

Low cycle fatigue behavior of magnesium matrix nanocomposite at ambient and elevated temperatures

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ABSTRACT

AZ31B alloy reinforced by 1.5 vol.% nano-sized Al_2O_3 particles has been subjected to fully-reversed strain-controlled uniaxial tension-compression cyclic loading at room temperature, 100 °C, and 200 °C. A combination of mechanical and magnetic stir casting methods followed by a hot-extrusion process was used to fabricate the composite material. Cyclic and fatigue behaviors of the composite were studied at the strain ranges of 0.8%–2.5%. The experimental results of the fatigue lives were used to assess and compare the life prediction capabilities of different existing strain-based and energy-based fatigue models. The results exhibited that the presence of the nano-sized reinforcing particles leads to a homogeneously fine microstructure and slightly changes the texture of the composite extrusion, compared to the typical microstructure and texture of monolithic AZ31B extrusion. The cyclic behavior of the composite is altered from an asymmetric shape at room temperature to a symmetric one at 200 °C, resulting in reduction of mean stress. Unlike the room-temperature behavior, twinning and detwinning are not governing plastic deformation mechanisms at the elevated temperatures, especially at 200 °C. Cyclic softening occurs by increasing the temperature, in a manner similar to the monotonic tensile tests. Due to the strain-controlled loading and increasing the composite ductility at the elevated temperatures, the fatigue lives are comparable at the different temperatures. Finally, considering the results at all the temperatures, Jahed-Varvani (JV) as an energy-based model shows a more promising life prediction.

1. Introduction

Magnesium and its alloys, as the lightest structural metals, have a growing range of applications in various industries such as transportation. These applications may be increased by reinforcing these metals as magnesium matrix composites and improving their unique mechanical properties, leading to decreased fuel consumption and consequently reducing greenhouse gas emissions [1]. Depending on the applications, the mechanical and metallurgical properties of the fabricated composites can be tailored by selecting an appropriate type, shape, size, distribution pattern, and the quantity of reinforcing phase [2,3]. The mechanical behaviors of the composites should be completely understood to ensure the requirements are provided for the intended service conditions. Under normal service conditions for vehicle parts, these are usually subjected to complex monotonic and cyclic loads [4]. The parts may have to tolerate high cyclic stresses locally in a low cycle regime due to stress concentration sites at geometrical complexities and

notches. Such a circumstance could get worse in environments with harsh ambient conditions such as elevated temperatures. Therefore, comprehensive investigations are required in order to specify the cyclic behavior of these new materials.

In the context of the cyclic behavior of magnesium alloys at high temperatures, different alloys have been subjected to mechanical and thermo-mechanical cycling loading under stress-controlled and strain-controlled conditions [5–10]. In a manner similar to monolithic alloys, the fatigue life and strength of metal matrix composites decreases by increasing the temperature [11]. Gabb et al. [12] investigated the isothermal and non-isothermal fatigue behavior of titanium alloy reinforced by SiC fibers at a temperature range of 300 °C–550 °C. For the isothermal fatigue at the low cyclic stresses, fatigue cracks were initiated from the fiber-matrix interfaces. At 550 °C and the higher cyclic stresses, stress relaxation reduced the fatigue resistance. Perng et al. [13] conducted LCF tests on hot-extruded 6061-T6/ Al_2O_3 aluminum matrix composite at various temperatures. They presented the results of the cyclic stress-strain curves and also the elastic and plastic strain

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Nomenclature

E	elastic modulus
$\sigma_{n,max}$	maximum normal stress
σ_y	yield stress
ΔE	total strain energy density
σ_{UTS}	ultimate tensile stress
ΔE_e^+	positive elastic strain energy density
ϵ	maximum strain
ΔE_p	plastic strain energy density
$\frac{\Delta \epsilon}{2}$	total strain amplitude
σ_{max}	maximum tensile stress of the hysteresis loop
$\frac{\Delta \epsilon_e}{2}$	elastic strain amplitude
σ_{mean}	mean stress of the hysteresis loop
$\frac{\Delta \epsilon_p}{2}$	plastic strain amplitude
σ_a	stress amplitude
N_f	number of cycles to failure

σ_x	normal stress component
$2N_f$	number of reversal
$d\epsilon_{xx}^p$	normal strain component
$\sigma_f', \epsilon_f', b, c$	Coffin-Manson-Basquin model parameters
E_e', E_f', B, C	Jahed-Varvani model parameters

Acronyms

LCF	low cycle fatigue
DRX	dynamic recrystallization
CMB	Coffin-Manson-Basquin
CRSS	critical resolved shear stress
SWT	Smith-Watson-Topper
FE-SEM	field emission scanning electron microscope
JV	Jahed-Varvani
EBSD	electron backscatter diffraction
RT	room temperature
RMSLE	root mean squared logarithmic errors

amplitudes versus the fatigue lives using Ramberg-Osgood, Basquin and Coffin-Manson equations, respectively. The results showed that the LCF behavior of the composite was degraded in comparison to the monolithic alloy. Srivatsan et al. [14] performed fully-reversed total strain-controlled cyclic loading on tool-steel/SiC particulate metal matrix composite. According to the obtained results, the LCF life was degraded by increasing the quantity of reinforcing particles at room and higher temperatures. In addition, the composite followed Coffin-Manson and Basquin relations between the strain amplitudes and the number of cycles to failure. Biermann et al. [15] studied the effect of temperature on fatigue and damage behaviors of aluminum matrix composite AA6061/20 vol.% Al_2O_3 (mean size of 12 μm) at different temperatures between $-100^\circ C$ and $300^\circ C$ under tension-compression loading. At the highest temperature, cyclic softening was observed due to the over-aging (coarsening) of the precipitations in the matrix. On the other hand, the composite exhibited a stable behavior at the ambient and lower temperatures under lower strain ranges. At larger strain amplitudes, initial hardening (due to the greater dislocation multiplication levels in the aluminum matrix) followed by a cyclic softening was reported. Furthermore, damage occurred due to the particle fracture at the low and room temperatures and debonding at the higher temperatures. They also investigated the role of particulate and short-fibers reinforcing phases on the fatigue behavior of aluminum matrix composite at the same temperature range [16]. In comparison to the particulate composite, short-fiber reinforced composite offered more cyclic hardening.

To the best of the authors' knowledge, while a few researches have been carried out on the high cycle fatigue behavior of magnesium matrix composite at the ambient temperature [17–27], only Hassan et al. [28] investigated the low cycle fatigue behavior of magnesium matrix composite at room-temperature. They added SiC particles with an average size of 15 μm to AZ91D alloy and produced AZ91D/SiC composite using squeeze casting method. The Holloman equation was used to represent the relation between the cyclic stress and strain. Furthermore, the Basquin and Coffin-Manson equations were employed for elastic and plastic strain amplitudes versus the fatigue lives. The results revealed that enhancing the content of SiC particles yields a degradation in the low cycle behavior.

Masaki et al. [29] studied the high cycle fatigue of AZ91D alloy reinforced by 10 and 18 vol.% of alumina short fibers at room temperature and $200^\circ C$. The composite having more reinforcing phase showed a comparable fatigue behavior to that of AA6061/25 vol.% Al_2O_3 aluminum matrix composite at $200^\circ C$. Srivatsan et al. [30] implemented high cycle fatigue tests on Z6 magnesium alloy reinforced by SiC particles (with a mesh size of 600 grit) at the ambient temperature and

$150^\circ C$. The degradation of the fatigue life by increasing the temperature was attributed to the reduction of the elastic modulus at the higher temperature.

As explained, although the high cycle fatigue of magnesium matrix composites reinforced by nano-sized particles has been investigated in a few studies [17,18,20–22,26,31], low cycle fatigue behavior of these composites has never been studied before, either at room or elevated temperatures. Therefore, this article is aimed at investigation of the cyclic behavior of magnesium matrix nanocomposite in low cycle fatigue regime at room and elevated temperatures, as well as fatigue life modeling.

2. Experimental details

2.1. Materials

AZ31B alloy ingots and Al_2O_3 particles (average size of 50 nm) were used as the matrix and the reinforcing phases. It has been established that adding nano-sized aluminum oxide particles is able to improve the high cycle fatigue behavior of AZ31B alloy at room and elevated temperatures [17,18,31]. AZ31B/1.5 vol.% Al_2O_3 composite was fabricated by combination of mechanical and electromagnetic stirring [18,32]. To increase the density and the mechanical and microstructural properties of the composite, hot-extrusion process was performed at $350^\circ C$ in two passes with a total extrusion ratio of 20:1. The outer diameter of the composite extrusion rods was 10.5 mm.

2.2. Microstructural and mechanical tests

The composite extrusion rods were cut and prepared in order to carry out the microstructural and mechanical tests. In order to evaluate the microstructure, the transverse cross-sections of the samples were first ground and then mechanically polished. Subsequently, they were etched using an acetic-picric etchant (10 mm acetic acid, 4.2 g picric acid, 70 mm ethanol, 10 mm distilled water) [33]. Field emission scanning electron microscope (FE-SEM) equipped by electron backscatter diffraction (EBSD) was used to observe the particles distribution and the texture of the composite.

