by alignment of the basal plane with the working direction with the c-axis perpendicular to it. The two plastic deformation mechanisms, slipping or twinning, can be activated depending on the loading orientation with respect to the basal plane. An extension along the c-axis activates the tension twins and a subsequent contraction causes detwinning of the lattice. During cyclic loading, twinning occurs in the compression reversal leading to low stress yielding. Detwinning starts as the load is reversed, i.e., during the tension reversal. However, as the tension load increases the hard pyramidal slip is activated in order to accommodate additional strain. This change from detwinning to slip is reflected on the cyclic hysteresis as an inflection point and a concave upward hardening behavior. A representative cyclic hysteresis loop for different magnesium extrusion loaded along the extrusion direction is shown in **Figure 6**.

The strain-life ($\varepsilon - N$) curve is usually used to represent the relation between applied strain amplitude, ε and fatigue life N_f in a log-log scale. Strain life curves for AZ31B, AZ61A and ZK60 magnesium extrusions are presented in **Figure 7**.

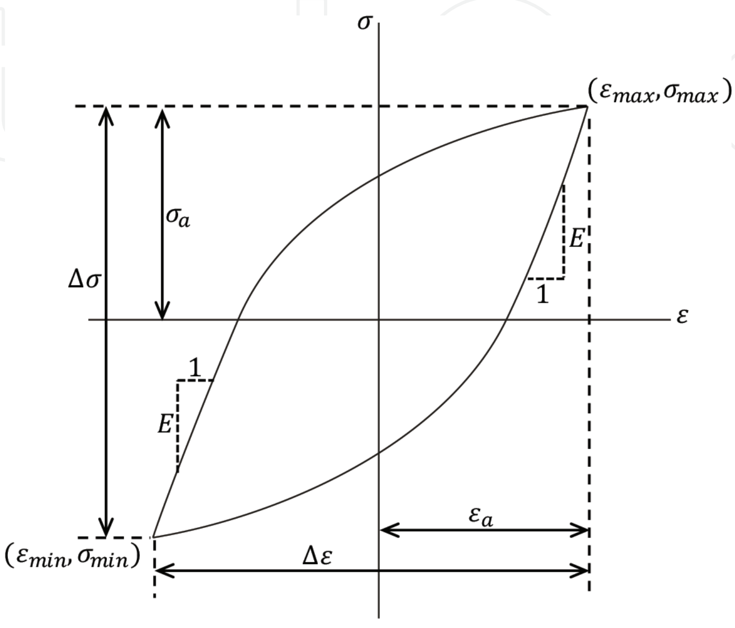

Figure 5.
A typical cyclic hysteresis loop [2].

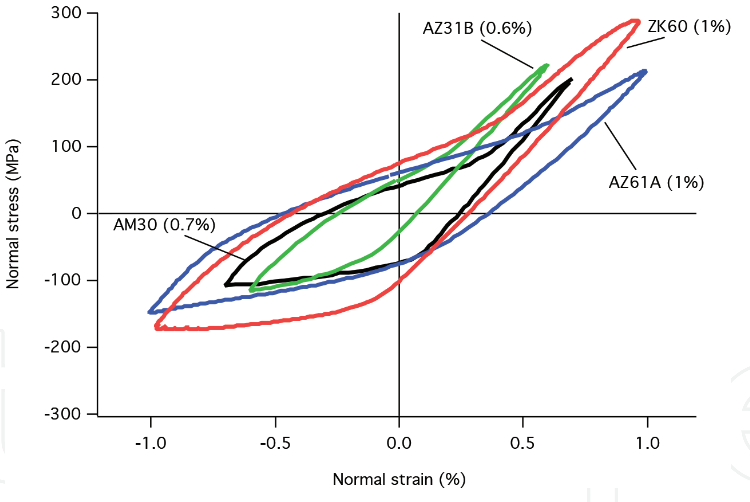

Figure 6.
Cyclic hysteresis loops of AZ31B, AZ61A, AM30 and ZK60 magnesium extrusions [15–18].

