Journal of Mechanical Engineering and Sciences (JMES)
ISSN (Print): 2289-4659; e-ISSN: 2231-8380;
Volume 10, Issue 1, pp. 1827-1834, June 2016

DOI: http://dx.doi.org/10.15282/jmes.10.1.2016.7.0175

Evaluating effect of magnetic flux leakage signals on fatigue crack growth of mild steel

M.I.M Ahmad*, A. Arifin and S. Abdullah

Department of Mechanical and Materials Engineering
University Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
*Email: meoriqram@yahoo.com
Phone: +60-389116411; Fax: +60-389259659

ABSTRACT

In engineering applications, analysis of crack growth life is useful in situations where an unexpected crack has been found in a component of a machine, vehicle, or structure. The objectives of this research are to investigate the correlation curve of magnetic flux leakage, *Hp(y)* signals by evaluating their critical value point with respect to step size. Moreover, the relation of the fatigue crack growth rate, *da/dN* with the stress intensity range, *ΔK* and *Hp(y)* in metal components is also discussed in this paper. The tension–tension fatigue test was conducted with the metal magnetic memory (MMM) scanning device and crack opening displacement (COD) gauges at 10 Hz (testing frequency) by applying a load of 3.0–5.0 kN. As a result, the correlation curve of *Hp(y)* was built with the R-squared values in the range of 0.99 and a mathematical model was developed for estimation analysis. The sigmoidal shape curve was plotted on the graph of *da/dN* versus *ΔK* and also with *Hp(y)*. Thus, for validation, the linear relation is represented between *ΔK* and *Hp(y)* and presents a good approach for magnetic parameters to be developed for fatigue crack growth analysis. Therefore, the magnetic method has a greater capability to analyse the fatigue crack propagation life in a real application.

***Keywords*:** Fatigue test; crack growth life; magnetic signals; stress intensity range.

INTRODUCTION

The high possibility of failure whilst in operation was taken into consideration in order to develop this case study. Based on the principle of linear elastic fracture mechanics, the effect of the fatigue crack growth rate, *da/dN* is dominated by the stress intensity factor range, *ΔK* as a driving force parameter and is often formulated by a power law expression known as the Paris equation (as shown in Equation 1). Subsequently, many researches have enhanced this equation and proposed a new mathematical model for the solution of the fatigue crack growth problem. For instance, a new crack growth law was proposed by [1] to characterize the fatigue crack growth of a crack body in constant amplitude cyclic loading by considering the effect of load ratios. Therefore, by using the concept of magnetic flux signals, *Hp(y)* that were proposed first by Dubov in 1997, the fatigue prediction mechanisms and life assessment for ferromagnetic materials are investigated [2]. The MMM method has a special capability to detect stress concentration zones (SCZ) and assess the actual stress status and deformation of metal components [3]. A theoretical model was established that illustrates the impact of stress concentration and microdefects on the magnetic signal of metal components [4]. This method was used to monitor the activity of cracking or damage in steel structures by referring to the dynamic variation of amplitude and gradient of MMM signals [5, 6]. When a fatigue crack propagates under a constant loading, the axial stress, σ increases and produces a stress concentration zone in the metal surfaces. Hence, more magnetic charges are accumulated on the surface of the fatigue crack, generating a more significant abnormal magnetic peak [7]. The MMM mechanism was described in elastic stress using a modified J-A model in fatigue testing [8] and the relationship between the magnetic gradient and the stress was investigated under different measuring conditions [9]. Other research investigated the law of fatigue damage in a period of high-cycle fatigue testing using the magnetic signals [10-12]. From this, the quantitative analysis was obtained of the relationship between the magnetic flux leakage gradient, *dHp/dx* and the crack location in the formation of early defects [13]. Subsequently, the authors of Huang, Jiang [14] discussed the regularity of magnetic signals in fatigue crack growth under a dynamic bending load. However, this still does not clarify the relationship between the magnetic signals and fatigue crack propagation, thus it is necessary to conduct further analysis to gain a better understanding of fatigue crack growth. In this paper, through a tensile–tensile fatigue experiment, the authors investigated the relationship between the signals of magnetic flux leakage, *Hp(y)* and the fatigue crack growth effects on mild steel by referring to the correlation curve of magnetic signals in time steps and also the important relations between the stress intensity range, ΔK and *Hp(y)* with respect to the fatigue crack growth rate, *da/dN*.