The microhardness of the composite was measured in the cross-sections parallel and perpendicular to the direction of the extrusion. During Vickers microhardness test, the indenter applied 2 N for 10 s to the composite cross section. Two samples were used to obtain the results and in each region, the microhardness test was carried out at least three times and the average value was presented.

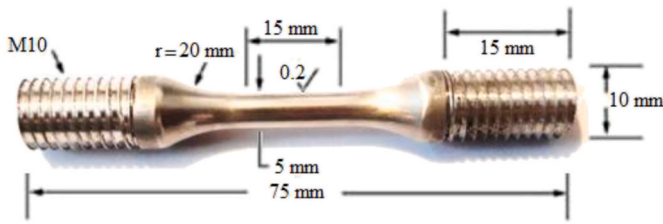


Fig. 1. Low cycle fatigue sample.

The samples machined along the extrusion direction were subjected to uniaxial tensile and LCF tests at different temperatures including the ambient temperature, 100 °C, and 200 °C. Gleeble 3800 system was used to implement the tests. During the tensile and fatigue tests, constant strain rates of 0.001 s^{-1} and 0.005 s^{-1} were applied, respectively. A high-temperature extensometer, Epsilon 39071, measured the strain. Before starting the high-temperature tests, the samples were kept at the elevated temperatures for 30 min in order to reach a steady state heat

condition. The fatigue sample was mechanically ground and polished in the longitudinal direction to remove the circumferential effects of the machining [21], is shown in Fig. 1 [34,35].

During the LCF tests, fully-reversed tensile-compressive cyclic loading was performed on the samples. Strain ranges between 0.8% and 2.5% were applied under a strain-controlled condition. The termination of the fatigue test was considered as either a complete separation in the samples or the first severe drop in the maximum tensile stress history (more than 50%) [36].

3. Results and discussions

3.1. Microstructure

The inverse pole figure (IPF) map and the grain sizes distribution are demonstrated in Fig. 2. The average grain size in the matrix is approximately 6.5 μm . The presence of the nano-sized reinforcing particles causes grain refinement in both the casting and hot-extrusion processes [18,37]. During the solidification, these hard particles act as grain

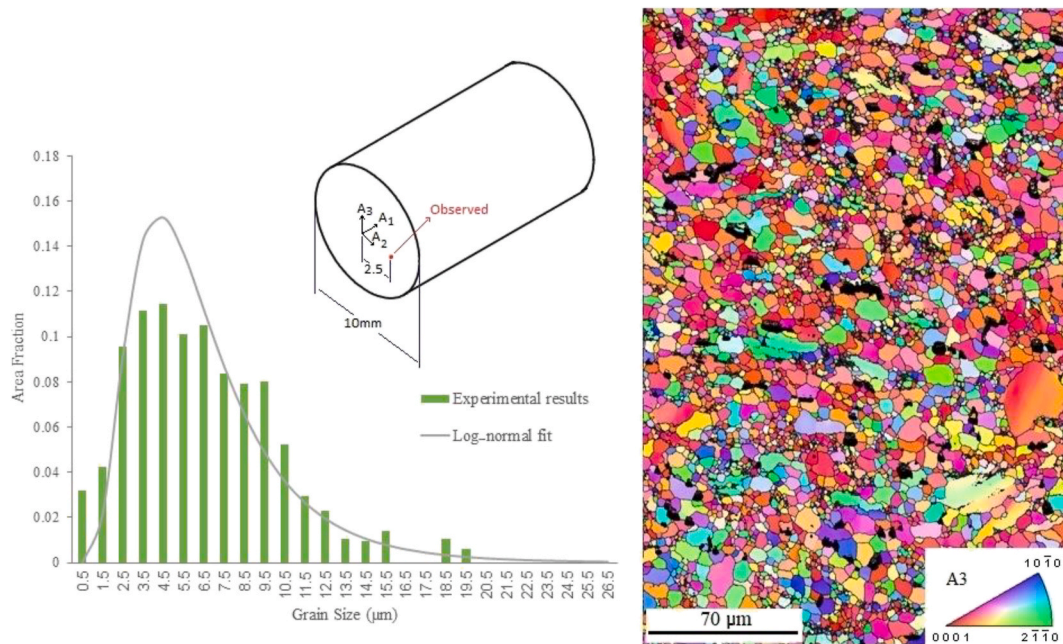


Fig. 2. Grain sizes distribution and the inverse pole figure map of the composite.

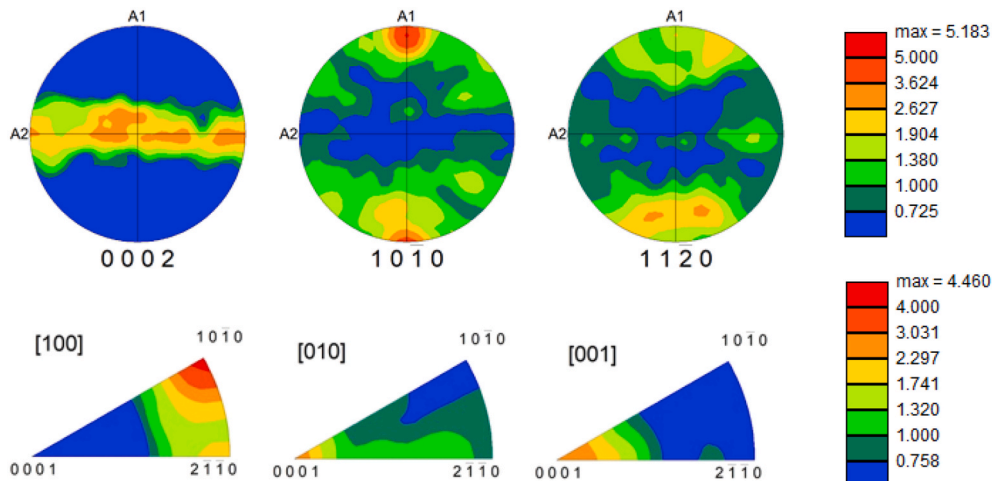


Fig. 3. Pole figures of the composite extrusion at its cross-section.

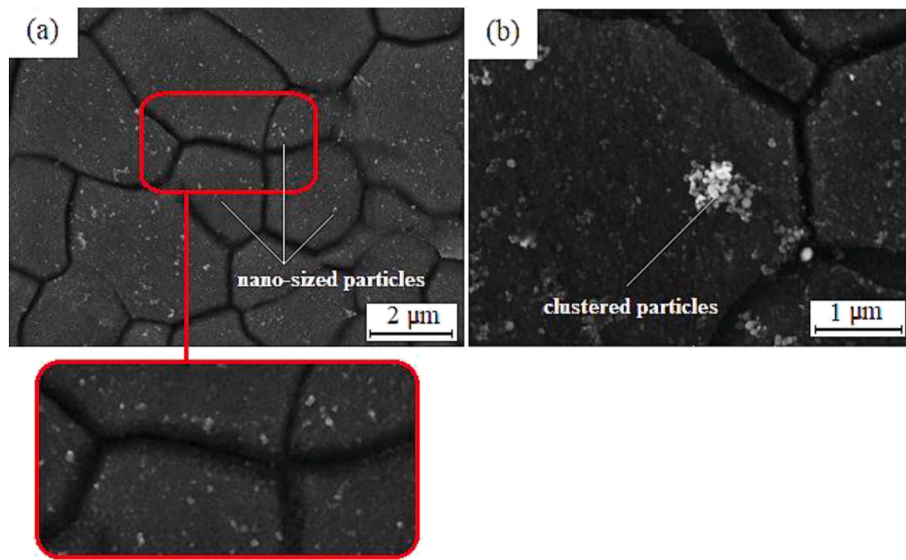


Fig. 4. Nano-sized particles distribution: (a) desirable distribution and (b) cluster of the particles.