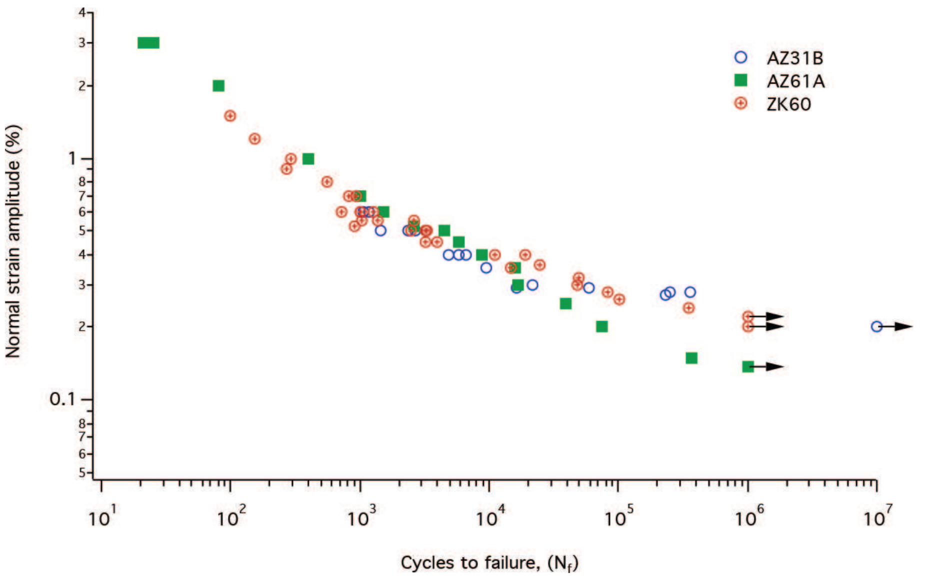

Figure 7.
Strain life curves for AZ31B, AZ61A and ZK60 magnesium extrusions [17–19].

This region is represented by the Coffin-Manson [20, 21] equation as

$$\varepsilon_a = \frac{\sigma_f'}{E}\left(2N_f\right)^b + \varepsilon_f'\left(2N_f\right)^c \quad (2)$$

where σ_f' and b are defined in Eq. (1) and ε_f' and c are the axial fatigue ductility coefficient and the axial fatigue ductility exponent, respectively.

Ellyin, Golos and Xia [22] energy model is considered as the basis for the application of strain energy in correlating multiaxial fatigue damage. The model considers the plastic and the positive elastic strain energy densities as the damaging variables as shown in **Figure 8**.

The plastic strain energy density is the area enclosed by the cyclic hysteresis loop which is calculated as [23]:

$$\Delta W^p = \int_{cycle} \sigma d\varepsilon \quad (3)$$

While the positive elastic strain energy density is calculated as

$$\Delta W_e^+ = \frac{\sigma_{max}^2}{2E} \tag{4}$$

The total strain energy density is often calculated as the sum of torsional of the plastic and positive elastic energies

$$\Delta W_t = \Delta W_e^+ + \Delta W_p \tag{5}$$

The inclusion of the positive elastic strain energy density is a method for considering the mean stress effect in energy method.