METHODOLOGY

A specimen with a crack starter notch at the centre was fabricated from an A283 Grade C mild steel plate, which is most frequently used in heavy engineering applications, such as the manufacturing of storage tanks, vessels, and structural applications [5]. A specimen with 3 mm thickness and 22 mm width as an initial crack length was used for this experiment, designed according to ASTM: E647, International and Materials [15]. The setup of the experiment and the overall process flow are shown in Figure 1. The tension–tension fatigue test was conducted using an INSTRON 8801, 100 kN, servo-hydraulic machine, with a testing frequency of 10 Hz, and different loadings (3.0 kN, 4.0 kN and 5.0 kN) were loaded for each specimen in order to observe the stable crack growth propagation. Two types of instrument were used to capture the data analysis. The first device to measure the magnetic flux signals by using MMM scanning is the TSCM-2FM, with two sensors, *Hp(y)*1 and *Hp(y)*2. The distance between sensor 1 and sensor 2 was 10 mm, and the spacing from the specimen surface to the sensors surface was 2 mm [4]. A device was placed to be vertical to the crack notch, so that the data recorded would be passed through the stress concentration and normal zone. The second device was a Crack Opening Displacement (COD) device which is used to measure and control the propagation of the crack length on the specimen. The specimen was loaded in 3.0 kN for every cycle until the cracks on the specimen surface were propagated and approaching failure, at which point the load cycles stopped. Simultaneously, the MMM response signals, *Hp(y)* and also the propagation of the crack length were captured directly for the specimen. This entire procedure was repeated with different loadings of 4.0 kN and 5.0 kN and all the related data parameters were recorded and will be discussed further in other sections.

Fatigue Crack Propagation Model

A simple method for predicting fatigue crack propagation is the power law described by Paris and Erdogan in 1963 [16]. The equation represents the first application of fracture mechanics to fatigue and the related equation is shown below:

$$da/dN = C\,(\Delta K)^{m} \tag{1}$$

where C is the intercept and m is the slope of the log–log plot of the *da/dN* versus *ΔK* graph. In this study, Eq. (1) has to be manipulated to produce a new relation between *da/dN*, *ΔK* and *Hp(y)*.