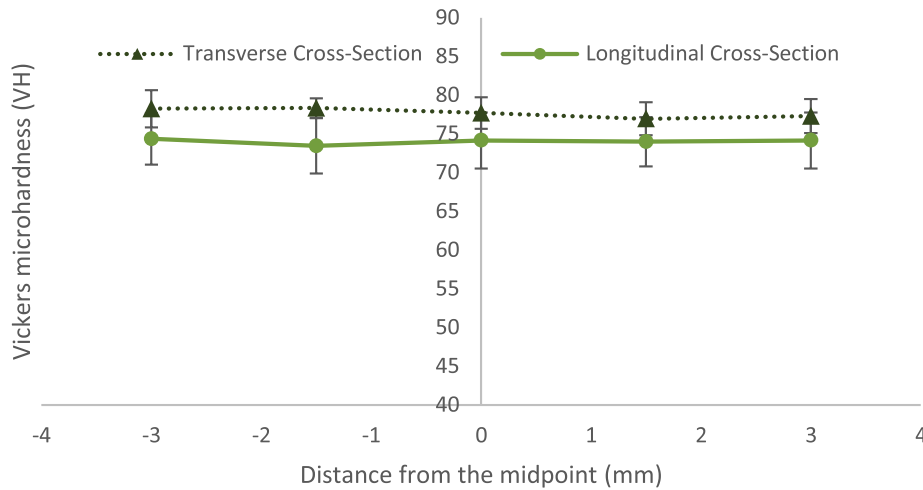


Fig. 5. Microhardness of the composite extrusion.

nucleation sites. Before starting the extrusion process, they also prevent grains from coarsening at the elevated temperatures as a pinning effect. Furthermore, they increase the dislocation density in the matrix, resulting in facilitating DRX during the hot-extrusion and a homogenous microstructure [31]. Hot-extrusion of magnesium and its alloy approximately above 175 °C can activate dynamic recovery and dynamic recrystallization [38,39]. According to Fig. 2, the grain size and the IPF map exhibit that a completely dynamic recrystallization (DRX) has occurred in the matrix, while the monolithic AZ31 alloy usually exhibits a limited DRX [40]. It was reported in the similar composites that a complete DRX can occur even at 150 °C due to the presence of the nano-sized Al_2O_3 particles [40,41]. The fitted log-normal distribution function ($f(x)$) is presented in Eq. (1), where x is the grain size:

$$f(x) = \frac{1}{1.324 x} \exp\left(-\frac{(\ln x - 1.733)^2}{0.559}\right) \quad (1)$$

Fig. 3 shows the pole figures and the inverse pole figures of the composite sample in the cross-section perpendicular to the extrusion direction. The extrusion process orients the basal planes approximately parallel to the extrusion axis, causing a strong basal texture [39,42]. Moreover, a $[10\bar{1}0]$ and $[11\bar{2}0]$ double fiber texture can be observed in

the inverse pole figures, although air-cooling can decrease $[10\bar{1}0]$ pole density as well as increase $[11\bar{2}0]$ due to the static recovery/recrystallization [43,44]. In addition, in comparison to the typical texture of monolithic AZ31 alloy, the nano-sized particles have decreased the intensity of the basal texture by deflecting the C-axis of the HCP structures in the matrix [44–47].

Fig. 4 exhibits the nano-sized particles distribution in the AZ31B matrix. Although the nano-sized Al_2O_3 tends to be agglomerated due to its low wettability, resulting in a few sites of clustered particles, the reinforcing phase has been appropriately distributed in the matrix.

3.2. Vickers microhardness

The microhardness of the composite is presented in Fig. 5 for both transverse and longitudinal directions. Similar values in different regions of the cross-sections indicate that the material has been deformed uniformly during the hot-extrusion process due to the extrusion conditions, resulting in a homogeneous microstructure [48]. Since the grains were extended parallel to the extrusion axis [44,49], less microhardness is expected in the longitudinal cross-section.

In the metal matrix composite, the presence of reinforcing particles increases the microhardness of the fabricated composite due to grain

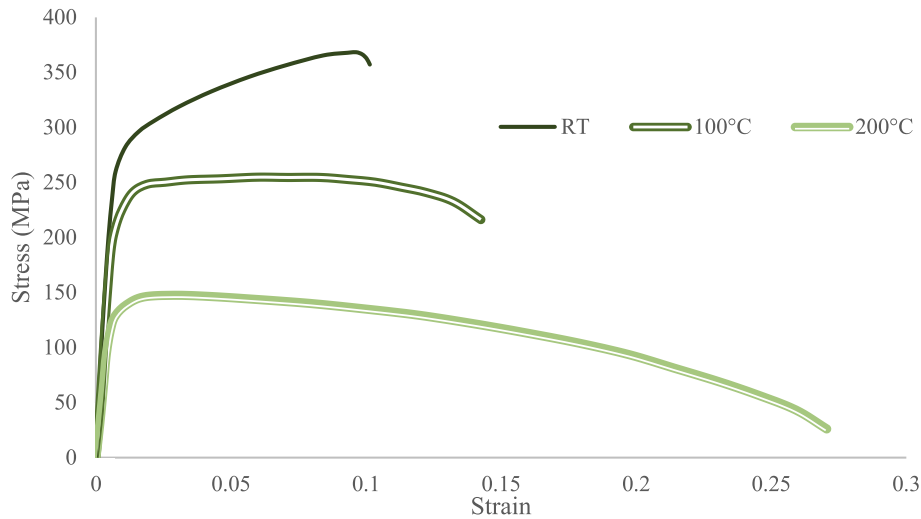


Fig. 6. Uniaxial tensile test results at room temperature, 100 °C, and 200 °C.

Table 1

Tensile properties of the composite samples.

Temperature	E (GPa)	σ_y (MPa)	σ_{UTS} (MPa)	ϵ (mm/mm)
RT	50 ± 1.24	265 ± 4.41	368.3 ± 4.65	0.1 ± 0.0084
100 °C	36.8 ± 0.97	214 ± 0.79	254.8 ± 5.95	0.143 ± 0.029
200 °C	26.5 ± 1.076	127 ± 7.01	147.5 ± 1.86	0.271 ± 0.048

refinement, enhancement of dislocation density, participation of reinforcing particles in the load bearing, and prevention of the dislocation motions and local plastic deformation [31,42,50,51].

3.3. Uniaxial tensile test

Fig. 6 shows the results of the uniaxial tensile test at room temperature (RT), 100 °C, and 200 °C. As expected, increasing the test temperature decreases both yield stress and ultimate tensile strength, while the ductility of the composite is improved. At the elevated temperatures, in addition to basal slip system, non-basal ones including prismatic and pyramidal are activated, helping to improve the ductility and decrease the flow stress [9,52,53]. In fact, at higher temperatures, the critical resolved shear stress (CRSS) decreases, leading to an increase in the ductility and a decrease in the yield stress and ultimate tensile strength. By comparing the stress-strain curves at the elevated temperatures, it can be observed that although the flow stress increases by enhancing the applied strain at room temperature, no strain hardening occurs at 100 °C. Moreover, the composite exhibits a strain softening behavior at 200 °C due to dynamic recrystallization and damaging [40]. At the elevated temperature, the fracture behavior of the composite changes to a complete ductile mode [31]. Hassan et al. [51] reported that nano-sized Al_2O_3 particles are able to maintain their strengthening capacity in the pure magnesium up to 150 °C, however, the strength reduction was significant beyond that temperature. Furthermore, these reinforcing particles effectively inhibited the grain growth of the pure magnesium matrix up to 200 °C. For AZ31/1.5 vol.% Al_2O_3 , the thermally stable reinforcing particle can have an exacerbating effect on the softening of the AZ31 matrix at the elevated temperatures [40].

The tensile properties of the composite at different temperatures within one standard deviations are presented in Table 1. In general, UTS and yield stress of magnesium matrix composites improved due to the Hall-Petch strengthening mechanism, Orowan mechanism, increasing the dislocation density, inhibiting the motion of dislocations, and enhancing capacity of load bearing [17,21,42,54]. The nano-sized particles not only increase the yield stress and UTS but can also improve the ductility

of the matrix. The ductility improvement can be attributed to more activity of the basal systems (due to the texture modification) and the initiation of prismatic slip systems even at room temperature, which is confirmed by dislocation studies [21]. It is also reported that Al elements can improve the activity of prismatic slip system at room temperature in Mg–Al alloys [55].

3.4. Low cycle fatigue

Fig. 7 exhibits the first, second, and half-life stress-strain hysteresis loops of the composite at room temperature for strain amplitudes of 0.5%, 0.8%, and 1.25%. A remarkable difference between the compressive behavior of the composite at the first and other cycles can be observed, especially for the strain amplitudes of 0.5% and 0.8%. This may be related to the back stress of the residual twins in the microstructure after the first cycle. It has been reported that during reverse loading, the back stresses generated by deformation twins can facilitate the dislocations movement in the backward direction [9]. The shape of the half-life loops depends on the total strain amplitudes that are applied. While the composite exhibits near a symmetric behavior at the strain amplitude of 1.25%, it behaves asymmetrically at other total strains due to the activity of twinning and detwinning deformation mechanisms during the compressive and reverse tensile loading, respectively [9,36,44,56]. Considering the fiber basal texture of the composite which was shown in Fig. 3, extension twinning $[10\bar{1}2]\langle 10\bar{1}1 \rangle$ is initially the dominant mechanism when the composite is compressed along the extrusion direction [44,56,57]. When the sample is subsequently subjected to a reversal tensile load, it is primarily deformed by detwinning mechanism [36,44]. Then, when detwinning is almost completed, the slipping systems will govern the deformation and increase the hardening rate. This transmutation causes an inflection point in the curve, resulting in a sigmoidal shape [55,56], which cannot be observed in the monotonic tensile test. At the strain amplitude of 1.25%, a similar behavior appeared under the reversal compressive load. By increasing the compressive strain up to 1.25%, the twinning is saturated and as a result, the slipping system plays the main role (in a manner similar to what happens by applying the higher tensile strains). Therefore, another inflecting point is added to the curve. Furthermore, twin-dislocation interaction increases the hardening rate due to the dislocation movement inhibition by twin boundaries [36,55].