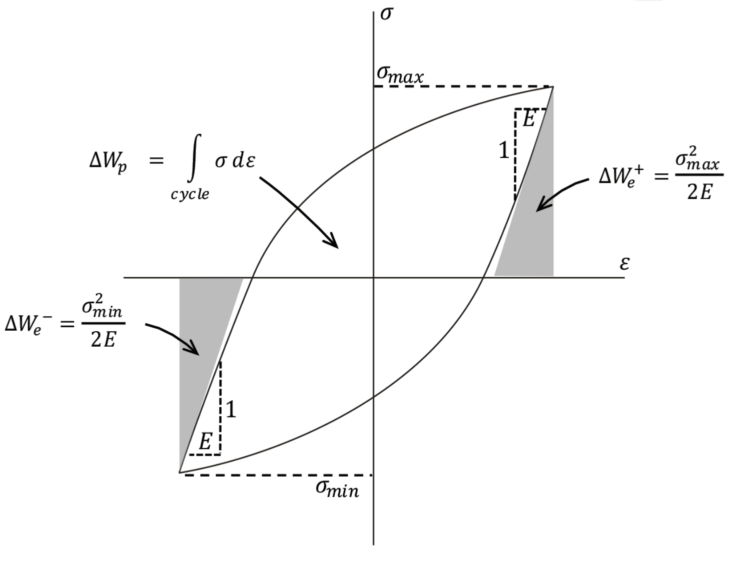

Figure 8.
Energy components in cyclic hysteresis loop [2].

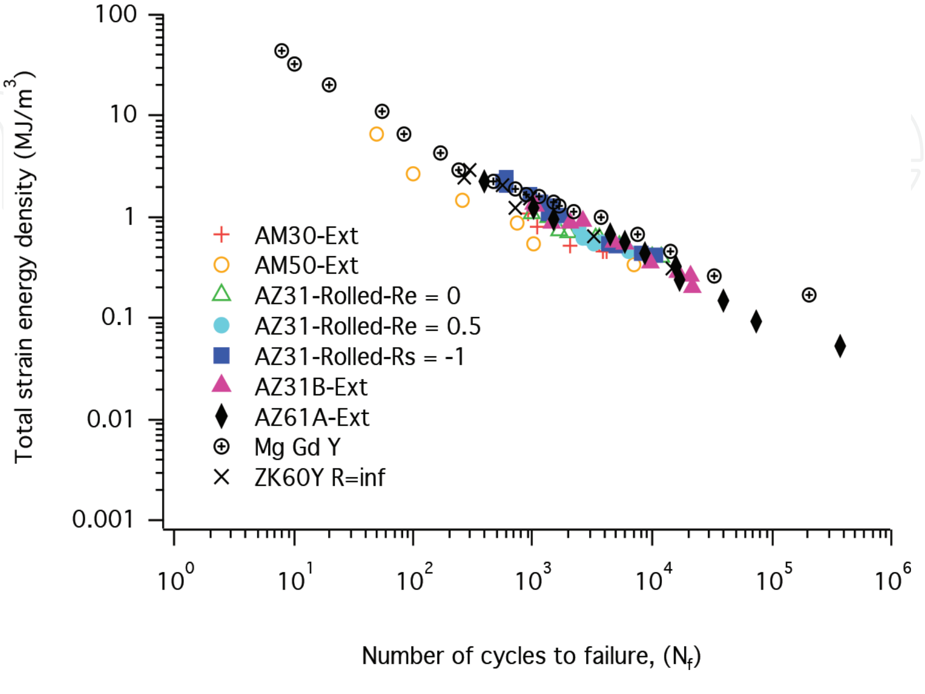

Figure 9.
Energy life curves of Mg [17–19, 24–27].

Property	AZ31B extrusion	AZ61A extrusion	AM30 extrusion
σ'_f	723.5	586.1	410.4
b	−0.159	−0.153	−0.130
ε'_f	0.252	1.823	1.480
c	−0.718	−0.832	−0.791
E'_e	20.29	7.01	2.995
B	−0.440	−0.373	−0.281
E'_f	510.74	924.14	1710.69
C	−1.052	−1.001	−0.975

Table 1.
Strain and energy fatigue properties of different Mg extruded alloys [16, 18, 28].

The fatigue life is estimated using

$$\Delta W_t = \alpha N_f^{\beta} \tag{6}$$

Figure 9 shows the correlation between the total strain energy density and fatigue life for several magnesium alloys tested at different loading conditions. This figure clearly shows the ability of the energy method to collapse all data in a single and narrow scatter band.

Strain- and energy-based fatigue properties for AZ31B, AZ61A and AM30 magnesium extrusions are listed in **Table 1**.

