International Journal of Engineering & Technology, 7 (4.36) (2018) 1502-1505

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

The Temperature-analysis Influence on Fatigue Crack Growth Behaviour of Magnesium Alloy

M.A. Fauthan[1,2], S. Abdullah[1], M.F. Abdullah[3]

[1] Centre of Integrated Design for Advance Mechanical System (PRISMA), Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[2] Machine Technology Centre, SIRIM Industrial Research, 40911 Shah Alam, Selangor, Malaysia
[3] Department of Mechanical Engineering, Faculty of Engineering, Universiti Pertahanan Nasional Malaysia, Kem Sg. Besi 57000 Kuala Lumpur, Malaysia
**Corresponding author E-mail: shahrum@ukm.edu.my*

Abstract

In this study, the temperature-based mechanical fatigue crack growth of a magnesium alloy was investigated. Since fatigue is an irreversible process and experience temperature change, the fatigue crack growth behaviour of AZ31B was investigated based on the temperature trend. For this objective, compact tension tests were carried out by applying different stress levels to the specimen. The temperature trend was monitored via an infrared sensor. During the cyclic load applied to metallic materials, mechanical energy is expended to bring about plastic deformations at a macroscopic level. At the point of fracture, there was a temperature increase of 2.2˚C when 5.12MPa stress level is applied. This temperature increase was due to the generation of thermal energy from the dislocation motion and grain friction on the material under cyclic loading which has caused an increase in the internal molecular average energy of the material. Thus, the temperature trend could be a new indication of fatigue crack growth behaviour.

Keywords: *AZ31B, fatigue, cyclic loading, dissipated energy magnesium alloy*

1. Introduction

The excellent features of magnesium alloys such as their high stiffness, good castability, high specific strength, and good heat conductivity have made them an attractive structural material in several industries like the aerospace, car and electronic industries [1]. However, the integrity of magnesium as a structural material still needs further investigation to ensure its safe application. Several investigations such as magnetic particle testing, radiographic testing, ultrasonic testing, and many others, could be performed to ensure a safe application of magnesium alloys. However, the dissipating energy during fatigue tests could also be used for predicting the fatigue life of the material [2]. Recently, thermodynamic entropy has been highlighted as a significant fatigue characterization technique to the non-destructive testing (NDT) methods. The approach depends on measuring the material's cyclic hysteresis energy, as well as its temperature profile. The entropy is then, determined as the ratio of the measured strain energy to the absolute temperature [3].

Previously, entropic approaches depend on the physical measurement of the temperature, hysteresis energy, and stress/strain; but these approaches are only applicable when examining total life which includes crack initiation and propagation for low-cycle fatigue (LCF), where there could be a considerable level of plastic deformation. At the point of failure, the accumulated entropy for LCF, aluminium 6061-T6, and stainless steel 304 has been reported as a constant value [4]. For LCF, the strain energy, which is approximated by the total plastic energy throughout the course of the fatigue study, has been used. A quantity called Fatigue Fracture Entropy (FFE) has also been introduced by Naderi when a material is about to fail [4]. Previous studies have used infrared thermographic methods to investigate the fatigue behaviour of magnesium alloy and its butt joints. These studies reported the highest temperature increase in the middle of the specimen under different loading levels. Zhang investigated the fatigue behaviour of magnesium alloy welded joint, where the temperature of the specimen was observed during cyclic loadings. The study also observed the mean temperature decline due to thermos-elastic effects. Furthermore, the impact of weld reinforcement on the fatigue pattern was investigated using an infrared thermography approach.

For LCF, the strain energy, which is approximated by the total plastic energy throughout the course of the fatigue study, has been used. A quantity called Fatigue Fracture Entropy (FFE) has also been introduced by Naderi when a material is about to fail [4]. Previous studies have used infrared thermographic methods to investigate the fatigue behaviour of magnesium alloy and its butt joints. These studies reported the highest temperature increase in the middle of the specimen under different loading levels. Zhang investigated the fatigue behaviour of magnesium alloy welded joint, where the temperature of the specimen was observed during cyclic loadings. The study also observed the mean temperature decline due to thermos-elastic effects. Furthermore, the impact of weld reinforcement on the fatigue pattern was investigated using an infrared thermography approach.