In magnesium and its alloys, applied strain, temperature, texture, and strain rate are the four effective parameters on the relative activity of deformation mechanisms and systems [58–62]. Unlike the basal slip system and extension twinning, the amounts of critical resolved shear

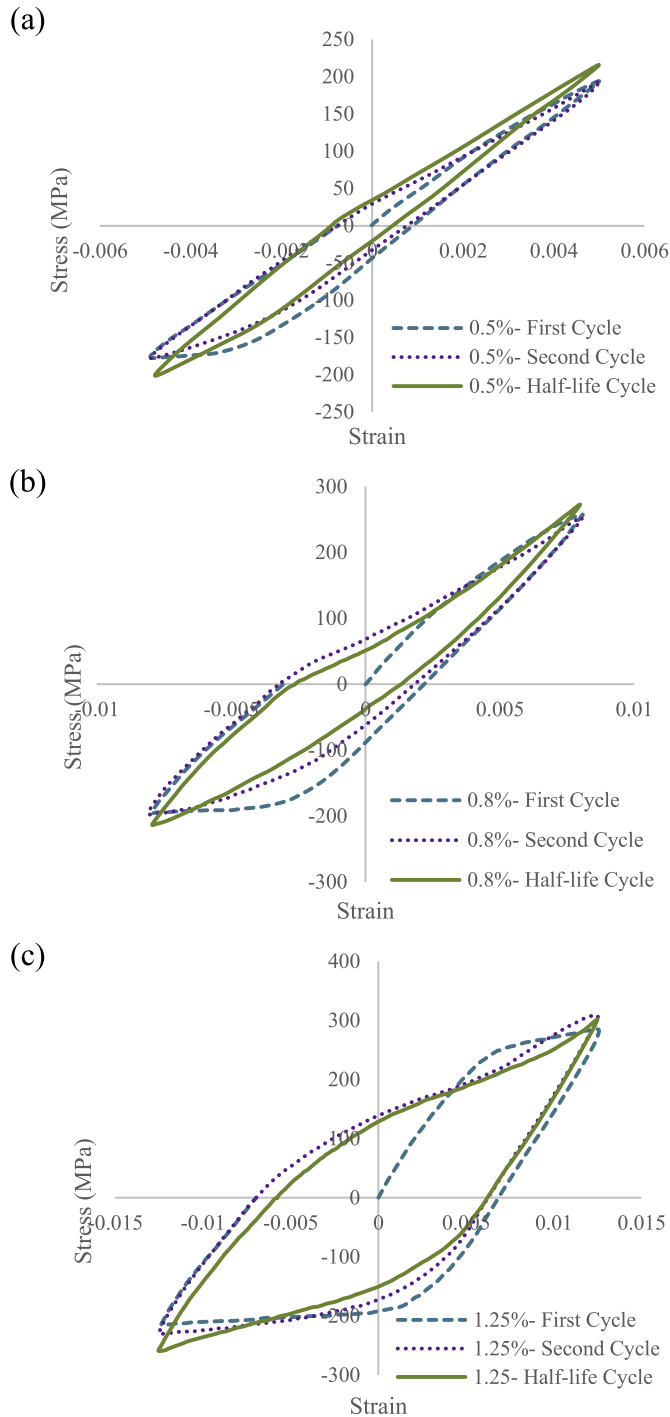


Fig. 7. Room-temperature stress-strain hysteresis loops at different strain amplitudes of: (a) 0.5%, (b) 0.8%, and (c) 1.25%.

stress (CRSS) of prismatic, pyramidal I & II, and contraction twinning depend to a great extent on temperature. At room temperature and with a limited applied plastic strain, basal slip (as the easiest system) and extension twinning play the major role in plastic deformation due to their low CRSS [58]. Increasing the temperature results in a significant drop in the CRSS of other deformation mechanisms and systems, causing more relative activity in them and a reduction in the yield stress.

As shown in Fig. 8, increasing the temperature to 100 °C decreases the asymmetric behavior of the composite extrusion marginally. As explained, the minor reduction of CRSS of prismatic and pyramidal slip systems at 100 °C can be considered as the main reason of attenuated

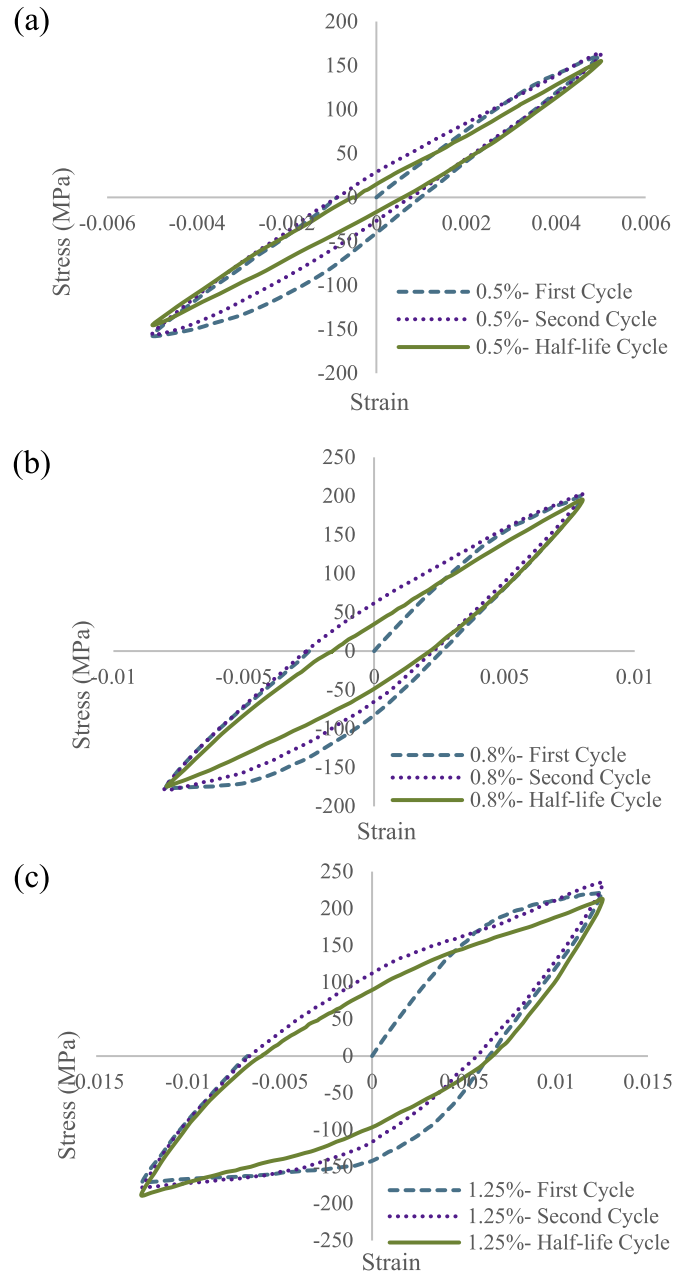


Fig. 8. Stress-strain hysteresis loops at 100 °C and different strain amplitudes of: (a) 0.5%, (b) 0.8%, and (c) 1.25%.

asymmetry, making the activity of non-basal slip planes more possible [56]. However, two inflecting points at the strain amplitude of 1.25% can still be observed, although the sigmoidal behavior is weakened considerably.

Fig. 9 illustrates the first, second, and half-life stress-strain hysteresis loops at 200 °C for different strain amplitudes. At this temperature, the prismatic and pyramidal slip systems can be activated and slip-based deformation mechanism is dominated in both loading directions, instead of twinning-detwinning, due to the significant reduction in their CRSS [9,10,58]. Consequently, the composite exhibits an approximately symmetric behavior under the cyclic loading. Unlike the cyclic behavior at room temperature and 100 °C, significant cyclic softening can be observed, which can be attributed to the DRX and damaging in the matrix and matrix-reinforcement interface. Considering the tensile tests results, the composites exhibited similar hardening/softening behaviour during the monotonic tensile loading at the corresponding