2.3 Mean stress effect

Mean stress has a significant effect on fatigue behavior of materials. It is generally observed that tensile mean stresses are detrimental and compressive mean stresses are beneficial. As explained earlier, the positive elastic strain energy density is used to account for the mean stress effect in energy methods. There are different models for stress-based methods that account for mean stress effect [29]:

The Modified Goodman:

$$\frac{\sigma_a}{\sigma_f} + \frac{\sigma_m}{\sigma_u} = 1 \tag{7}$$

Gerber:

$$\frac{\sigma_a}{\sigma_f} + \left(\frac{\sigma_m}{\sigma_u}\right)^2 = 1 \tag{8}$$

Morrow:

$$\frac{\sigma_a}{\sigma_f} + \left(\frac{\sigma_m}{\sigma'_f}\right)^2 = 1 \tag{9}$$

where σ_f is the fatigue limit.

Morrow's can be used for strain-based method as:

$$\frac{\Delta\varepsilon}{2} = \varepsilon_a = \frac{\sigma'_f - \sigma_m}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \tag{10}$$

Another equation suggested by Smith, Watson and Topper [30], commonly known as "SWT parameter", is as follows:

$$\sigma_{max}\varepsilon_a E = \left(\sigma_f'\right)^2 \left(2N_f\right)^{2b} + \sigma_f'\varepsilon_f' E\left(2N_f\right)^{c+b} \tag{11}$$

2.4 Environmental effects

Environmental effects such as corrosion or temperature have significant effect on fatigue life. The interactions between these effects and fatigue behavior are complex, therefore, quantitative models for estimating fatigue life may not always be possible. Magnesium is highly reactive and considered as one of the most electrochemically active metals. From structural view point, the reactivity of magnesium, and its alloys, in electrolytic or aqueous environments, is disadvantageous because it degrades their mechanical strength. In the contrary, this high reactivity of magnesium and its alloys make them a potential biodegradable materials.

The pH level of body fluid ranges from 1 to 9 in different tissues. It is also estimated that different parts of the body are subjected to different level of stresses. For example, bones are subjected to a stress of about 4 MPa during regular daily activities. On the other hand, tendons and ligaments experience peak stresses that range from 40 to 80 MPa. Hip joints usually subjected to 3 times the body weight which can increase to 10 times during jumping. These stresses are repetitive and fluctuating reaching to 1×10^6 cycles in a year [31, 32].

The poor corrosion resistance of many magnesium alloys is due to internal galvanic corrosion caused by second phases or impurities and the instability of the hydroxide film [33]. The most common method to assess the influence of corrosion on fatigue behavior is to perform stress-controlled testing at different environmental conditions. Strain-controlled testing is not common because it requires electronic strain measurement device that may not be possible to mount on the sample while being exposed to corrosive substances. Comparisons between stress-life curves for different biomedical magnesium alloys tested at different simulated body fluids "SBF" are shown in **Figures 10** and **11**. These figures show that the fatigue life of AZ91D at a given stress amplitude is significantly influenced by the condition of the corrosive environment.