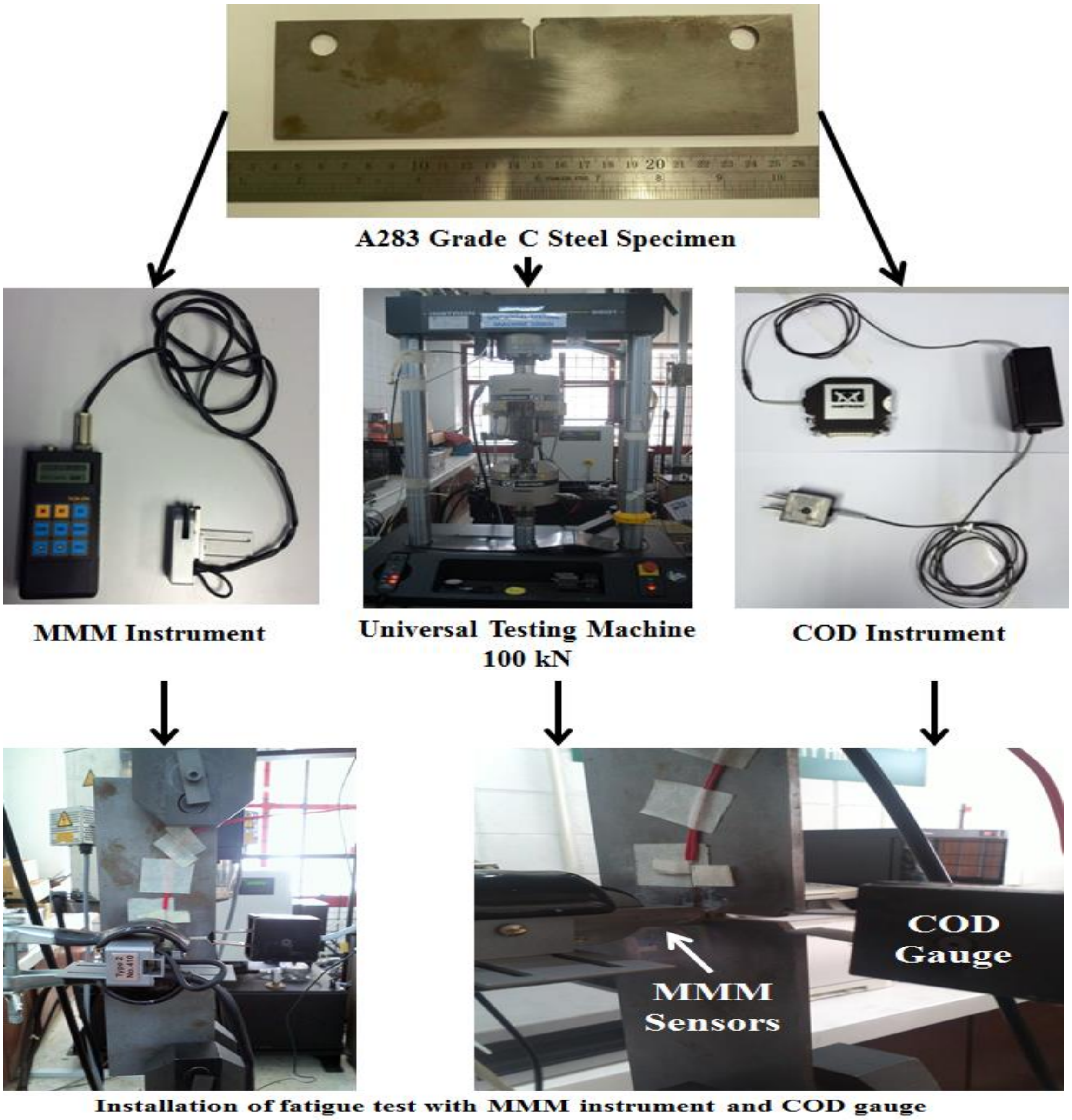

Figure 1. Overall process flow of the experimental procedure.

RESULTS AND DISCUSSION

Estimation of Magnetic Flux Signals Curve

Figure 2 illustrates the magnetic flux signals in two sensors, *Hp(y)*1 and *Hp(y)*2 of the MMM device for each load during the fatigue test. The patterns of the curves for every applied load show identical trends which increase steadily at the early crack initiation stages, and continue, inducing a spontaneous abnormal magnetic peak (drastically changed) when the crack starts to propagate [17]. This happens due to the formation of stress concentration zones, which are the main source of crack propagation until culminating in fracture.

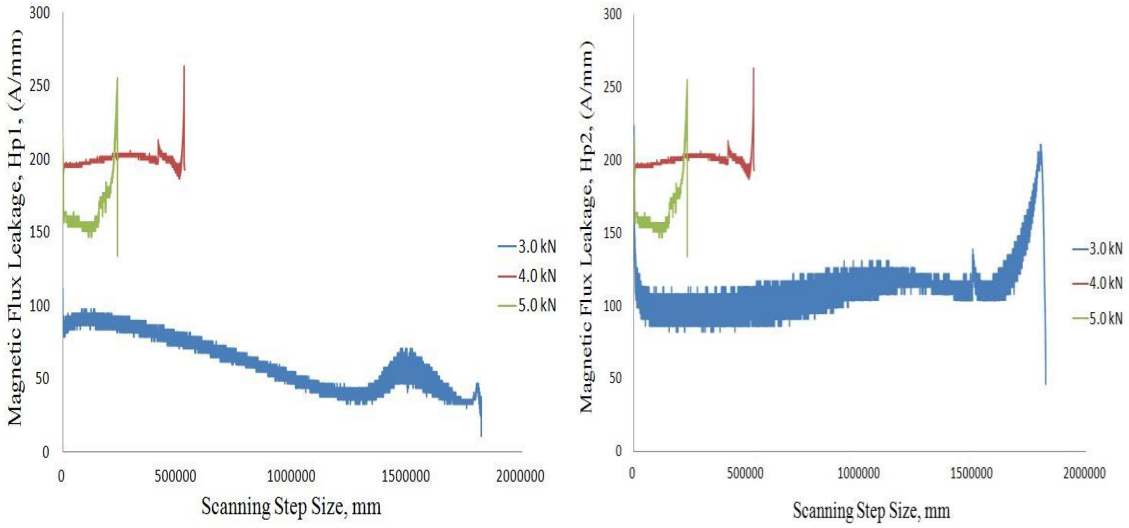

Figure 2. Magnetic signals pattern.