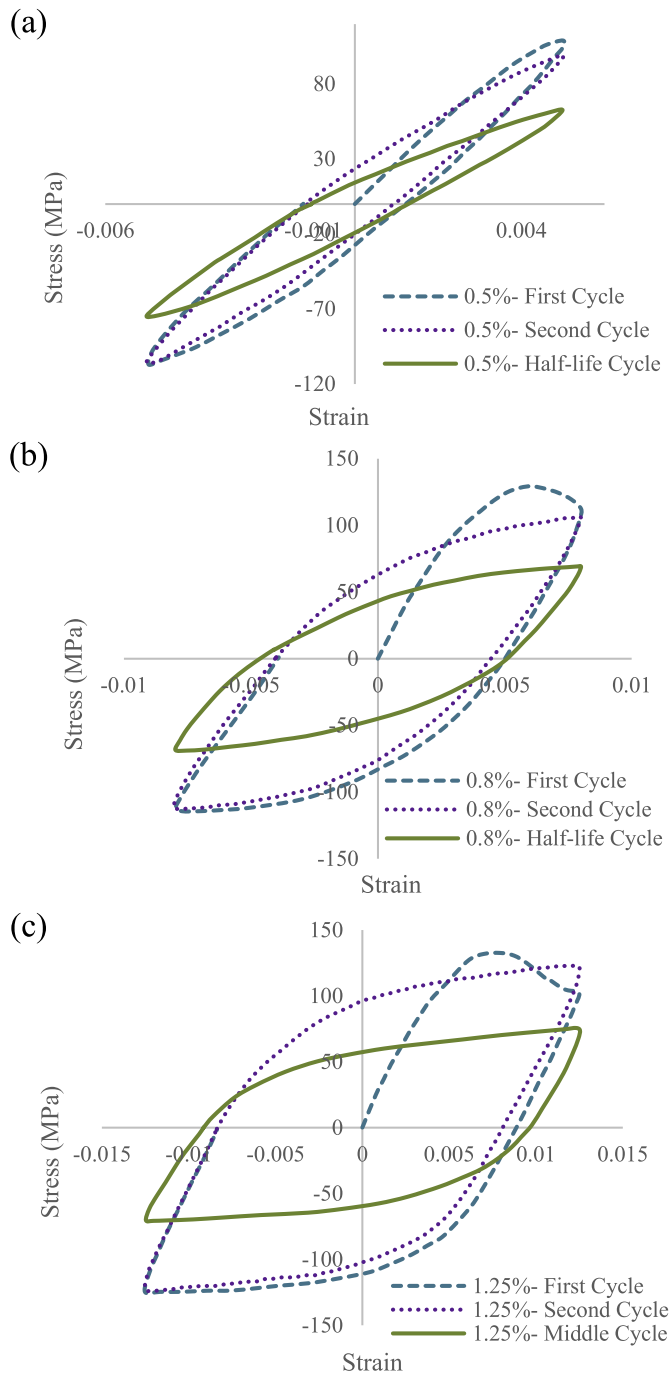


Fig. 9. Stress-strain hysteresis loops at 200 °C and different strain amplitudes of: (a) 0.5%, (b) 0.8%, and (c) 1.25%.

temperatures. It is worth noting that the presence of nano-sized particles in the matrix increases the DRX, resulting in more softening behaviour and also a homogenise microstructure, as it was observed in Figs. 2 and 5.

Half-life cycles of the composite at different strain amplitudes and temperatures are demonstrated in Fig. 10. In addition to the change of the asymmetric behavior to a symmetric one and elimination of the deflecting points, wider hysteresis loops can be observed by elevating the temperature. Moreover, although the absolute amounts of the maximum and minimum stresses in the half-life loops increases by applying higher total strain amplitudes at room temperature and 100 °C, the composite show almost similar or decreased minimum stresses at 200 °C.

The minimum and maximum stresses of the hysteresis loops at the different conditions and cycles are shown in Fig. 11. In general, the hardening trend is influenced by the applied strain amplitude [55]. At room temperature, tensile mean stresses can be observed for all the strain amplitudes due to the asymmetric behavior. Similar results were reported for AZ31 [63]. At the strain amplitude of 0.5% and 0.6%, cyclic hardening is inconsiderable. While cyclic hardening has been usually reported for AZ31 extrusion at the ambient temperature, a cyclic softening was observed by Huppmann et al. [44] under small strain ranges. At the strain amplitudes of 0.7% and 0.8%, the composite experienced a hardening during the applied loading. Cyclic loading generates some residual twins in the microstructure due to twinning-detwinning [55,64,65]. The amount of this residual twins increases at higher strain amplitudes [66]. Twin-dislocation interaction and/or dislocation-dislocation interaction can result in cyclic hardening [36]. As well as increased dislocation densities, more residual twinning boundaries enhances the required stress for slip and twinning activities [64,67]. At 0.9%, 1%, and 1.25%, an initial cyclic hardening with a high hardening rate followed by a cyclic softening or constant behavior was seen in the maximum tensile stress, which may be related to the damaging and/or twins capacity saturation [55]. On the other hand, continued hardening occurs under the compressive loads. This can be attributed to the damage evolution, which decreases the strength of the material under the tensile loading with no effect on the compressive strength [36].

At 100 °C and the strain amplitudes between 0.5% and 0.8%, a slight cyclic softening occurred after approximately 500 cycles, while an insignificant hardening can be observed at the beginning. For the strain amplitudes above 0.8%, an initial slight hardening is followed by a cyclic softening under tensile loading. In addition, the material is marginally hardened by compressive loading at the strain amplitudes of 0.9%, 1%, and 1.25%. By increasing the test temperature to 200 °C, the composite at all the strain amplitudes and loading directions exhibits a cyclic softening behavior. Similar results were reported for the monolithic AZ31 alloy [9]. Under tensile loading and at the initial and final cycles, the softening occurred with higher rates. While the initial softening could occur due to the DRX, the final one is in relation with damaging in the composite. Applying more strain amplitudes results in more severe softening, which could indicate the effect of damaging.

Fig. 12 illustrates the mean stress values of the hysteresis loops. Like AZ31 alloy at the ambient temperature [68], positive mean stresses generally generated in the samples during the cyclic loading at room temperature and also 100 °C. On the other hand, it decreases to approximately zero values at 200 °C due to the symmetric behavior [9]. At room temperature, the samples at the strain amplitudes of 0.5%–0.8% experience significant increase in the mean stress after a reduction in the first 100 cycles. Albinmoussa et al. [36] reported similar behavior for AZ31B. In contrast, the specimens subjected to the strain amplitudes of 0.9%, 1%, and 1.25% exhibit an initial increase and subsequently considerable decrease in the mean stress. The similar cyclic hardening and softening under tensile loads and also the cyclic hardening in the compression loads could be the main reason of this behavior, as was shown in Fig. (11-a). At 100 °C, samples usually show an initial mean stress enhancement followed by a reduction, which is consistent with their hardening/softening behavior under the tensile loading. In the case of 200 °C, regarding the symmetric behavior of the composite, the mean stresses drop to very low levels.

A comparison between the monotonic and cyclic stress-strain curves (for both tensile and compressive loads) at different test temperatures is shown in Fig. 13. At room temperature, cyclic and monotonic tensile stress-strain curves are similar. In fact, although a slight cyclic hardening occurred initially in the composite, further softening (which could be attributed to the damaging) counteracts its effect. Nonetheless, the cyclic compressive stress-strain curve shows a hardening in comparison with the monotonic one. In general, damages show less effects under compressive loads [36].

