Jurnal Teknologi

Full paper

Quantitative Relationship between Strain and Acoustic Emission Response in Monitoring Fatigue Damage

M. Mohammad[a,b]*, S. Abdullah[a], N. Jamaludin[a], O. Innayatullah[b]

[a]*Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*

[b]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Malaysia*

*Corresponding author: mazian@eng.ukm.com

Article history

Received :15 January 2013
Received in revised form :
28 October 2013
Accepted :5 December 2013

Graphical abstract

Abstract

This study was carried out to investigate the relationship between the strain and acoustic emission (AE) signals, thus, to confirm the capability of AE technique to monitor the fatigue failure mechanism of a steel component. To achieve this goal, strain and AE signals were captured on the steel specimen during the cyclic fatigue test. Both signals were collected using specific data acquisition system by attaching the strain gauge and AE piezoelectric transducer simultaneously at the specimen during the test. The stress loading used for the test was set at 600 MPa, and the specimens were fabricated using the SAE 1045 carbon steel. The related parameters for both signals were determined at every 2000 seconds until the specimen failed. It was found that a meaningful correlation of all parameters, i.e. amplitude, kurtosis and energy, was established. Finally, all AE parameters are correlated with the damage values, which have been estimated using the Coffin-Manson model. Hence, it was suggested that the AE technique can be used as a monitoring tool for fatigue failure mechanism in a steel component.

Keywords: Fatigue; failure; steel; strain; acoustic emission

Abstrak

Kajian ini dijalankan untuk menyiasat hubungan di antara isyarat terikan dan pancaran akustik (PA) dan seterusnya mengesahkan keupayaan kaedah PA dalam memantau mekanisma kegagalan lesu bagi komponen keluli. Bagi mencapai matlamat ini, isyarat terikan dan PA dicerap daripada spesimen keluli semasa ujikaji lesu. Kedua-dua isyarat dikumpulkan dengan menggunakan sistem pemerolehan data yang spesifik dengan melekatkan tolok terikan dan sensor piezoelektrik PA secara serentak semasa ujikaji. Daya tegasan yang dikenakan semasa ujikaji ialah 600 MPa, dan spesimen yang digunakan diperbuat daripada keluli karbon SAE 1045. Parameter yang berkaitan bagi kedua-dua isyarat ditentukan pada setiap 2000 saat dari permulaan ujikaji sehinggalah spesimen mengalami kepatahan. Kajian mendapati bahawa hubungan yang bermakna bagi semua parameter, iaitu amplitud, kurtosis dan tenaga, diperolehi. Akhirnya, semua parameter PA ini menunjukkan korelasi yang baik dengan nilai kerosakan, yang telah dianggarkan dengan menggunakan model Coffin-Manson. Oleh itu, teknik PA ini dicadangkan boleh digunakan sebagai alat pemantauan yang berkesan untuk mekanisma kegagalan lesu dalam komponen keluli.

Kata kunci: Lesu; kegagalan; keluli; terikan; pancaran akustik

■1.0 INTRODUCTION

In such a huge and complex steel structure, automotive components and piping system, safety aspects become one of compulsory factors to be considered to prevent sudden breakdown that could lead to loss of equipment and human life. In this case, fatigue can be said as one of major contributors of many mechanical failures. Hence, many research have been carried out either to detect, monitor or predict the fatigue failure mechanism in various type of materials such as semiconductors, composites, polymers etc. [1]. As acoustic emission (AE) sensor has the capability to detect very high frequency wave in the material, it offers an alternative technique in assessing the fatigue failure mechanism. The AE monitoring has been developed as an effective non-destructive technique for the detection, location and monitoring of fatigue cracks in a variety of metal structures including airframes, steel bridges, pipeline and pressure [2,6, 7, 8,9].

Conventionally, the strain signal was used to analyse fatigue failure. Complicated process in conducting very small strain gauges as the sensor to detect fatigue signals and less of skilled personnel in practicing this conventional technique inspires the idea of this research. The unique capability of an AE sensor makes it possible to assist the conventional technique in detecting and monitoring crack in steel specimens. Realising that, this research was carried out to analyse as well as correlates both strain and acoustic responses to monitor the fatigue damage of the steel structures. The signals behaviour of SAE 1045 steel during the first stage of crack initiation was observed in this research.

