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Fatigue and Fracture Characterization of HPDC AM60B Magnesium Alloy at Cold Temperature

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An investigation of the fatigue and fracture characterization of the high pressure die cast (HPDC) AM60B magnesium alloy at −40 °C temperature was conducted by means of the constant load amplitude fatigue test. The results demonstrated that low temperature had a significant influence on alloy's fatigue life; the life increased at −40 °C temperature as compared to that at room temperature. The fracture surfaces of the tested specimens were observed under a scanning electron microscope (SEM) to further understand the fracture phenomenon at low temperature.

Keywords AM60B magnesium alloy, brittle, ductile fracture, SEM (scanning electron microscope), S-N curves, stress ratio

1. Introduction

Magnesium alloys are increasingly being utilized as one of the important structural materials due to their relatively lower weight and high specific strengths. As a result, Mg alloys have been used in several automobile applications and their use is increasing. Among all other magnesium alloys, cast magnesium alloys are finding incremental use in the automotive industries. Therefore, the ongoing interest in the use of cast magnesium alloys in the automotive industries has recently triggered substantial research efforts, mainly focusing on characterization of the structural properties of the alloys (Ref 1). Most magnesium applications presently used in the automotive industry are in the form of high pressure die cast (HPDC). Applications of HPDC AM60B magnesium alloy, such as those in front and support assemblies, steering wheel armature, instrument panel, and steering column support brackets, play a vital role in automotive industry (Ref 2). The more significant use of the alloy in different fields demands knowledge about the fatigue response of the alloy. However, relatively low fatigue strength under service conditions has been a pressing issue, restricting the application of magnesium alloys to low-stress designs (Ref 3, 4).

In this study, AM60B alloy, which has been characterized as an alloy with outstanding ductility and energy-absorbing properties combined with good strength, less weight, and castability, is considered.

Materials, especially those with relatively low fracture toughness, could fail at stress levels below their ultimate strength. It has been indicated that the porosity level of components can influence materials' mechanical properties, such as the ultimate tensile strength (UTS), yield strength (YS), and elongation (ε_f) (Ref 5, 6).

In the recent years, some studies have been done on fatigue characterization of various die-cast magnesium alloys. However, a very limited number of studies has been done on fatigue characterization of HPDC magnesium alloys. It should also be noted that the fatigue of HPDC AM60B magnesium alloys at low temperature has hardly been studied. The increase in the fatigue strength and endurance limit as a function of decreasing temperature is a common tendency in some materials (such as for steel alloys). On the other hand, fatigue strength is known to decrease due to increase in the ambient temperature. Kotch (Ref 7) also investigated the fatigue limit of HPDC AM60 magnesium alloy. Later, Lu et al. (Ref 8-10) reported the fatigue characterization of HPDC AM60B magnesium alloy at room temperature. However, the last two sets of studies did not investigate the fatigue behavior of the alloy at cold temperature.

Moreover, Sajuri et al. (Ref 11) studied the effects of humidity and temperature on the fatigue behavior of an extruded AZ61 magnesium alloy. According to the results found by Sajuri, it was identified that a significant reduction in fatigue strengths was observed with an increase of temperature to 150 °C. Venkateswarana et al. (Ref 12) reported the fatigue crack growth behavior of a die-cast AZ91D magnesium alloy. Grinberg et al. (Ref 13) described the effect of low temperature on the fatigue failure of a magnesium alloy of MA12. According to the Grinberg's results, it was identified that reductions in temperature led to an increase in fatigue limit. When the temperature was reduced from 20 to −120 °C with identical cyclic loading, the fatigue life of MA12 magnesium alloy was increased due to the crack initiation stage. As one of the main objectives of this research, the fracture and fatigue response of HPDC AM60B magnesium alloy was investigated at cold (sub-freezing) temperature. In addition, the influence of temperature on the fracture surfaces of the test specimens was characterized using SEM fractography. Moreover, to gain a better understanding of the response of the alloy, basic tensile properties of the alloy were also obtained by conducting static tensile tests.