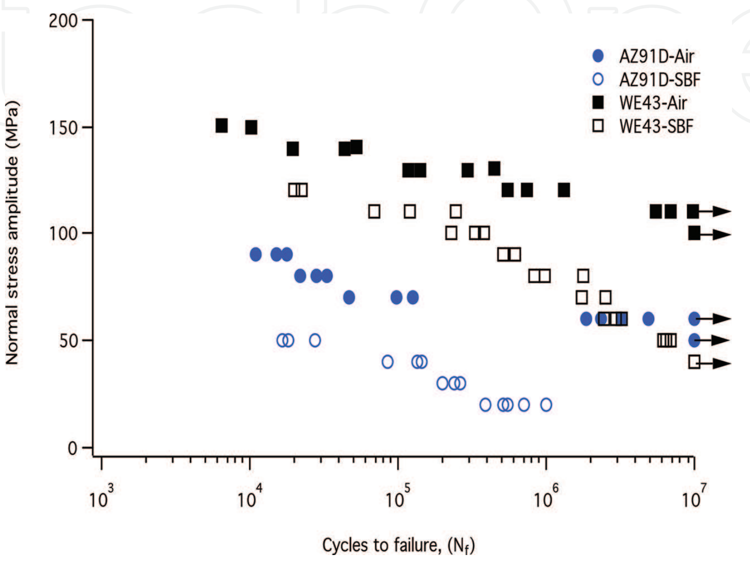

Figure 10.
Comparison between the stress life curves for biomedical AZ91D and WE43 tested in air and simulated body fluid "SBF" [33].

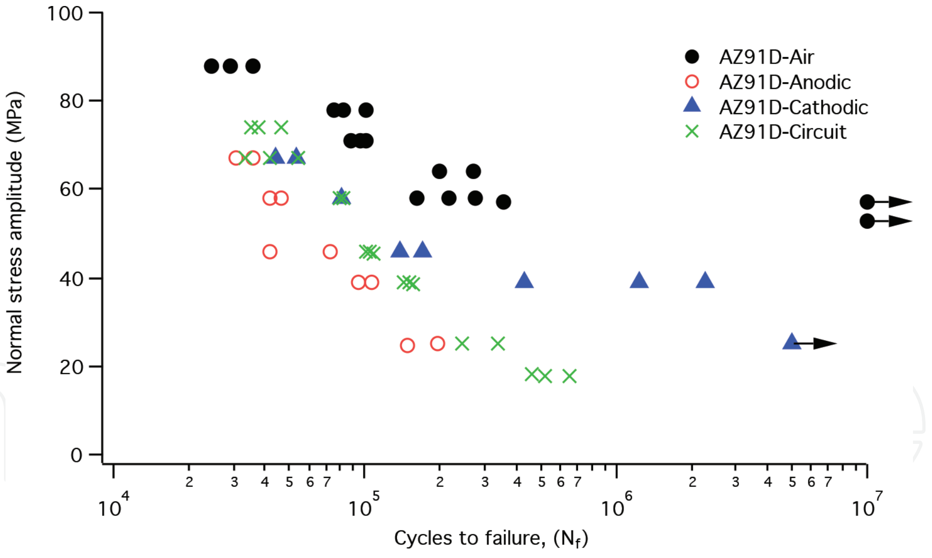

Figure 11.
Comparison between the stress life curves for biodegradable AZ91D tested in air and different simulated body fluids "SBF" [11].

3. Metal matrix composites

Metal-matrix composites (MMCs) are a class of materials that are usually made by reinforcing conventional metallic matrix using high-performance second phase constituents. Metal-matrix composites MMCs can be tailored to improve different properties such as strength, stiffness, thermal conductivity, and corrosion, wear, creep resistance. In general, metal-matrix composites (MMCs) can be produced by stir casting, squeeze casting and powder metallurgy.

Magnesium matrix composites can be fabricated by using different reinforcements to obtain different characteristics. For example, Mg_2Si/Mg composites have a mechanical strength that is comparable to that of industrial magnesium cast alloys (AZ63) but with a damping capacity that is 100 times higher [34]. Carbon nanotubes (CNTs) can be used as reinforcements with magnesium [35] or its alloys