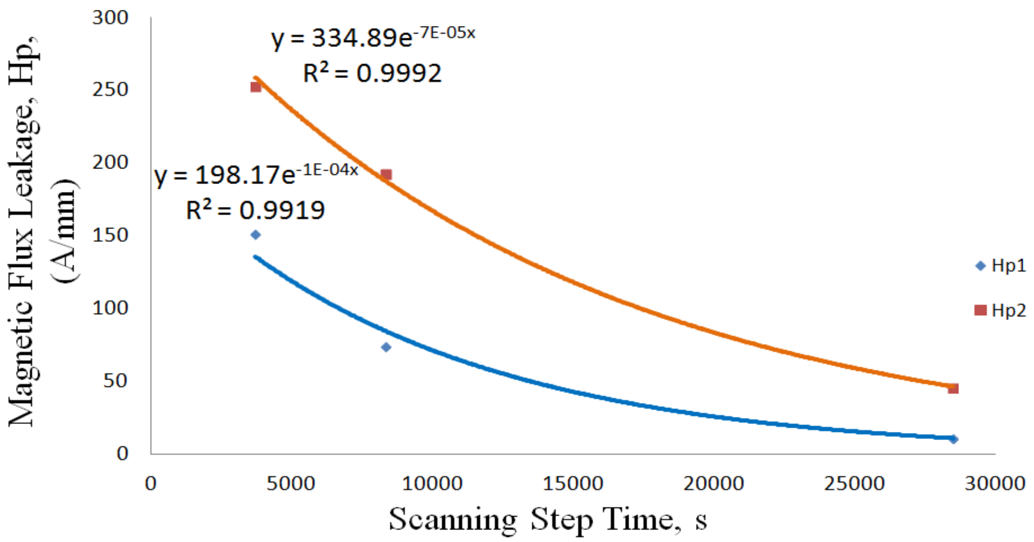

Figure 3. Correlation curve of magnetic signals.

Normally, any applied load can induce the generation of a spontaneous stray field on the metal components, even without an external magnetic field [7]. The variations of the *Hp(y)* amplitude and its gradient can clearly differentiate between deformation stages (from elastic, plastic deformations and up to fracture) and determine the location of the point of maximum stress concentration on the condition of the tension [18]. In addition, the magnetic signals under 3.0 kN of applied load for both sensors were captured in wide ranges of data because of the time required for a specimen to develop from initiation to fracture. The critical region (drastic changes) in the MMM signals graph is manipulated for further analysis. The maximum point values of *Hp(y)* for every applied load were stated together, thus one correlation curve of *Hp(y)* signals is represented (as shown in Figure 3) with R-squared values in the range of 0.99. From this curve, the value of *Hp(y)* can be estimated directly by referring to the time duration of the step size during operating, without the need to set up the experiment again. From Figure 3 also, a mathematical model has been developed based on the *Hp(y)*1 and *Hp(y)*2 curves and this equation is shown below:

$$Hp(y) = Ae^{-Bx} \tag{2}$$

in which the values of A and B are dependent on the sensor used.

Relations of *Hp(y)* and *ΔK*

For further analysis, the relationship between the fatigue crack growth rate, *da/dN* and the stress intensity range, *ΔK* for each applied load was investigated (as shown in Figure 4). In graphical observation, the value of *da/dN* will increase with increase of the *ΔK* value, with the R-squared values in the range of 0.83–0.92. This plot of *da/dN* versus *ΔK* forms a sigmoidal shape that can be divided into three major regions [19]. Firstly, in region I, the specimen starts to initiate the crack with a very low *da/dN* value. Next, in region II, the relationship follows the Paris formula which yields a straight line on the logarithmic coordinates, followed by region III, which has high values of *ΔK* that promote a rapid crack growth rate.