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2. Material and Compositions

Most commercial casting Mg alloys contain 2-9 wt.% aluminum. Under equilibrium conditions, the cast Mg alloy should solidify as a single phase α-Mg solid, and upon further cooling, should lead to the solid-state precipitation of β-$Mg_{17}Al_{12}$ within the α-grains (Ref 1). The presence of the brittle eutectic phase $Mg_{17}Al_{12}$ affects mainly the mechanical properties of cast Mg alloys (Ref 14). For this study, test specimens were extracted from die cast AM60B Mg alloy plates provided by the Meridian Technologies Inc. (Strathroy, Ontario). The chemical composition of the alloy is shown in Table 1.

3. Experimental Procedures

Flat dog-bone-shaped tensile and fatigue specimens were extracted from the plates according to ASTM standard E-8M (Fig. 1a) and E-466 (Fig. 1b), respectively, for static and cyclic tests (Ref 15, 16). The samples were prepared with proper surface-finishing procedure, and the damaged metal on the machined surface was removed by grinding and polishing. The mechanical properties of the alloy were measured by uniaxial tensile test conforming to ASTM E8 (Ref 15). Monotonic and cyclic tastings (at room as well as at cold temperature of −400 °C) were conducted using a servo-hydraulic Instron 8501 machine controlled with the test star system. For the cyclic tests, four stress amplitudes were considered from 85 to 115 MPa with 10 MPa increment. All fatigue tests were load controlled at a stress ratio of 0.1 with 30 Hz frequency. A standard extensometer (from Instron, Norwood, MA) was used to measure the strain within the gauge length of the specimens during tensile testing. Fatigue tests at cold temperature (−40 °C) were conducted in a ZBB-104 environmental chamber, manufactured by the Associated Environmental System (Ayer, MA). This chamber was operated by cryogenic liquid N_2. Fracture surfaces of the specimens were observed in detail using a scanning electron microscope (SEM).

4. Results and Discussion

4.1 Monotonic Tension Tests

Figure 2 shows the stress versus strain response of the HPDC magnesium AM60B alloy under a uniaxial tensile load applied at a strain rate of 1.99 mm/min. The curves do not

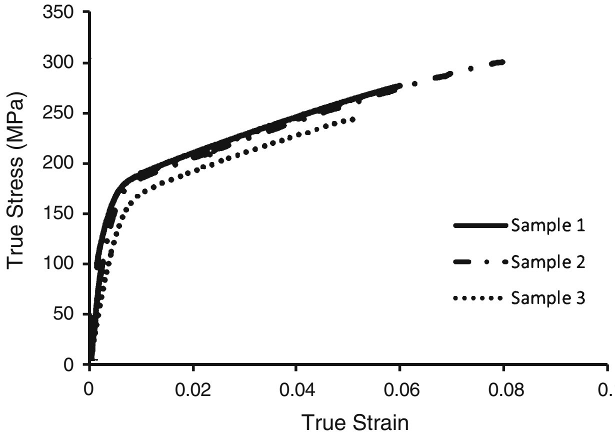

Fig. 2 Stress-strain response of HPDC AM60B magnesium alloy under uniaxial tensile load

Table 1 Composition of cast AM60B magnesium alloy in wt.%

Alloy	Al	Mn	Si	Zn	Cu	Fe	Ni	Other	Mg
Cast AM60B	5.5-6.5	0.25 min	0.10 max	0.22 max	0.010 max	0.005 max	0.002 max	0.003 (total)	Bal.