■2.0 METHODOLOGY

2.1 Experimental

The test material used in this study was medium carbon steel with the series of SAE 1045. This type of steel is often used as structure components and pipes material (usually as seamless tube type) in power plants industries. It has been designed according to ASTM E8 [5] with 146 mm, 20 mm and 3 mm of length, width and thickness, respectively (refer to Figure 1). Before undergo both tensile and cyclic fatigue test, all specimens were polished using different grades of silicon carbide abrasive papers. It is due to have a mirror-like surface finish condition as fatigue properties are very sensitive to surface condition. This kind of surface finish helps to reduce the stress concentration that leads to crack initiation on the material surface.

Figure 1 Standard fatigue specimen

In order to determine the mechanical properties of the material, tensile test was carried out by using the ASTM E8 [3] procedure with the 100 kN servo-hydraulic universal testing machine with 1.2 mm/min crosshead speed. Detail mechanical properties of the SAE 1045 steel are tabulated in Table 1 and the data is important in order to set the applied load for the cyclic tests.

The cyclic fatigue tests were then performed using the 25 kN servo-hydraulic fatigue testing machine. The tests were conducted using load ratio, R=-1 condition at 600 MPa which is 75% of the UTS. Loading frequency of 8 Hz [4] was set and a 2 mm strain gauge was fixed using the cyano-acrylate type adhesive material on the specimen in order to record the strain response during the cyclic fatigue test. Throughout the test, the strain data was collected at the sampling frequency of 100 Hz [5]. This sampling frequency value was enough to record the data because of the strain gauges sensitivity in recording the changes of the strain response that exist during the test. At the same time, the piezoelectric AE sensor was also attached to the specimen to measure AE signals. A wide range sensor of 100-2000 kHz was used and the selected sampling frequency for the test was 5000 kHz [6]. For any AE case, the sampling frequency has to be greater than twice of the maximum frequency range of the sensor to avoid alias effect. In this study, both signals were observed every 2000 seconds as this time period is long enough to trigger any differential behaviour of signals during the time. Figure 2(a) and (b) show the image of the cyclic test setup.

Table 1 Mechanical properties of SAE 1045 steel

Properties	Values
Condition	As received
Ultimate tensile strength, S_u (MPa)	798
Modulus of Elasticity, E (GPa)	196
Static yield stress 0.2%, S_y (MPa)	414

2.2 Signal Analysis

Global signal statistical analysis was used to analyse all collected signals from both strain gauge and AE sensor. In AE, the maximum amplitude of the signals has been used widely in detecting the mechanical fault [7]. In this study, the maximum amplitude of the AE data is matched with the amplitude of the strain data taken at the same time. As for strain signals, the amplitude is determined using the peak and valley (PV) analysis. The formula to calculate the strain amplitude using the PV analysis is shown in Equation 1 and Equation 2.

$$\text{Strain range, } \Delta\varepsilon = \text{Peak} - \text{Valley} \tag{1}$$

$$\text{Strain amplitude, } \varepsilon_a = \Delta\varepsilon / 2 \tag{2}$$

Besides amplitude, kurtosis also plays main role in damage detecting for major engineering problems. The kurtosis, which is the signal's 4th statistical moment, is a global signal statistic which is highly sensitive to the spikiness of the data [8]. Equation 3 shows the basic formula to calculate the kurtosis.

$$K = \frac{1}{n(r.m.s)^4} \sum_{j-1}^{n} \left(x_j - \bar{x}\right)^4 \tag{3}$$

The Power Spectral Density (Equation 4) method was used to convert the time domain signal into the frequency domain. It indicated each of frequency existed in the signal. The distribution of vibrational signal energy across the frequency domain can be observed using this method. As in fatigue and AE study, energy was proved to be one of the important parameter to describe the damage behaviour in the structures [9].

$$S_x(f) = \lim_{T\to\infty} E\left\{ \frac{\mathbf{1}}{\mathbf{2}T} \left| \int_{-T}^{T} x(t) e^{-j2\pi ft} dt \right|^{\mathbf{2}} \right\} \tag{4}$$

To show the relationship that exist between AE and strain signals, all parameters are correlated using the coefficient of determination, R^2. The purpose of correlation analysis is to measure and interpret the strength of a linear or non-linear (such as exponential or polynomial) relationship between two continuous variables [10]. In fatigue, a lot of research used this technique in order to interpret the relationship between data [9, 11].