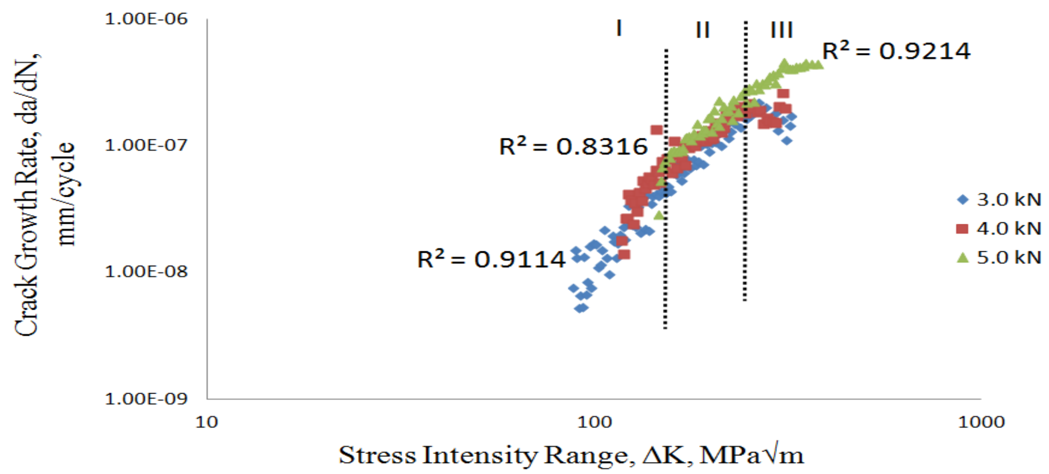

Figure 4. Crack growth rate curve (*da/dN* versus *ΔK*).

In order to see the relationship between *ΔK* and *Hp(y)*, the graph of *Hp(y)* with *da/dN* is identified in advance and is shown in Figure 5. It can be observed that the pattern of the curves for *Hp(y)*1 shows an identical trend to the curve in Figure 4, but the curves for *Hp(y)*2 are not very consistent for every load applied. This occurs because of a certain effect of the position and accuracy of the sensors used in this experiment that influenced the accuracy of the magnetic data [20]. From Figure 5 also, a modified power law equation for fatigue crack growth analysis was introduced as in the equation below.

$$da/dN = C\,(Hp(y))^{m} \quad (2)$$

where C is the intercept and m is the slope of the log–log plot of the *da/dN* versus *Hp(y)* graph.

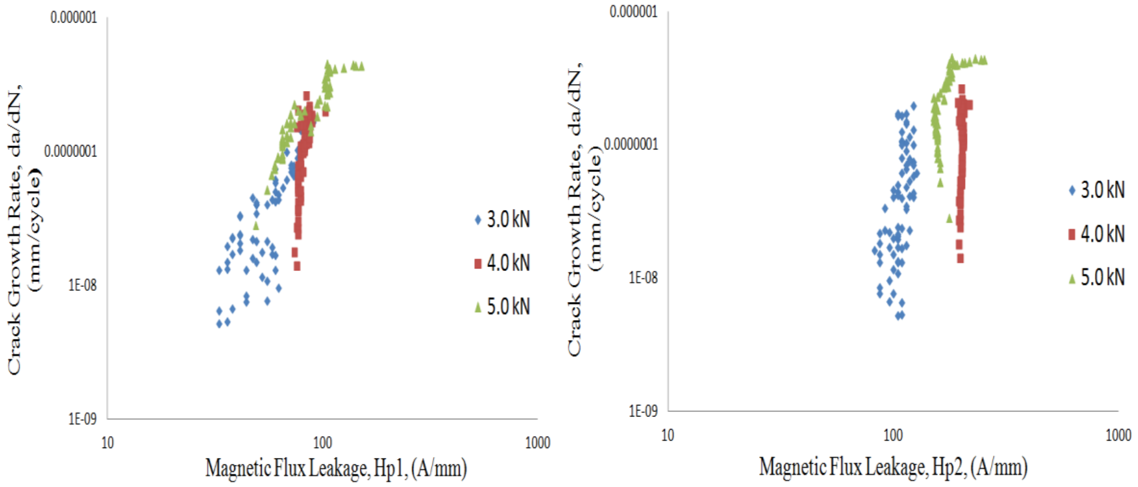

Figure 5. Crack growth rate curve (*da/dN* versus *Hp(y)*).