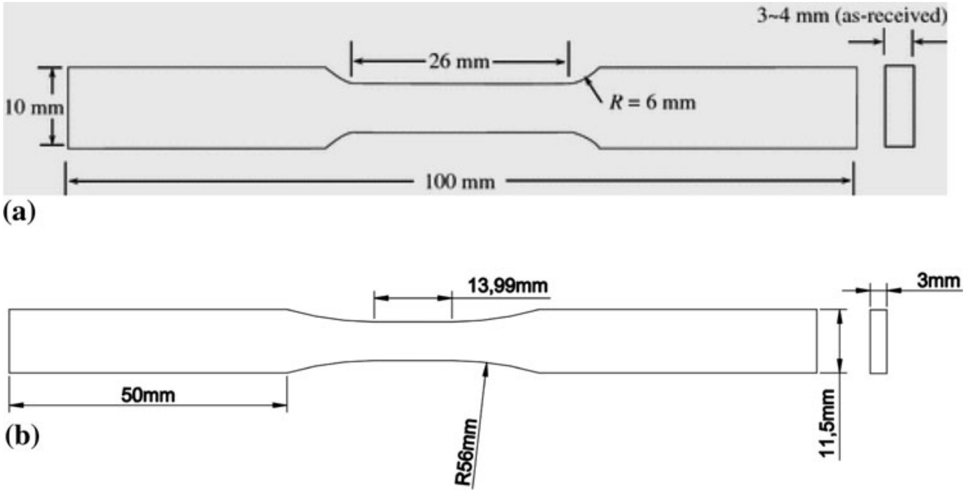

Fig. 1 Specifications of ASTM standard specimens; (a) E-8M tensile specimen (Ref 15); (b) E-466 fatigue specimen (Ref 16)

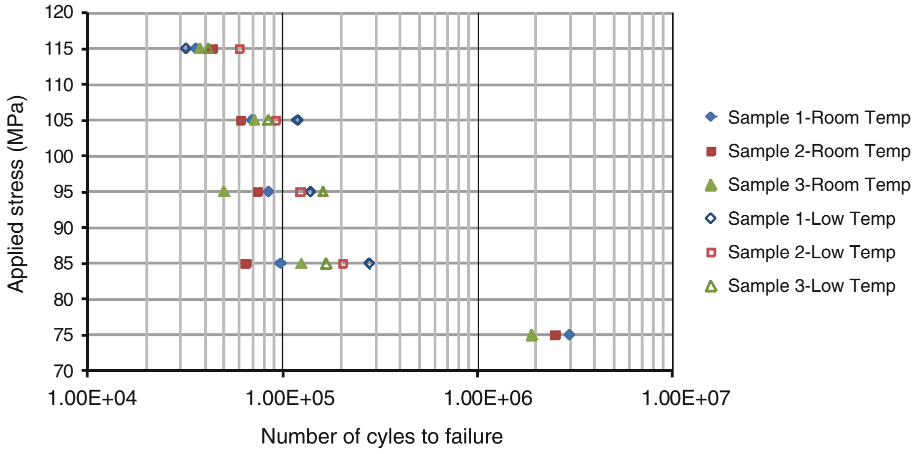

Fig. 3 S-N curves for AM60B magnesium alloy tested at room and low (−40 °C) temperatures