2.3 Fatigue Life Assessment

In this paper, one of the strain-life damage i.e., Coffin-Manson, was used to determine the fatigue life of the material. The Coffin-Manson Model was chosen because it theoretically determine the fatigue life for zero mean stress effect condition i.e. $R=-1$ [6]. The fatigue life is representated by the damage value that have been calculated using specific software. The Coffin-Manson relationship is shows in Equation 5.

$$\boldsymbol{\varepsilon_a} = \frac{\boldsymbol{\sigma'_f}}{\boldsymbol{E}}\left(\mathbf{2}\boldsymbol{N_f}\right)^{\boldsymbol{b}} + \boldsymbol{\varepsilon'_f}\left(\mathbf{2}\boldsymbol{N_f}\right)^{\boldsymbol{c}} \tag{5}$$

To summarize the methodology used in this paper, a process flow is shown in Figure 3.

Figure 2 25 kN servo-hydraulic fatigue machine

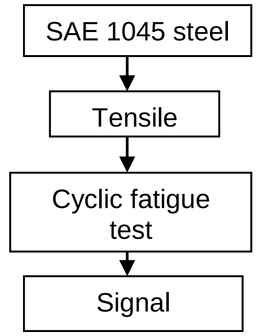
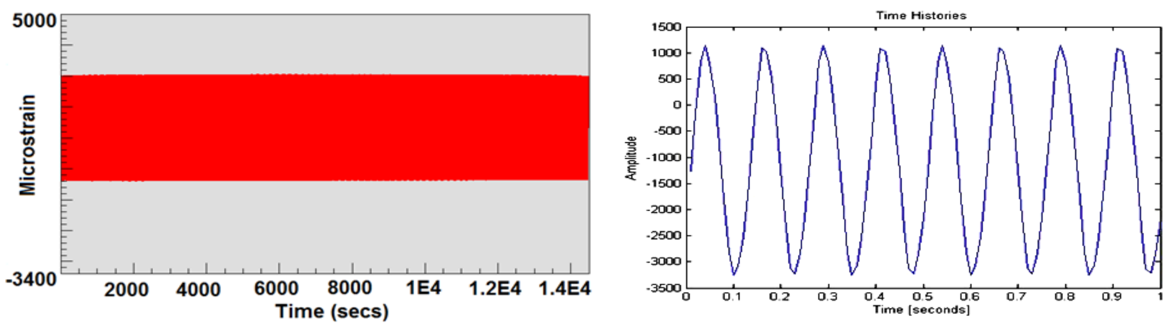


Figure 3 Process flow used in this study

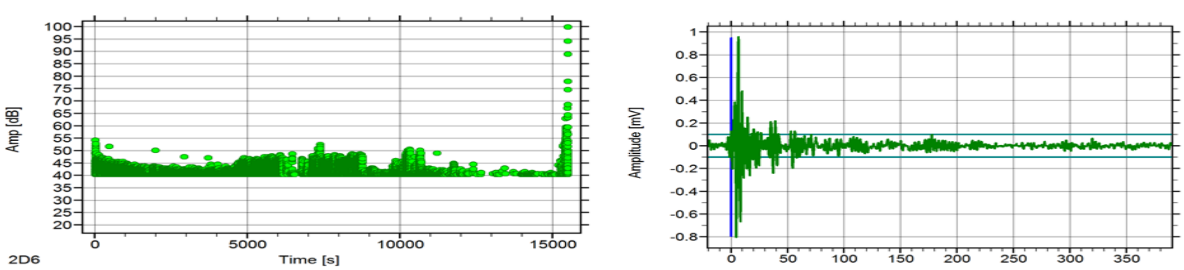
■3.0 RESULTS AND DISCUSSION

Figures 4 and 5 show the original time history for strain and AE collected signal at 600 MPa, respectively. Figure 4(a) shows the overall time history display for the strain signal where as the next diagram shows the clear sinusoidal signal for 1 second (Figure 4(b)). As in Figure 5, the overall signal points of AE signals is shows and every signal points are actually represented by a burst signal as shown in Figure 5(b).