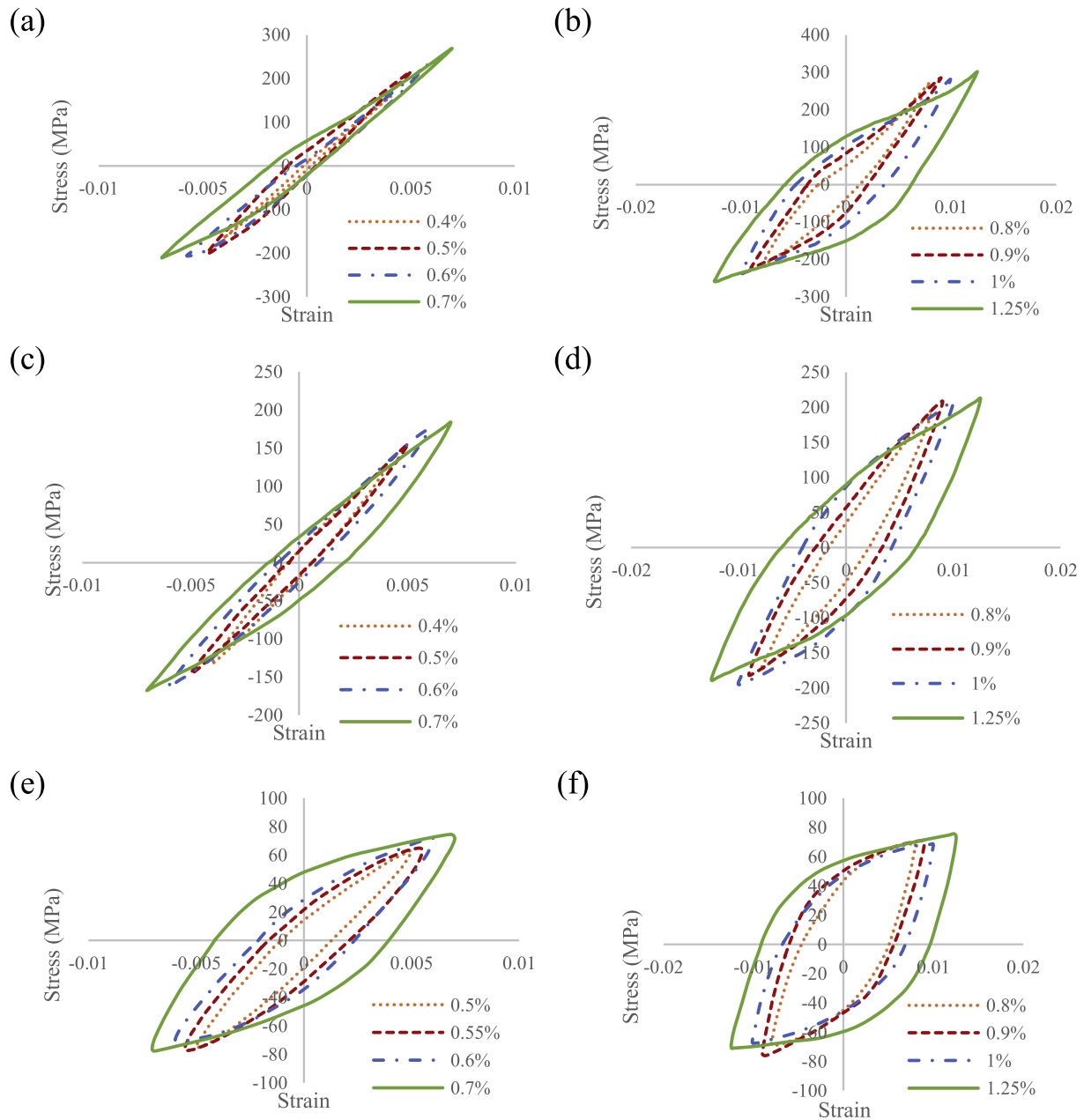


Fig. 10. Half-life hysteresis loops at: (a), (b) room temperature, (c), (d) 100 °C, and (e), (f) 200 °C.

At 100 °C, a slight strain softening with similar trend can be observed in the cyclic stress-strain curves under the tensile load. However, the cyclic compressive stress-strain curve exhibits a comparable behavior with a limited hardening at the large strain amplitudes. Finally, the material indicates a strain softening under both tensile and compressive cyclic loading at 200 °C, compared to the monotonic curves.

3.5. Fatigue life models

Three main approaches are widely used for modelling fatigue life and fatigue damage of magnesium and its alloys subjected to uniaxial and multiaxial cyclic loading at room temperature including strain based approaches (regardless of prediction of crack propagation direction), critical plane strain based approaches and energy based approaches. It is worth noting that the stress based approaches cannot predict the fatigue life of magnesium alloys correctly due to unusual changes of maximum and mean stresses during strain-controlled fatigue tests [55]. The

power-law equation between applied total strain range and the number of cycles to failure is known as the Coffin-Manson-Basquin (CMB) equation [69]. In order to predict the cracking direction in addition to the fatigue life and damage, critical plane models such as Smith-Watson-Topper (SWT) and Fatemi-Socie were developed. In these models, the plane with the maximum SWT parameter and the maximum value of shear strain are considered respectively as the critical planes for SWT and FS models [70,71].

Since the mechanical behavior of anisotropic materials depends on the loading direction, a scalar valued function such as energy can be considered as a potential fatigue parameter for damage measurement [36]. Energy based methods are able to take into account the effect of mean stress, leading to a more promising prediction of fatigue life in anisotropic materials. It has been established in different studies that Jahed-Varvani (JV), as an energy-based model, has the capability to predict fatigue life of magnesium alloys under uniaxial and multiaxial cyclic loading including proportional and non-proportional conditions

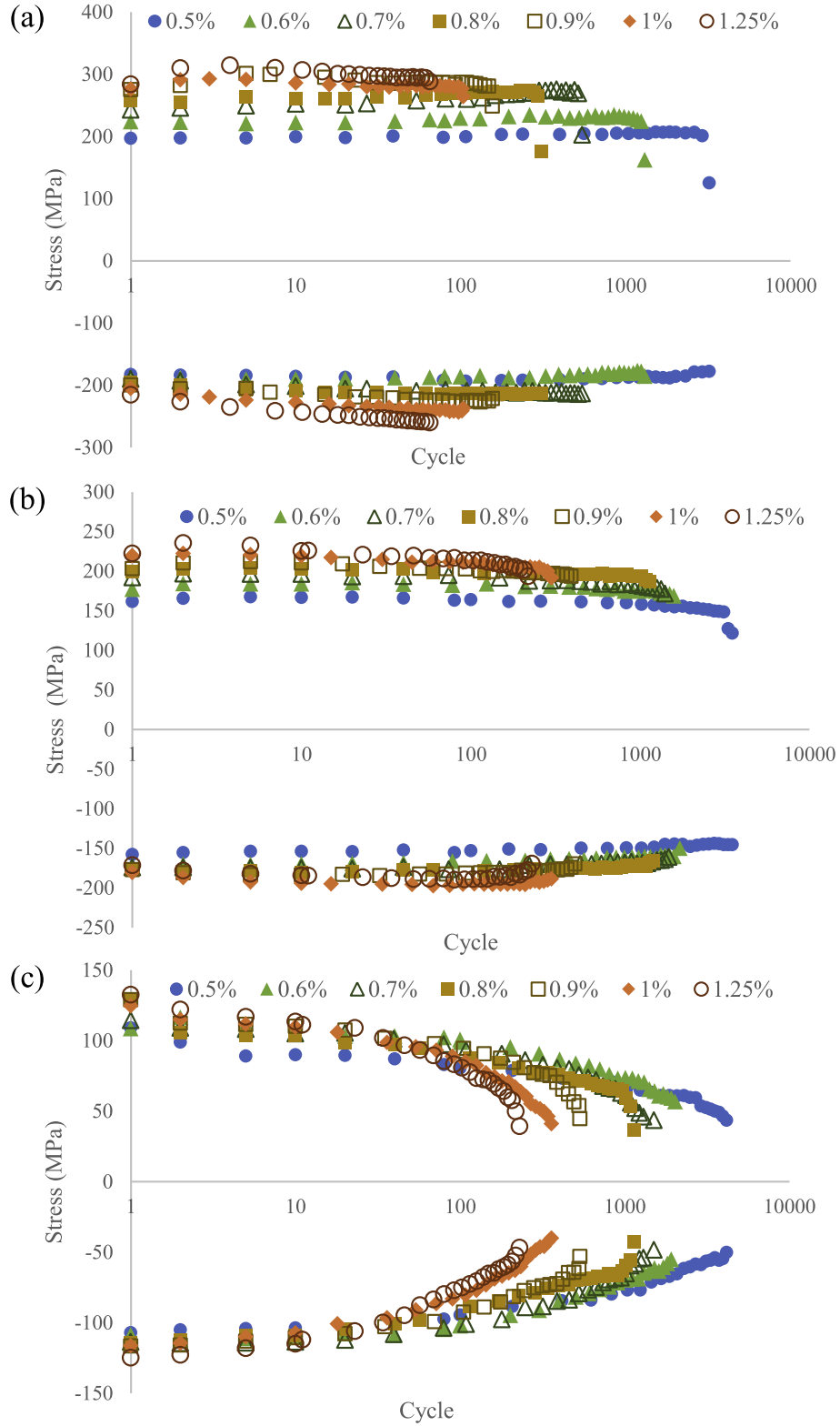


Fig. 11. Minimum and maximum stresses at different cycles: (a) room temperature, (b) 100 °C, and (c) 200 °C.

[4,55,72].

In the context of anisotropic and asymmetric behavior of wrought magnesium alloys, employing an appropriate model for prediction of fatigue life and fatigue damage is a challenging process. In Coffin-Manson-Basquin (CMB) as a strain based model, the fatigue life is a function of the summation of elastic strain $\left(\frac{\Delta\epsilon_e}{2}\right)$ and plastic strain $\left(\frac{\Delta\epsilon_p}{2}\right)$

amplitudes as it is presented in Eq. (2) [69].

$$\frac{\Delta\epsilon_e}{2} + \frac{\Delta\epsilon_p}{2} = \left(\frac{\sigma_f'}{E}\right)(2N_f)^b + \epsilon_f'(2N_f)^c \quad (2)$$

where E is the elastic modulus, σ_f' and ϵ_f' are the fatigue strength and fatigue ductility coefficients, b and c are the exponents of fatigue