Lastly, to verify the results above, the relation of *ΔK* and *Hp(y)* is investigated and is shown in Figure 6. The linear relation is represented, whereby the value of *ΔK* rises with the increase of *Hp(y)* respectively, with the R-squared values in the range of 0.84–0.98. Therefore, the correlation of *da/dN* and *Hp(y)* in Figure 5 can be accepted theoretically and the parameter value of *Hp(y)* actually has the capability to replace *ΔK* as a variable parameter for fatigue crack growth analysis. The good relation between *ΔK* and *Hp(y)* gives an advantage for the magnetic parameters to be analysed together by developing the knowledge of fatigue crack growth to a new stage.

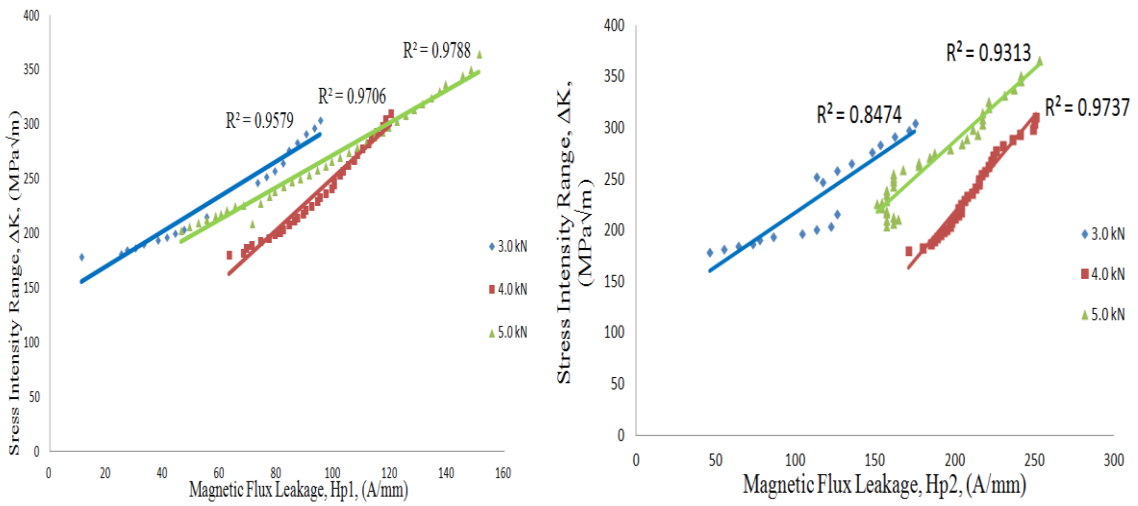

Figure 6. Correlation of stress intensity range, *ΔK* and magnetic flux leakage, *Hp(y)*.

CONCLUSIONS

The MMM technique provides great potential to evaluate and predict fatigue crack damage and remaining life. In this paper, the possibility of adopting the MMM method to predict fatigue crack propagation life on mild steel under different loadings is presented. A correlation curve of *Hp(y)* signals was successfully plotted based on the critical point in MMM signals and a mathematical model was developed to predict the value of *Hp(y)* for any position of step size. For investigating the fatigue crack growth, the relationship between *da/dN* and ΔK for each applied load was analysed and the result formed a sigmoidal shape that obeys the concept of the Paris law. Moreover, the modified Paris law model was presented by considering the magnetic parameter, *Hp(y)*, instead of the ΔK parameter for fatigue crack growth analysis. For verification, the linear relation was represented between the ΔK and *Hp(y)* graph with R-squared values in the range of 0.84–0.98. Therefore, the good correlation that was obtained between *Hp(y)* and ΔK gives a new achievement for developing the magnetic knowledge concept and a new solution of the application problem in fatigue crack growth. For future study, in order to develop MMM knowledge, some correlations will be taken into account, such as evaluating the relation between the MMM signals and strain signals in the fatigue crack growth analysis of specific components.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Universiti Kebangsaan Malaysia and Ministry of Education Malaysia through the fund of FRGS/1/2012/TK01/UKM/01/1 and FRGS/1/2012/TK01/UKM/03/2 for supporting this project research.