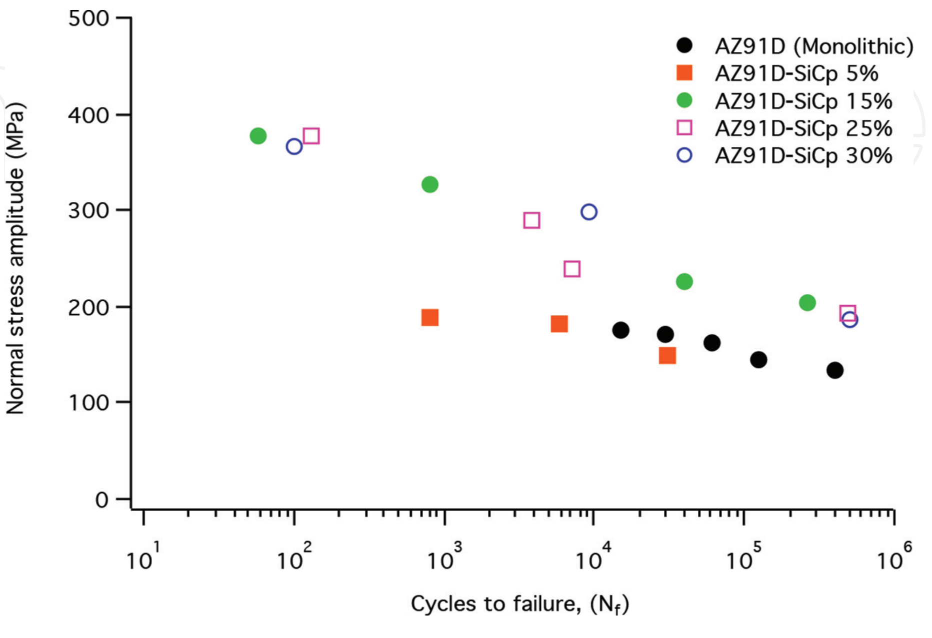

Figure 12.
The effect of different volume fractions of SiCp on the stress-life curve of AZ91D magnesium metal matrix composite [41, 42].

such as AZ31, AZ91, ZK60 and AZ61 to improved their ultimate tensile strength, yield strength and modulus of elasticity composite [36]. Different reinforcements such as aluminum oxide particulate Al_2O_3 [37], nickel particles [38] or nano-size Y_2O_3 particles [39] have been tested with magnesium and its alloys and found to yield different results.

Fatigue behavior of magnesium AZ91 can be improved by adding ceramic reinforcements [40]. In addition, the elastic modulus, yield strength and ultimate tensile strength of AZ91 can be increased using SiCp particles as discontinuous reinforcements. **Figures 12** and **13** show the effects of two different reinforcements

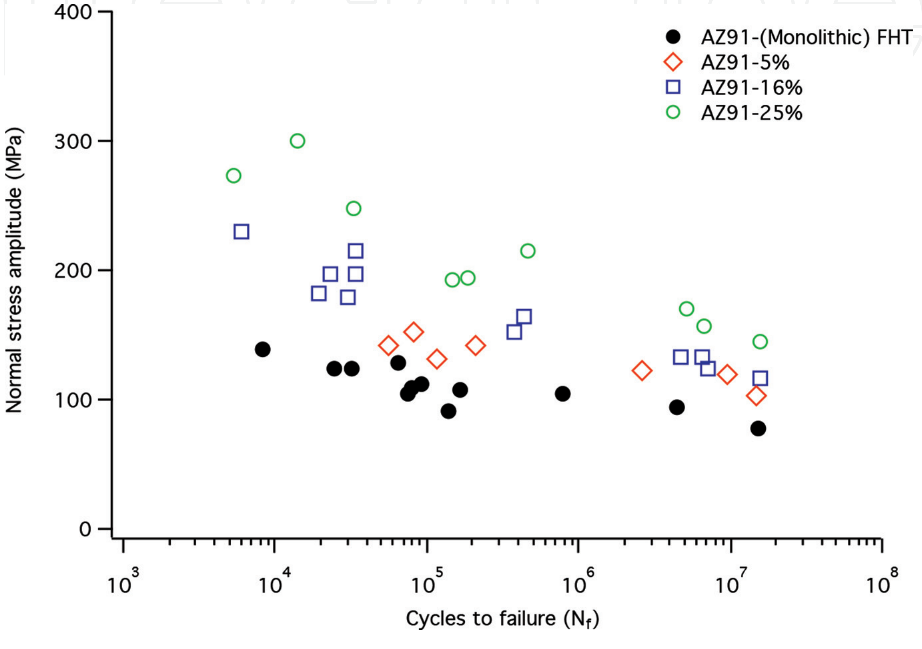

Figure 13.
The effect of different volume fractions of Saffil alumina fibers on the stress-life curve of AZ91D magnesium metal matrix composite [40].