Some components have their own problem to be monitored to determine the remaining life. In this study, AZ31B magnesium alloy was used in order to study the basic relationship between fatigue crack growth behaviour and dissipation energy based on

Copyright © 2018 Authors. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

the temperature trend. Fatigue is an energy dissipation process comprising of thermal dissipation and energy storage. The thermal dissipation of the specimen under compact tension was characterized using an infrared sensor. The temperature changes showed a strong relationship between fracture and temperature. Owing to the broad potential application of magnesium alloys, it is necessary to further investigate the suitability of magnesium as a component material. This study explored the potential of using temperature trend as an approach for monitoring and predicting the characteristics of a structural component.

1.1. Theoretical Background

Fatigue can be described in terms of a dissipative process under the small perturbation hypothesis. Besides, the local heat equation can be established through a combination of the first and the second laws of thermodynamics as follows [5]:

$$\rho C T^{\cdot} - div\,(k\ grad\ T) = d_i + s_{the} + s_{ic} + r_{ext} \qquad (1)$$

Where ρ is the mass density, C is specific heat and k is the material conduction tensor.
The first part of Equation (1) is a differential operator which is applied to T (temperature), while the other part is the group of dissimilar heat sources. The heat sources are respectively the intrinsic dissipation, the source of thermo mechanical coupling (consisting of the thermo elastic sources) and the other internal coupling sources s_{ic}, and the external volume heat supply $r_{ext.}$
As has been analysed by Zhang [2], the temperature profile during fatigue without an outside heat source can be affected by the thermoplastic effect, the inelastic effect, and the heat-transfer effects.

2. Methodology

2.1. Material and Equipment

This study utilized the commercial AZ31B magnesium alloy whose chemical composition is listed in Table 1 [6].

Table 1: Chemical composition of AZ31B

Al (%)	Zn (%)	Mn (%)	Cu (%)	Ca (%)	Fe (%)	Ni (%)
2.8	0.7	0.4	0.1	0.04	0.005	0.001

For the first step, mechanical properties should be determined by performing tensile test. Then, to study the fatigue crack growth (FCG), test specimens of compact tension (CT) were prepared following the recommendation of ASTM E647. The specimens were machined using a CNC milling machine and cut to the required dimensions using an electrical discharge wire-cutting machine. A fatigue pre-crack of 4 mm, extending from the notch root in the CT specimen was introduced. The specimens were further polished and cleaned with sandpaper (having 800, 1000 and 1500 grit) to remove oxides and grease prior to thermos-effect measurements. Besides, the polishing process could also delay the initiation of fatigue-crack through the elimination of the surface stress concentration.
Before the fatigue tests, the surface of the specimens that face the thermal sensor was coated with a layer of black paint to improve the thermal emissivity and to reduce the error rate [3]. A uniaxial servo-hydraulic load frame was used to perform all the FCG experiments at a load capacity of 100kN. During the fatigue process, a non-contact infrared sensor was used to monitor and record the surface and ambient temperature of the material. It is important to use the infrared sensor because it can capture small changes in temperature due to elastic deformation. These small changes may not be captured by the traditional sensors such as a thermocouple.

2.2. Experimental procedure

The FCG studies were executed by applying a sinusoidal waveform of 10 Hz frequency and a constant load amplitude. Three stresses of 4.80 MPa, 4.96 MPa, and 5.12 MPa were applied to the specimen at a stress ratio of R = 0. The stresses are chosen due to appropriate time length of the experiment to reach total fracture. All the experiments were finished in not more than eight hour to avoid two times setting. Different stress ratios were not investigated because the mean stress effect was not considered in this study. During the test, the temperature trend of the specimen was detected with the infrared sensor which was set up according to the manufacturers' instruction as in Figure 1. The accuracy of this sensor is 0.1˚C in -20˚C to 800˚C measurement range. The sensor was positioned in front of the specimen at a distance of 50 mm, directly facing the surface of the pre-crack earlier done.

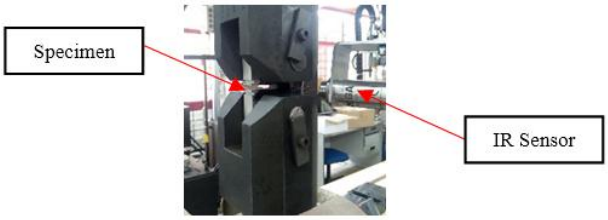

Fig. 1: The IR sensor and the specimen set up

3. Result and discussion

3.1. Mechanical properties

Prior to the fatigue testing, the magnesium alloy was subjected to a static test to determine the basic mechanical properties. The mechanical properties of the alloy were determined in a lab at an average tensile strength of 238 MPa, total elongation of 12.6%, and 0.2% offset yield strength of 144 MPa before the test. In Table 2, presents the result of the mechanical properties of the studied alloy (AZ31B).