REFERENCES

[1] Li Y, Wang H, Gong D. The interrelation of the parameters in the Paris equation of fatigue crack growth. Engineering Fracture Mechanics. 2012;96:500-9.

[2] Ren SK, Li Y, Li XL. Residual life assessment for ferromagnetic components based on metal magnetic memory technology. Advanced Materials Research. 2011; 504-9.

[3] Ariffin A, Ahmad MIM, Abdullah S, Jusoh WZW. Detection of cracked position due to cyclic loading for ferromagnetic materials based on magnetic memory method. Jurnal Teknologi. 2015;75.

[4] Wang ZD, Yao K, Deng B, Ding KQ. Theoretical studies of metal magnetic memory technique on magnetic flux leakage signals. NDT & E International. 2010;43:354-9.

[5] Shen G, Hu B, Gao G, Li Y. Investigation on metal magnetic memory signal during loading. International Journal of Applied Electromagnetics and Mechanics. 2010;33:1329-34.

[6] Xing HY, Wang RX, Xu MQ, Zhang JZ. Correlation between crack growth rate and magnetic memory signal of X45 steel. Key Engineering Materials: Trans Tech Publ; 2007. p. 2293-6.

[7] Dong L, Xu B, Dong S, Chen Q, Dan W. Monitoring fatigue crack propagation of ferromagnetic materials with spontaneous abnormal magnetic signals. International Journal of Fatigue. 2008;30:1599-605.

[8] Xu M, Xu M, Li J, Xing H. Using Modified J–A model in MMM detection at elastic stress stage. Nondestructive Testing and Evaluation. 2012;27:121-38.
[9] Jian X, Jian X, Deng G. Experiment on relationship between the magnetic gradient of low-carbon steel and its stress. Journal of Magnetism and Magnetic Materials. 2009;321:3600-6.
[10] Yunoh MFM, Abdullah S, Saad MHM, Nopiah ZM, Nuawi MZ. Fatigue feature extraction analysis based on a K-Means clustering approach. Journal of Mechanical Engineering and Sciences. 2015;8:1275-82.
[11] Mohamed MA, Manurung YHP, Ghazali FA, Karim AA. Finite element-based fatigue life prediction of a load-carrying cruciform joint. Journal of Mechanical Engineering and Sciences. 2015;8:1414-25.
[12] Fauzun F, Aqida SN, Naher S, Brabazon D, Calosso F, Rosso M. Effects of Thermal Fatigue on Laser Modified H13 Die Steel. Journal of Mechanical Engineering and Sciences. 2014;6:975-80.
[13] Zhang Y, Gou R, Li J, Shen G, Zeng Y. Characteristics of metal magnetic memory signals of different steels in high cycle fatigue tests. Fatigue & Fracture of Engineering Materials & Structures. 2012;35:595-605.
[14] Huang H, Jiang S, Liu R, Liu Z. Investigation of magnetic memory signals induced by dynamic bending load in fatigue crack propagation process of structural steel. Journal of Nondestructive Evaluation. 2014;33:407-12.
[15] International A. Annual book of ASTM standards: ASTM International; 2004.
[16] Beden S, Abdullah S, Ariffin A. Review of fatigue crack propagation models for metallic components. European Journal of Scientific Research. 2009;28:364-97.
[17] Dong L, Xu B, Dong S, Song L, Chen Q, Wang D. Stress dependence of the spontaneous stray field signals of ferromagnetic steel. NDT & E International. 2009;42:323-7.
[18] Yao K, Wang ZD, Deng B, Shen K. Experimental research on metal magnetic memory method. Experimental Mechanics. 2012;52:305-14.
[19] Wu DB, Xu MQ, Xing HY. Detection of crack growth rate in 45 steel by metal magnetic memory. Applied Mechanics and Materials. 2010; 855-8.
[20] Dong LH, Xu BS, Wang HP, Xue N. A physical model for self-emitting magnetic signals during fatigue crack propagation. Applied Mechanics and Materials. 2012; 415-8.