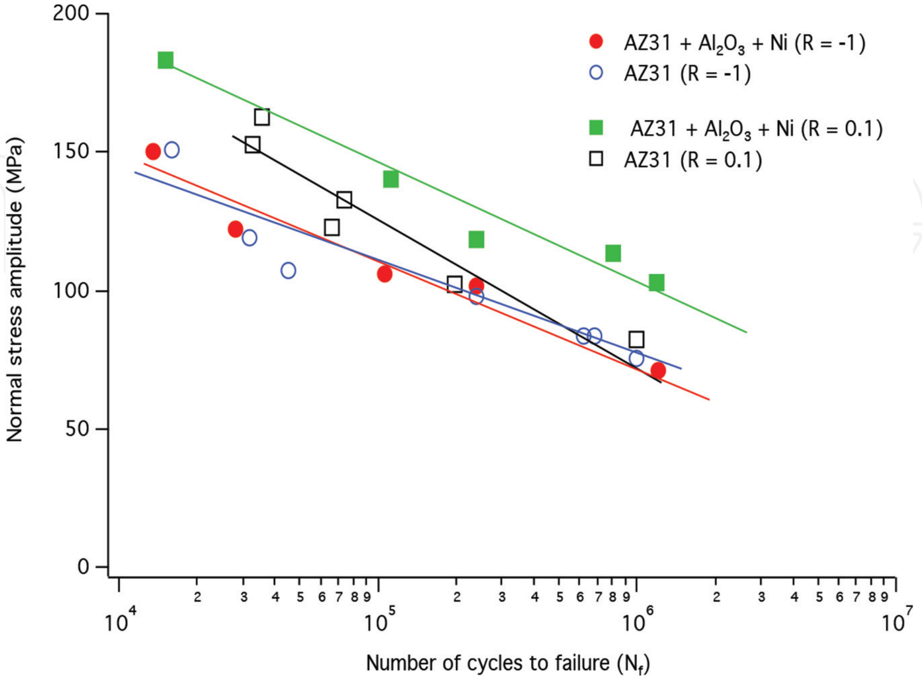

Figure 14.
Comparison of stress-strain curves of the dual particle reinforced magnesium alloy (AZ31 + Al_2O_3 + Ni) with the unreinforced matrix alloy (AZ31) cyclically deformed at room temperature (T = 25°C) at R = 0.1 and − 1.0 [38].

on the stress-life curve of magnesium AZ91D. These figures show that fatigue life at a given stress amplitude can be increased by adding proper volume fraction of the reinforcements.

In addition, fatigue life of AZ31 can be improved by using nano-particulates of aluminum oxide and micron size nickel particles reinforcements as shown in **Figure 14**.

4. Summary

Magnesium is a promising material for biomedical applications. Because body parts such as hip joints, bones and knees are subjected to cyclic loading fatigue is an essential tool for designing implants and replacement components for these parts. Accurate determination of the stress and strain states is critical for a successful fatigue design process. Magnesium has a hexagonal close packed crystal structure resulting in a complex stress-strain behaviors. It has been explained that the involvement of slipping, twinning and detwinning deformation mechanisms causes the unusual cyclic hysteresis loop of wrought magnesium alloys. Therefore, suitable cyclic plasticity model is required for estimating the cyclic stress-strain state. Different fatigue damage models such as stress-, strain- and energy-based parameters can be used to correlate the fatigue damage with life. Although biodegradability is an attractive characteristic of biomedical materials, the high reactivity of magnesium in electrolytic or aqueous environments calls for further developments. The properties of magnesium and its alloys can be improved by reinforcing them using selected reinforcements.

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