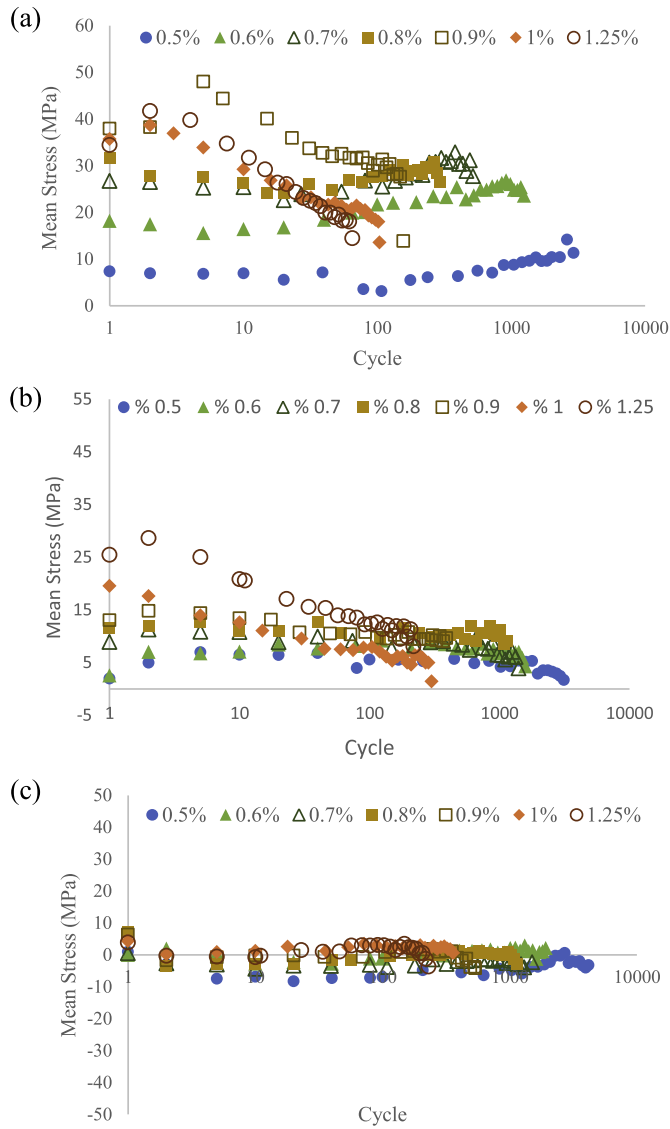


Fig. 12. Mean stresses versus the number of cycles at: (a) room temperature, (b) 100 °C, and (c) 200 °C.

strength and fatigue ductility, and $2N_f$ is the number of reversals. To predict the crack growth direction in addition to the fatigue life and damage, critical plane approaches have been proposed. In the Smith-Watson-Topper (SWT) model, as one of the most widely used models, the plane with the maximum SWT parameter is defined as the critical plane [71]. In order to consider stress effects, the maximum normal stress was added (on the critical plane with the maximum normal strain), $\sigma_{n,max}$, to CMB equation according to Eq. (3):

$$SWT \text{ Parameter} = \sigma_{n,max} \frac{\Delta \epsilon}{2} = \left(\frac{\sigma_f^2}{E} \right) (2N_f)^{2b} + \sigma_f \epsilon_f (2N_f)^{b+c} \quad (3)$$

The Jahed-Varvani (JV) model was presented to predict the fatigue life and damage under uniaxial and multiaxial loading [73,74]. The total strain energy (the summation of positive elastic and plastic strain energy densities) was considered as the main factor of the fatigue damage and an equation based on CMB was proposed (Eq. (4)) [55,75]:

$$\Delta E = \Delta E_e^+ + \Delta E_p = \frac{(\sigma_{max} + \sigma_{mean})\sigma_a}{2E} + \oint_{cycle} \sigma_x d\epsilon_{xx}^p = E_e (2N_f)^B + E_f (2N_f)^C \quad (4)$$

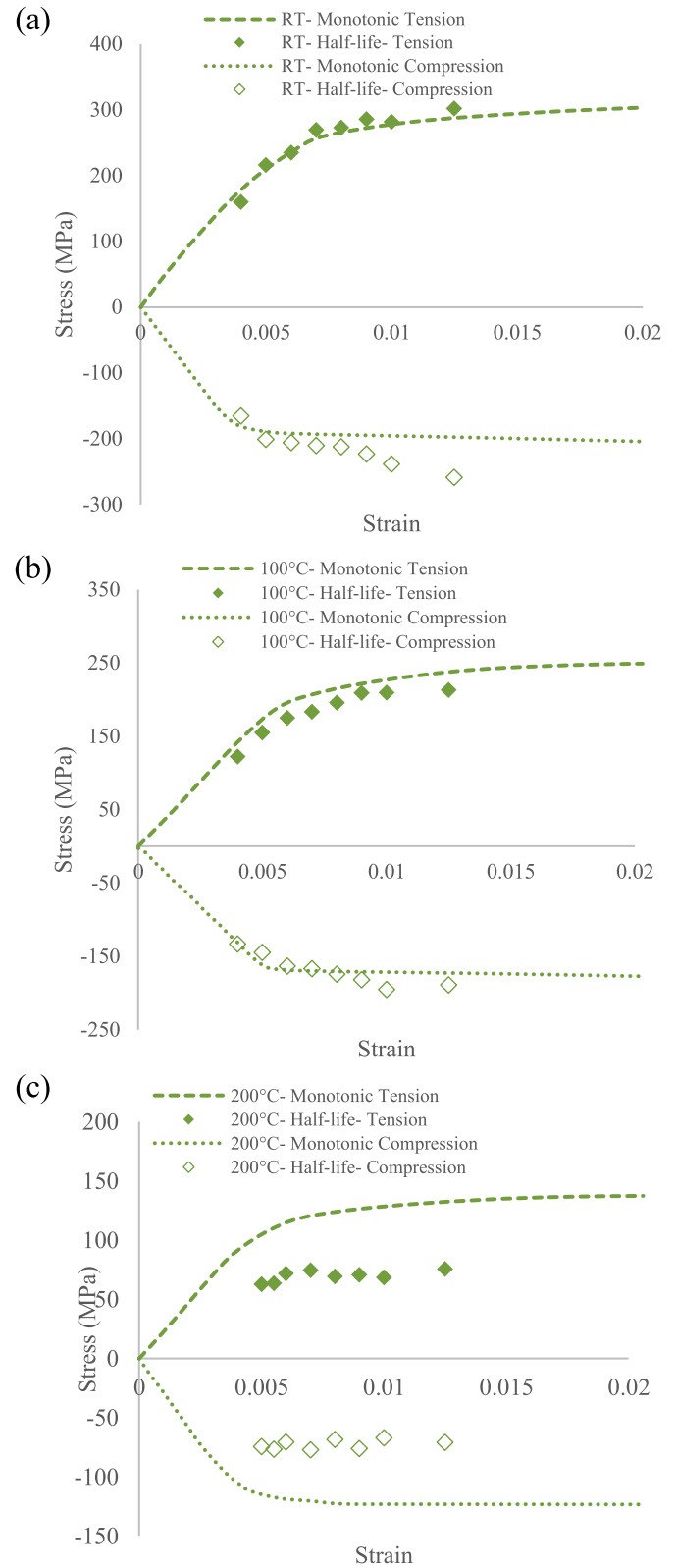


Fig. 13. Cyclic and monotonic stress-strain curves for both tensile and compressive loadings at: (a) room temperature, (b) 100 °C, and (c) 200 °C.

Here, ΔE , ΔE_e^+ , and ΔE_p are the total strain energy density, positive elastic strain energy density, and plastic strain energy density, respectively. Also, E_e and E_f are the fatigue strength and fatigue toughness coefficients and B and C are the fatigue strength and fatigue toughness exponents σ_{max} , σ_{mean} , σ_a , σ_x , $d\epsilon_{xx}^p$ respectively represent the maximum

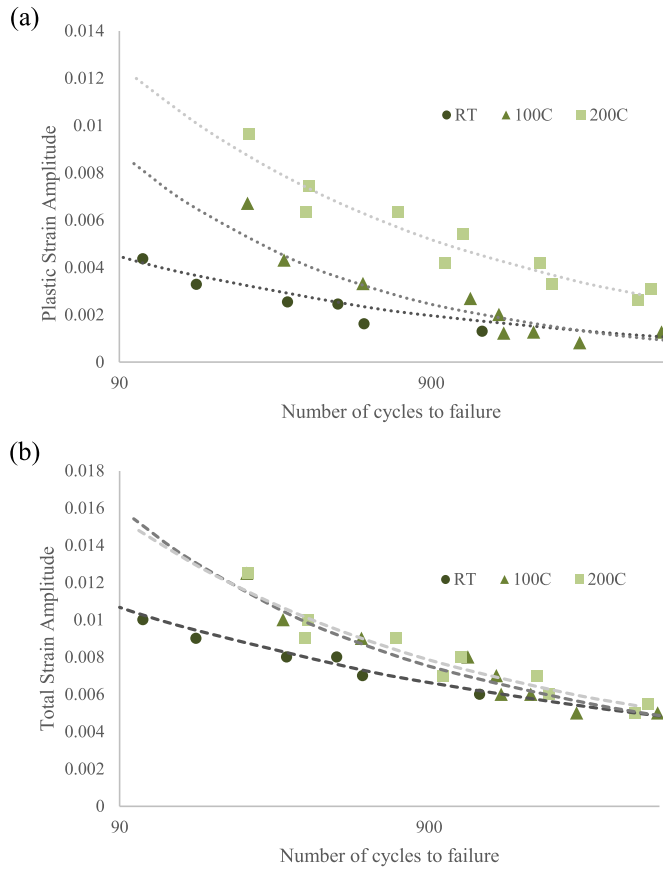


Fig. 14. Plastic and total strain amplitudes versus the number of cycles to failure curves at different temperatures: (a) plastic strain, (b) total strain.

tensile stress of the hysteresis loop, the mean stress, the stress amplitude, the normal stress component, and the normal strain component.