Table 2: The mechanicals properties of AZ31B

Specimen	Yield strength, σ_s (MPa)	Ultimate strength, σ_{UTS} (MPa)	Modulus Young, E (GPa)
AZ31B	144	238	40.66

3.2. Fatigue crack growth

For the first step, the fatigue crack growth was observed from the experiment. The relationship between the fatigue crack growth $^{dA}/_{dN}$ and ΔK was investigated. Fig. 2 shows the crack length during different stress of 4.80 MPa, 4.96 MPa, and 5.12 MPa were loaded. The specimen showed the initiation of crack at the early stages of the cyclic loading compared to stainless steel [4]. This is due to lower mechanical properties compared to stainless steel. At an amplitude loading of 4.80 MPa, the crack started after 4343 cycles, while for the 4.96MPa amplitude loading, cracking started after 3739 cycles. The fastest cycle among the three loadings was at 2288 cycles for 5.12 MPa. The increase in the amplitude loading leads to a lower final crack cycle, showing that the total fracture occurred at 2.87 x 10^4, 2.70 x 10^4, and 2.55 x 10^4 cycles, respectively as in Table 3.

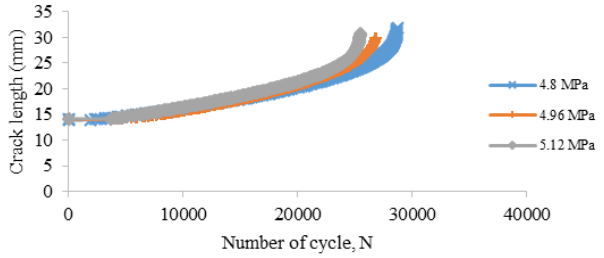

Fig. 2: The fatigue crack growth at different load

Table 3: Comparison of number of cycle when the crack start and final crack at different loading

Stress, MPa	Crack start at cycles, n	Final crack cycles, n
4.8	4343	28704
4.96	3739	26970
5.12	2288	25498

Three different results were obtained based on the amplitude of the applied load although the geometry of the specimens and the experimental setting were the same. However, the scattered band of the rate of fatigue crack growth was expected to be the same in the log-log relationship. This was confirmed by the linear relationship between $^{dA}/_{dN}$ and ΔK values in the double log scale, as shown in Fig. 3. The constant *m* was observed to be 3.6 for the load amplitudes of 4.80 MPa, 4.96 MPa and 5.12 MPa, while the *C* value was in the range of 1.0 x 10^{-7} to 3.0 x 10^{-10} (m/cycle)/ MPa.$m^{1/2}$. There was a progressive increase in the rate of fatigue crack growth as they tend towards instability in region III [7].

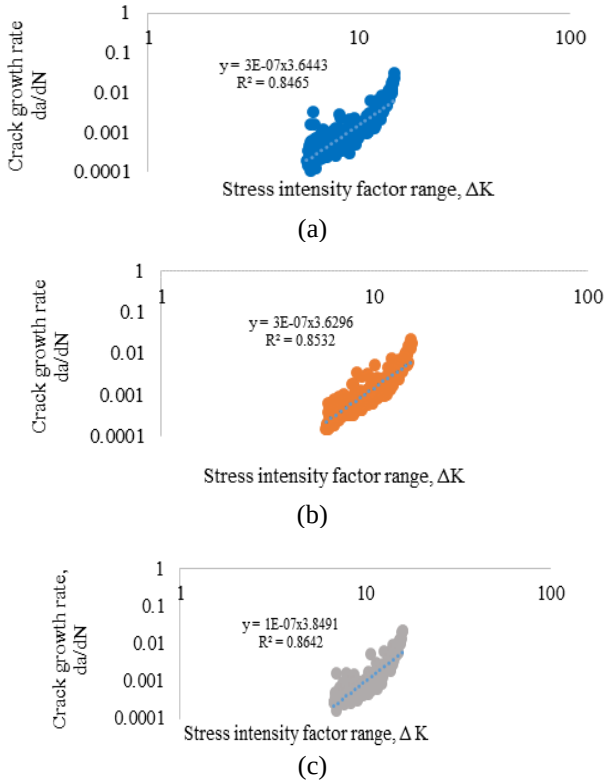

Fig. 3: The relationship between crack growth rate and stress intensity, ΔK for loading a) 4.80 MPa b) 4.96 MPa and c) 5.12 MPa

3.3. Temperature trend during fatigue

Since the stress level of this test was in low cycle fatigue, the elastic zone of the AZ31B has been exceeded to plastic zone. When the stresses is below the fatigue limit and above elastic limit, the heating of the fatigue sample will experience the viscous-elastic effect [8]. Fig. **4** shows the comparison of maximum temperature when the fracture occur at different stress level. It was clearly indicates that the higher stress level, the higher increment of temperature was recorded.