(a) (b)

Figure 4 Original time history signal for strain at :(a) overall time (b) 1 s



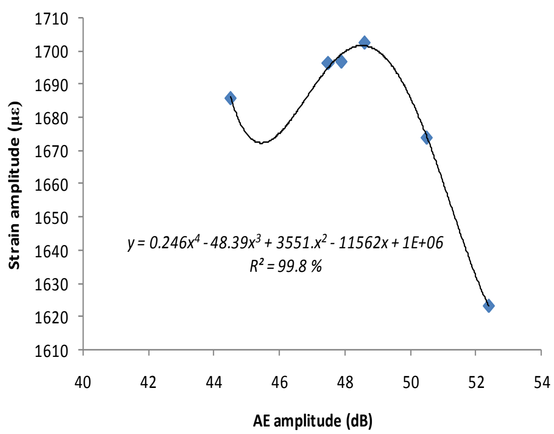
(a) (b)

Figure 5 Original time history signal for AE at: (a) overall time (b) one point of signal

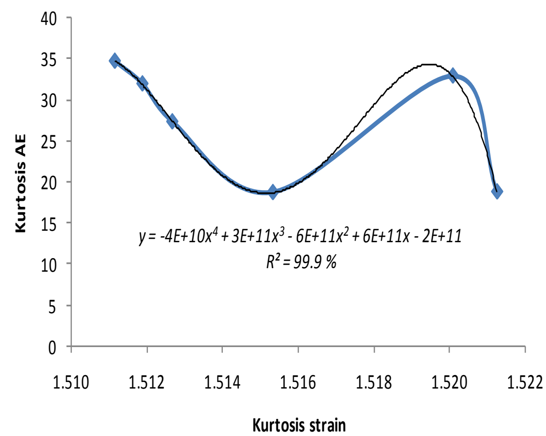
The correlations between the amplitude and kurtosis of strain and AE signals are shown in Figures 6(a) and 6(b), respectively. Meanwhile, the correlation of energy between both signals is shown in Figure 6(c). Both statistical parameters that have been used, i.e., amplitude and kurtosis, shows higher coefficient of determination, R^2 value with 99.8 % and 99.9 %, respectively compared to the energy, 71.0 %. All results that have been shown were represented by a polynomial equation as the coefficients of determination fit accurately to this relationship. The relationships show that the specimen had experienced an unstable behaviour during the test. It's maybe due to the cyclic loading (tension-compression) that affects the elastic-plastic activities of the material.

In order to relate the material damage to the AE parameters that have been selected, the correlation of between the data should be performed. Figure 7 shows the correlation between the damage value to the energy, amplitude and kurtosis of AE. The damage value is calculate using the Coffin-Manson relationship with spesific software by inputing the strain signals. As Figure 7, all correlations in the graph also exhibit the polynomial relation. The polynomial regression reflects the nonlinear relationship between damage and all AE parameters. This nonlinear behavious may be due to the material characteristics of the specimen during the test.

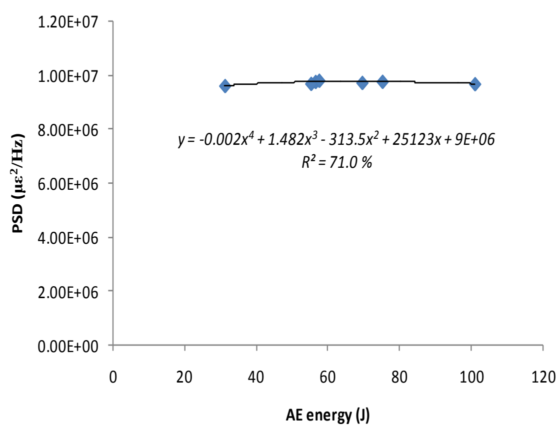
The highest R^2 value can be found from the AE amplitude graph, 98.2 % follows by kurtosis with 97.7 % and energy with 80.8 %. Based on the R^2 values, it can be concluded that either the amplitude or kurtosis should be used to predict damage for this specimen. The equation for all correlations is show in Table 2. The basic equation can be used to predict the fatigue damage of the material.



(a)



(b)



(c)

Figure 6 Correlation between (a) amplitude (b) kurtosis and (c) energy of AE and strain signal