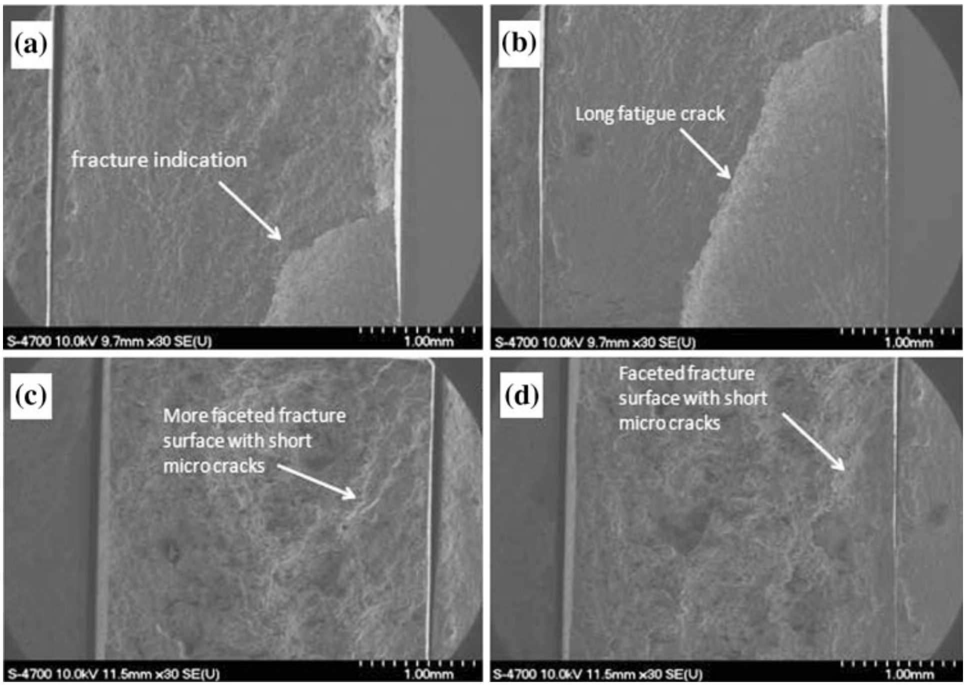

Fig. 4 Fracture surfaces of specimens: (a and b) at room temperature, $N_f = 64893$; (c and d) at −40°C, $N_f = 171317$ tested at a stress level of 85 MPa (lower magnification)

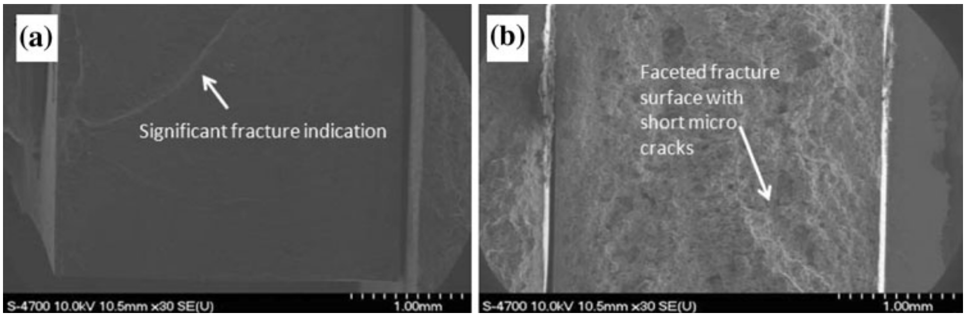

Fig. 5 Fracture surfaces of specimens: (a) at room temperature, $N_f = 38743$; (b) at −40 °C, $N_f = 59658$, tested at a stress level of 115 MPa (lower magnification)