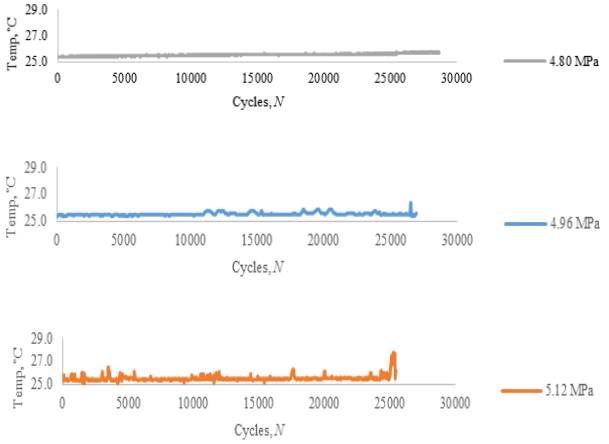

Fig. 4: Temperature evolution for different stress level

The temperature was measured with the infrared sensor mounted at the tip of the pre-crack. From the Fig. **5**, it was evident that there was a significant increase in the temperature when stress level at 5.12 MPa was applied. The highest temperature revolution occurred during the cycles which total failure was approaching and the temperature increase from 25.5˚C to 27.7˚C, which is about 2.2˚C increment. The most significant increase in temperature was observed when a stress of 5.12 MPa was applied compared to other stress levels. The increment of 0.9˚C and 0.4˚C was recorded during the stress level of 4.96 MPa and 4.80 MPa respectively. Both of these increment were under 1˚C.

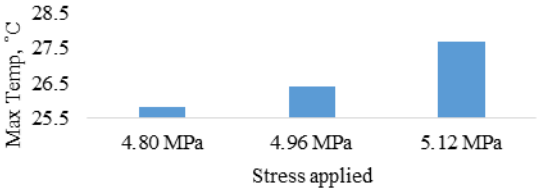

Fig. 5: Comparison maximum temperature for each stress level

During these stages, the maximum temperature was observed at the cyclic plastic zone of the fatigue macro-crack tip. The macro crack is originally formed by a combination of different micro crack propagations at different positions. The mechanical work was used to propagate macro-cracks. Thus, there was an obvious increase in heat generation under the applied stresses. Similarly, the fatigue effects caused a continuous accumulation of plastic dissipation which can result in a complete failure. The large deformation ahead of the crack tip was taken at smaller crack sizes compared to the other dimensions of the specimen during the crack propagation. The dislocation movement promotes the grain friction and increases both the temperature and the internal molecular kinetic energy [6]. The plastic work performed at the cyclic plastic zone ahead of the crack tip was considered as a source of heat; so, there was a sudden increase in temperature at the crack tip until failure. The distribution of temperature around the crack tip can be determined by considering an irreversibly deformed process zone as a source of internal heat. In this study, the distribution of temperature at the crack tip was analysed under a constant amplitude loading. The plastic energy within the reversed plastic zone was considered as an irreversible work done at the crack tip based on the notion that there is a direct relationship between plastic deformation and increase in temperature.

This increase in temperature evidently showed that a part of the input mechanical energy in fatigue of metallic materials is converted into heat. This converted energy can be considered as a source of heat under a fatigue process. The energy liberated by the

material in a unit volume per cycle (or heat-dissipation rate) can be represented the sum of mechanical energy input per cycle and the heat dissipation. This is equal to change in the internal energy per cycle [9]. Therefore, based on this test, the temperature can be considered as an indicator of fatigue crack growth since it can significantly influence fracture failure.

However, at the early of this life cycle, the viscous– elastic effect will cause an unnoticeable temperature increase but the crack still occur in this specimen as in Fig. **6**. A significant temperature change at this period may be difficult to be observed and may require the use of a high-resolution thermal camera to be detected. Even though the change in temperature is little, it is a significant influence of energy generated by plastic deformation which can be converted into heat if the stress level exceeds the fatigue limit of the body [8].