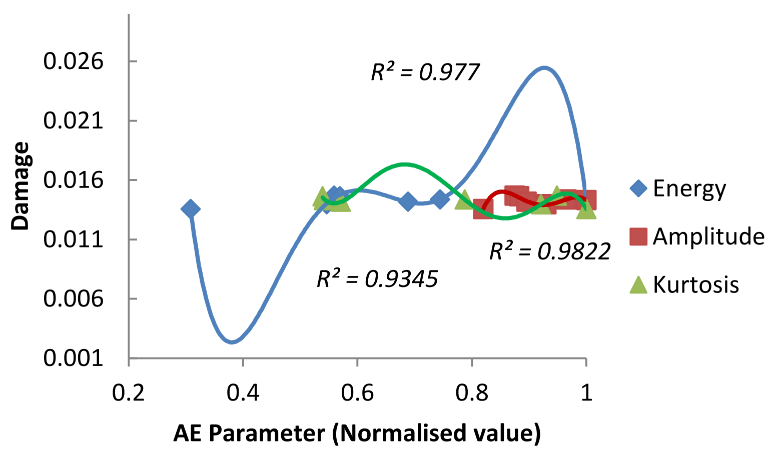


Figure 7 Correlation between damage and AE parameters

Table 2 Equation for AE parameters and damage

AE parameter	Equation
Energy	$y = -4.676x^5 + 15.82x^4 - 20.79x^3 + 13.21x^2 - 4.025x + 0.478$
Amplitude	$y = -46.88x^4 + 172.5x^3 - 237.8x^2 + 145.4x - 33.27$
Kurtosis	$y = -25.44x^5 + 97.49x^4 - 147.3x^3 + 109.7x^2 - 40.25x + 5.831$

4.0 CONCLUSION

The relationship for both strain and AE signal during fatigue fracture mechanism was determined in this paper. Based on the correlation given by the amplitude, kurtosis and energy of both signals, shows that there is a strong relationship between these two techniques. The correlation between the AE and strain parameters show 71% to 99.9 % of the R^2 value that fitted the polynomial regression line with a quartic equation. Besides that, the relationship between all AE parameters and the damage value that have been calculated using Coffin-Manson model, also produced the polynomial equation. The correlations of all AE parameters and damage are tabulated around 80 % to 98 % of the R^2 value. The non-linear behaviour that represent by the quartic perhaps, can be as a guidance in advance research in determine the fatigue life in steel component using AE technique.

Acknowledgement

The authors would like to thank Universiti Kebangsaan Malaysia and Ministry of Higher Education for supporting the research financial.

Reference

[1] S. Abdullah, A. K. Ariffin, C. K. E. Nizwan, M. F. Abdullah, A. Jalar, M. F. Yunoh. 2010. Failure Analysis of a Semiconductor Packaging Leadframe using the Signal Processing Approach. *International Journal of Modern Physics B*. 24: 175.

[2] Zhiyuan Han, Hongyun Luo, Jingwei Cao, Hongwei Wan. 2011. Acoustic Emission During Fatigue Crack Propagation in a Micro-Alloyed Steel and Welds. *Materials Science and Engineering A*. 528: 7751.

[3] K. A. Sweitzer and N. S. Ferguson. 2005. Mean Stress Effects on Random Fatigue of Nonlinear Structures. Twelfth International Congress on Sound and Vibration.

[4] T. Tanaka and Y. Izawa. 2002. Detection Method of Fatigue Damage in Carbon Steel Using Laser Ultrasonics. *Journal of Nuclear Science and Technology*. 39: 514.

[5] K. Yamaguchi *et al*. 2007. Gigacycle Fatigue Data Sheets for Advanced Engineering Materials. *Journal of Science and Technology of Advanced Materials*. 545–551.

[6] M. Loman**.** 2010. A Study of Fatigue Crack Initiation using Acoustic Emission Technique. Thesis of Master Degree (Department of Mechanical and Materials, Universiti Kebangsaan Malaysia).

[7] C. Ennaceur, A. Laksimi, C. Herve´, M. Cherfaoui. 2006. Monitoring Crack Growth in Pressure Vessel Steels by the Acoustic Emission Technique and the Method of Potential Difference. *International Journal of Pressure Vessels and Piping*. 83: 197–204.

[8] M. Mohammad, S. Abdullah, N. Jamaludin, M. Z. Nuawi. 2012. Correlating Strain and Acoustic Emission Signals of Metallic Component Using Global Signal Statistical Approach. *Advanced Materials Research*. 445: 1064.

[9] M. Loman, S. Abdullah, N. Jamaluddin. 2008. Fatigue Analysis of Piping System Using Acoustic Emission Technique. International Conference on Science & Technology. Applications in Industry & Education.

[10] Kelly, H. Zou, Kernal, Tuncali, Stuart, G. Silverman. 2003. Correlation and Simple Linear Regression. *Radiology Journal*. 617–628.

[11] N. Ismail, M. Z. Nuawi, S. Abdullah and A. Arifin. 2010. Statistical Analysis of Vibration Signal of an Automotive Suspension System. 3rd Regional Conference on Noise, Vibration and Comfort (NVC) 28-30th June, Putrajaya, Malaysia.