Plastic and total strain amplitudes versus the number of cycles to failure at room temperature, 100 °C and 200 °C are illustrated in Fig. 14. The dotted lines and the dashed lines respectively show the Coffin-Manson and Coffin-Manson-Basquin models for the plastic strain and the total strain amplitudes.

By increasing the temperature to 200 °C, the biggest portion of the total strain amplitude belongs to the plastic strain (as the main factor in damaging [44]), compared to the elastic strain, which can be confirmed by considering the increased width of the hysteresis loops. At a constant total strain amplitude, the ratio of the applied total strain to the

maximum strain would decrease significantly, since the ductility of the composite improved at the higher temperatures. As a result, even though the strength of the material experiences a decrease at 100 and 200 °C, the strain-controlled fatigue life would be equal or improved at the elevated temperatures. It is worth noting that a brittle oxide layer can be formed on the surface of the samples at 200 °C. Since the fatigue crack is initiated at the early cycles in LCF regime at higher stresses [76], however, it has less effect on the fatigue life. To calculate the parameters of the different fatigue life models, regression analysis using the least squares method was employed. The parameters obtained for the CMB, SWT, and JV models are shown in Table 2. An uncertainty analysis can be done on the model outputs according to what has been presented in Ref. [77].

To assess and compare the capability of different models to predict the fatigue life of the composite at different temperatures, the root mean squared logarithmic error (RMSLE) between the predicted and the experimental lives were calculated (Table 3) [75]. Although the RMSLE at 100 and 200 °C are comparable in all the models, JV can predict the fatigue life at all the temperatures more appropriately and exhibits the least average RMSLE at different temperatures.

Fig. 15 presents the correlation of the predicted fatigue lives with the experimental lives at room temperature, 100 °C, and 200 °C. Diagonal solid, dash-dotted, and long-dashed lines indicate the perfect match, factor of 1.5 bounds, and factor of 2 bounds between the predicted and the experimental lives, respectively.

Due to the strain softening, the maximum and consequently the mean stress decreases on increasing the temperature. This reduction cannot be considered in the CMB model. Moreover, despite the fact that SWT takes the maximum stresses into consideration, it employs the CMB equation parameters. As a result, SWT does not have enough flexibility to derive modified parameters in the case of high-temperature fatigue. On the other hand the JV model, in addition to the independency on the loading direction, indirectly takes the effect of the mean stress into account.

4. Conclusion

Fully-reversed uniaxial tension-compression fatigue tests were conducted on AZ31B/1.5 vol.% Al₂O₃ nanocomposite at room temperature, 100 °C, and 200 °C. The experiments were performed under a strain-controlled condition for the applied strain amplitudes between 0.4% and 1.25%. The following conclusion can be drawn according to the presented results:

- 1) In comparison to the well-known texture of monolithic AZ31B extrusion, the basal planes of the composite samples are deviated slightly due to the presence of nano-sized reinforcing particles.

Table 2

The parameters of the fatigue life models.

Models parameters	Coffin-Manson-Basquin				Smith-Watson-Topper				Jahed-Varvani			
	$\frac{\sigma_f}{E}$	ϵ_f	b	c	$\frac{\sigma_f^2}{E}$ (MPa)	$\sigma_f \epsilon_f$ (MPa)	2b	b + c	E_e (MJ/m ³)	E_f (MJ/m ³)	B	C
RT	0.0108	0.0222	-0.123	-0.356	5.832	11.988	-0.246	-0.479	2.9757	78.704	-0.243	-0.733
100 °C	0.0139	0.1107	-0.148	-0.56	7.11	56.625	-0.296	-0.708	3.3247	-0.295	168.05	-0.762
200 °C	0.0034	0.0711	-0.035	-0.385	0.306	6.406	-0.07	-0.42	0.1557	66.243	-0.073	-0.645

Table 3

RMSLE calculated for different fatigue life models.

Temperature	Room Temperature			100 °C			200 °C			Average		
Model	CMB	JV	SWT	CMB	JV	SWT	CMB	JV	SWT	CMB	JV	SWT
RMSLE	0.116	0.072	0.102	0.128	0.109	0.114	0.127	0.115	0.150	0.124	0.099	0.122

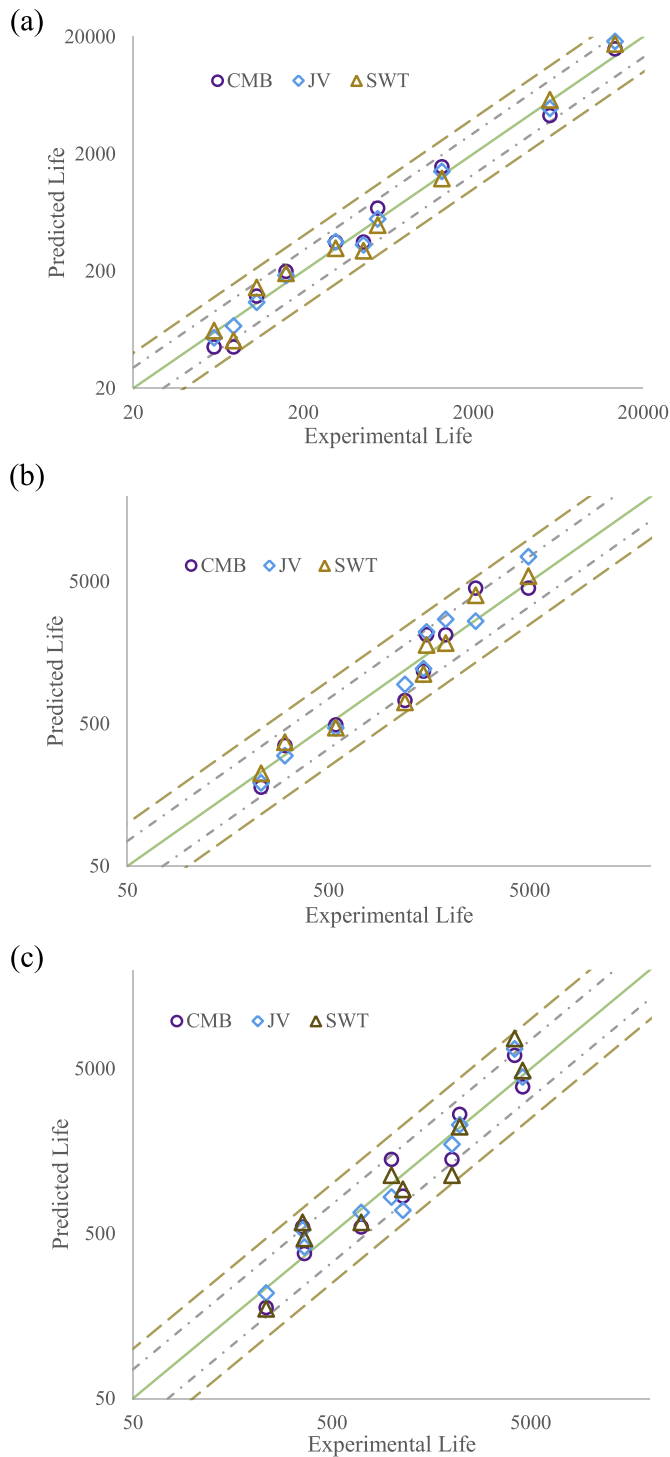


Fig. 15. Correlation of the predicted lives with the experimental lives at: (a) room temperature, (b) 100 °C, (c) 200 °C.

- 2) By increasing the temperature to 200 °C, the hysteresis loops of the composite changed from an asymmetric shape to a symmetric one, resulting in decrease of the mean stress at the higher temperatures.
- 3) Unlike the situation at room temperature, there is no inflection point in the hysteresis loops at 200 °C. This confirms that twinning and detwinning are not the major deformation mechanisms at the elevated temperatures due to the activation of prismatic and pyramidal slip systems.
- 4) Cyclic stress softening occurs at the elevated temperatures, similar to the uniaxial monotonic loading.

- 5) Under the strain-controlled condition, the composite shows an improved fatigue life at the higher temperatures compared to those of the room-temperature results. The ductility enhancement and consequently decreasing the fatigue damage during each loading cycle could be the main reason for the fatigue life enhancement at the elevated temperatures, although the yield and ultimate strengths of the material decrease considerably.
- 6) Among the various fatigue life prediction models examined, including Coffin-Manson-Basquin, Smith-Watson-Topper and Jahed-Varvani, the last of these three was in general able to offer a more desirable prediction of fatigue life, taking the results at all the temperatures into consideration.

Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time due to legal or ethical reasons.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: <https://www.elsevier.com/authors/journal-authors/policies-and-ethics/credit-author-statement>.

CRediT authorship contribution statement

A.H. Jabbari: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **A. Shafiee Sabet:** Formal analysis, Investigation, Resources, Writing - review & editing. **M. Sedighi:** Conceptualization, Methodology, Validation, Resources, Data curation, Writing - review & editing, Supervision, Project administration. **H. Jahed:** Methodology, Validation, Writing - review & editing. **C. Sommitsch:** Validation, Resources, Writing - review & editing.

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