Furthermore, the reason for the stable temperature during most of the test could be attributed to two heat dissipation processes; the first is the heat conduction between the machine body (clamping apparatus) and the specimen, while the second is the heat convection and radiation between the specimen and its surrounding air. The effects of heat conduction delayed the heat transfer from the zone of high temperature in the specimen to the zone of lower temperature. After generating the heat, it will dissipate to the surrounding air. The use of the IR sensor ensured the monitoring and capturing of the heat in real-time.

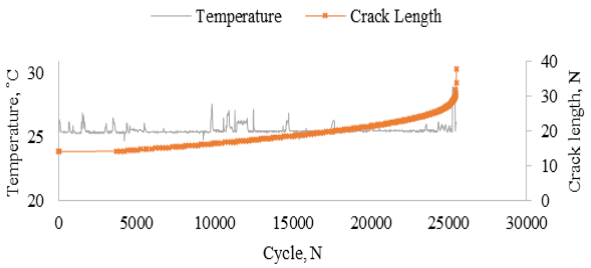

Fig. 6: Temperature evolutions of AZ31B magnesium alloy in low-cycle fatigue test for loading 3100N

4. Conclusion

Several low-cycle fatigue experiments were performed to investigate the failure behaviour of AZ31B magnesium alloy based on the temperature trend. An infrared thermography approach was used to monitor and capture the behaviour of the specimen's surface temperature during the fatigue process. Energy dissipation and entropy generation were deployed as an effective way of measuring the crack growth behaviour of the material as temperature change occur during the fatigue process. The results of the study showed that the application of a stress level of 5.12MPa resulted in a temperature increase of 2.2˚C at the point of complete failure. This temperature increase was due to the dissipation and generation of energy which obeys the first and second thermodynamic laws. The normalized cycle to failure was shown to have a good relationship with the generation of temperature during a fatigue process.

Acknowledgement

The authors would like to express their gratitude to Ministry of Higher Education Malaysia via Universiti Kebangsaan Malaysia and Universiti Pertahanan Nasional Malaysia (Research funding: LRGS/2013/UPNM/UKM/DS/04) for supporting this research.

References

[1] Z. F. Yan et al., "Temperature evolution mechanism of AZ31B magnesium alloy during high-cycle fatigue process Address : College of Materials Science and Engineering , Taiyuan University of," 2014.

[2] H. X. Zhang, G. H. Wu, Z. F. Yan, S. F. Guo, P. D. Chen, and W. X. Wang, "An experimental analysis of fatigue behavior of AZ31B magnesium alloy welded joint based on infrared thermography," Mater. Des., vol. 55, pp. 785–791, 2014.

[3] M. Liakat and M. M. Khonsari, "An experimental approach to estimate damage and remaining life of metals under uniaxial fatigue loading," J. Mater., vol. 57, pp. 289–297, 2014.

[4] M. Naderi, M. Amiri, and M. M. Khonsari, "On the thermodynamic entropy of fatigue fracture," Proc. R. Soc. A Math. Phys. Eng. Sci., vol. 466, no. 2114, pp. 423–438, 2010.

[5] S. Guo et al., "Thermographic analysis of the fatigue heating process for AZ31B magnesium alloy," Mater. Des., vol. 65, pp. 1172–1180, 2015.

[6] L. Xiao-qing, Z. Hong-xia, Y. Zhi-feng, W. Wen-xian, Z. Ya-guo, and Z. Qian-ming, "Fatigue life prediction of AZ31B magnesium alloy and its welding joint through infrared thermography," Theor. Appl. Fract. Mech., vol. 66–67, pp. 46–52, 2013.

[7] N. I. I. Mansor, S. Abdullah, and A. K. Ariffin, "Discrepancies of fatigue crack growth behaviour of API X65 steel †," vol. 31, no. 10, pp. 4719–4726, 2017.

[8] Z. Xu, H. Zhang, Z. Yan, F. Liu, P. K. Liaw, and W. Wang, "Three-point-bending fatigue behavior of AZ31B magnesium alloy based on infrared thermography technology," Int. J. Fatigue, vol. 95, pp. 156–167, 2017.

[9] G. Meneghetti and M. Ricotta, "The heat energy dissipated in a control volume to correlate the crack propagation rate in stainless steel specimens," vol. V, pp. 299–306, 2017.