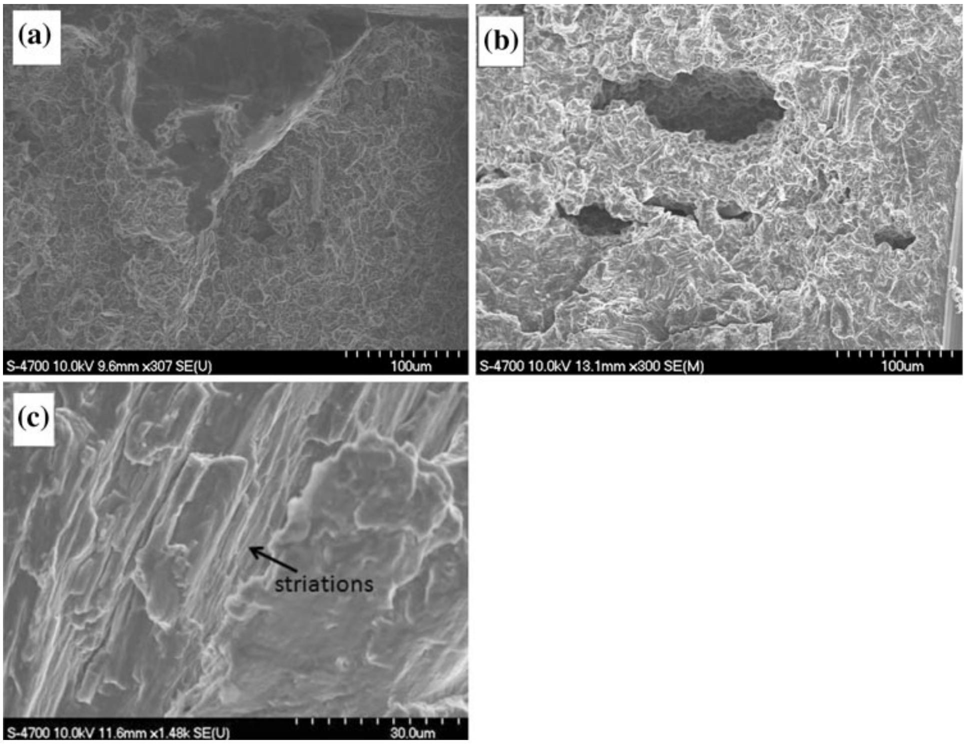

Fig. 6 Comparison of the shapes of typical shrinkage pore boundary: (a) smooth pore boundary found in the specimens tested at the low temperature; (b) lesser smooth pore boundary found typically in the specimens tested at the room temperature; and (c) SEM image showing large striations found in the specimen tested at room temperature, indicating plastic sharpening and blunting

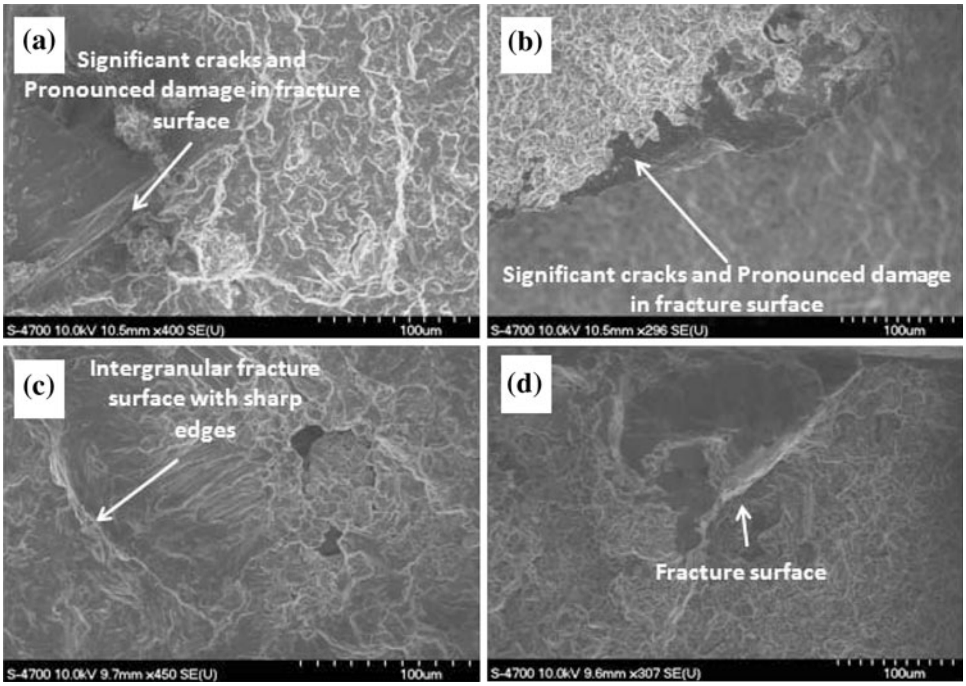

Fig. 7 Fracture surfaces of specimens: (a and b) at room temperature, $N_f = 64893$; (c and d) at −40 °C, $N_f = 171317$ tested at a stress level of 85 MPa (higher magnification)

show a clear elastic region, indicating that some plastic deformation is taking place. The average value of yield strength of the material was evaluated at 145 MPa. Note that there was a significant variation in the ultimate tensile strength due to large porosity variation as observed in the micrograph and SEM images.

4.2 Fatigue Tests

4.2.1 Influence of Cold Temperature on Fatigue and Fracture Characterization of AM60B Magnesium Alloy. Figure 3 illustrates the corresponding S-N curves plotted from the test results collected at room and cold (−40 °C) temperatures. From the figure, it can be seen that at low temperature, the number of cycles to failure is increased as compared to those tested at room temperature. This influence is more pronounced at lower stresses than at higher stress values. For example, at a stress value of 85 MPa, it is found that $N_f = 98924$, 64893, and 125888 for the three specimens tested at room temperature; whereas at cold temperature, for the same stress value, the number of cycles to failure were $N_f = 278867$, 206107, and 171317. This is almost two times higher than the fatigue life as observed at room temperatures. In other words, at a higher stress value of 115 MPa, the average number of cycles to fatigue failure was found to be 38246 at room temperature, compared to 44192, which was observed for the specimens tested at low temperature. Again, the difference is large, but not as significant as that at the lower stress value.

Further insight can be obtained on the fracture behavior of HPDC AM60B magnesium alloy through fractography analysis. Significantly, long fatigue cracks were observed in the SEM images of the whole cross-sectional area taken at lower magnification, for the specimen that failed at $N_f = 64893$, as shown in Fig. 4(a) and (b). However, short fatigue cracks with a faceted surface were observed in the SEM images of the specimen failed at $N_f = 171317$ at the low temperature, as shown in Fig. 4(c) and (d).

Figure 5 represents the SEM images, under lower magnification, of the fracture surfaces of specimen that failed at stress value of 115 MPa at room and low temperatures. Similarly, a significant fracture indication was observed for the case of room temperature. At low temperature, the phases of AM60B magnesium alloy become harder, resulting in a mismatch of hardnesses between the two phases. As a result, the material consumes more loading cycles to reach the critical stress intensity factor at the crack tip. Another anomaly is due to the hard brittle microstructure existing around the voids. The tendency for the crack initiation at the void regions is less at low temperature as opposed to that at room temperature. This is

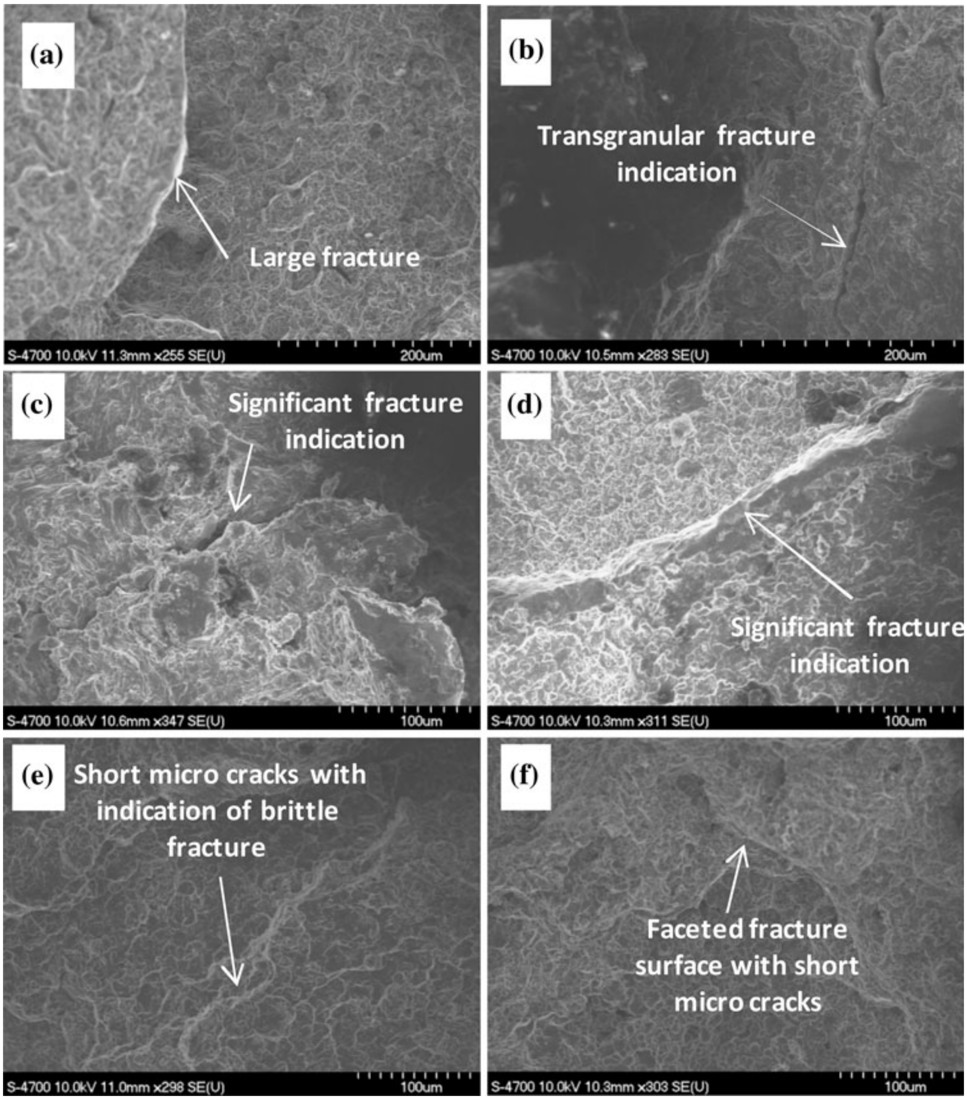

Fig. 8 Fracture surfaces of specimens: (a, b, c, and d) at room temperature, $N_f = 38743$; (e and f) at −40 °C, $N_f = 59658$ tested at a stress level of 115 MPa (higher magnification)

believed to be due to two factors. First, pores were common in all specimens. However, the pores in the specimen undergoing the cold temperature had smoother boundaries (as clearly seen in Fig. 6a), in comparison to the more jagged boundaries seen in the pores of specimens tested at room temperature (as shown in Fig. 6b). Obviously, stress concentration would be larger in the uneven boundaries of the room temperature tested specimen, thus causing lower fracture strength of the specimens in comparison to those tested at the cold temperature. Second, the grain boundaries act as a significant barrier to growing micro-cracks. At low temperatures, when alloy's strength characteristics are improved (as described), additional force would be required to move a micro-crack beyond the grain boundary, hence, causing an increase in the observed fatigue limit at the cold temperature.

Figures 7 and 8 illustrate the higher magnification SEM images of fracture surfaces of specimens that failed under the lower and higher stress values (i.e., of 85 and 115 MPa), both at room and low temperatures. Distinct and sharp fracture surfaces were observed for the room temperature-tested specimens; this phenomenon is believed to occur because the material requires less number of cycles to fail, as compared to that at low temperature. Huge striations can be observed in the SEM images of the fracture surfaces of the specimens tested at the room temperature, indicating sharpening and blunting through ductile fracture, as seen in Fig. 6(c). As stated, pores existed in all the specimens, with smooth pore boundaries seen in the SEM images of fracture surfaces of the specimens tested at the low temperature, demonstrating less tendency of fracture with microvoid coalescence as seen in the Fig. 6(c). The more jagged boundary shrinkage porosities were observed in specimens tested at room temperature, as seen in Fig. 6(b). As such, it is believed that these are the agents responsible for accelerating the crack propagation rate.

5. Conclusion

At low temperature (−40 °C), the fatigue life of HPDC AM60B magnesium alloy was observed to increase, as compared to the fatigue life at room temperature. This increase is much more significant at low stress levels than at high stress levels; the difference was found to be almost twice on average.

A difference was also observed in the fracture surfaces of HPDC AM60B magnesium alloy. The reflectivity observed in the SEM images of the fracture surfaces of the specimens tested at room temperature was relatively dull, indicating a relatively ductile fracture. In comparison, shiny and faceted surfaces were observed for the specimens at the low temperature, thereby revealing a brittle fracture mode.

It is believed that at the low temperature, the existence of large stress concentration regions at the grain boundaries of HPDC AM60B magnesium alloy caused brittle intergranular fracture with microvoid coalescence, as observed in the SEM images of specimens' fracture surfaces.

Large variations in the fatigue behavior were also observed, which is believed to be due to the variation in the porosity size and distribution within each specimen.

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