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Evaluation of magnetic flux leakage signals on fatigue crack growth of mild steel

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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 objective of this research is 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 fatigue crack growth rate, *da/dN* toward 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 scanning device and crack opening displacement (COD) gauges in 10 Hz (testing frequency) by applying a load for 3.0-5.0 kN respectively. As a result, the correlation curve of *Hp(y)* was built with the R-Squared values in the range of 0.99 and one mathematical model has been 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)* that present a good approach for magnetic parameter to be developed in the fatigue crack growth analysis. Therefore, the magnetic method has greater capability to analyze 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 fatigue crack growth problem. For instance, new crack growth law was proposed by [1] to characterize the fatigue crack growth of 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 was proposed first by Dubov A. in 1997, the fatigue predicting mechanisms and life assessment for ferromagnetic materials are investigated [2]. Metal magnetic memory (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, which 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 crack or damage in steel structures by referring to the dynamic variation of amplitude and gratitude of MMM signals [5, 6]. When fatigue crack propagated under a constant loading, the axial stress, σ increased and produced a stress concentration zone in the metal surfaces. Hence, more magnetic charges were accumulated on the surface of fatigue crack, generating a more significant abnormal magnetic peak [7]. According to previous studies, MMM mechanism was described in elastic stress using modified J-A model in fatigue test [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 the period of high-cycle fatigue test using the magnetic signals. From here, the quantitative analysis was obtained between the magnetic flux leakage gradient, *dHp/dx* and the crack location in the formation of early defects [10]. This is followed by the study by [11] that discussed the regularity of magnetic signals in the fatigue crack growth under the dynamic bending load. However, it still does not clarify any relation between the magnetic signals and fatigue crack propagation, thus it is still necessary to conduct further analysis to gain a better understanding of the fatigue crack growth. In this paper, through 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

Specimen which has 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 manufacture of storage tanks, vessels, and structural applications [5]. The 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 [12]. The set-up of the experiment and the overall process flow is shown in Figure 1.

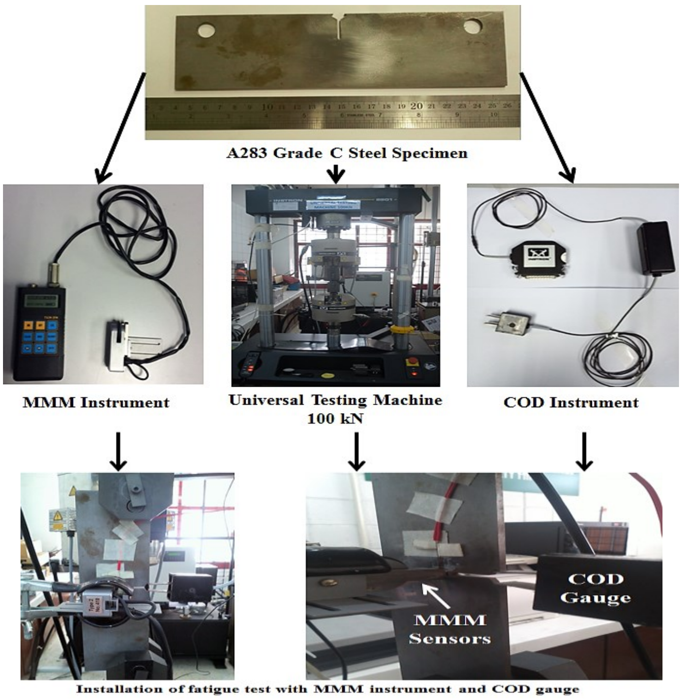

Figure 1. Overall process flow of the experimental procedure.

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 loading (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 instruments were used to capture the data analysis. The first device to measure the magnetic flux signals is by using MMM scanning, 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 recorded data taken would be passed through the stress concentration and normal zone. The second device was Crack Opening Displacement (COD) device which is used to measure and control the propagation of crack length on the specimen. The specimen was loaded in 3.0 kN for every cycle until the cracks of a specimen surface were propagated and approaching failure, then the load cycles were stopped. Simultaneously, the MMM response signals, *Hp(y)* and also the propagation of crack length were captured directly toward a 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 a power law described by Paris and Erdogan in 1963 [13]. 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 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)*.

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 MMM device for each load during a fatigue test. The pattern of the curves for every applied load shows identical trends, which steadily increase the early crack initiation stages, and continue to induce a spontaneous abnormal magnetic peak (drastically changed) when the crack starts to propagate [14]. This happens due to the formation of stress concentration zones, which are the main source of crack propagation until it culminates in fracture. Normally, any applied load can induce the generation of spontaneous stray field on the metal components even without an external magnetic field [7]. The variations of *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 [15]. In addition, the magnetic signals in 3.0 kN of applied load for both sensors were captured in the wide ranges of data because of time required for a specimen from initiation to fracture.

The critical region (drastic changes) in the MMM signals graph is manipulated for further analysis. The maximum point value of *Hp(y)* for every applied load was stated together, thus one correlation curve of *Hp(y)* signals is represented (as shown in Figure 3) with the 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 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 in Eq. (2).

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

which the value of A and B depend on the sensor use.

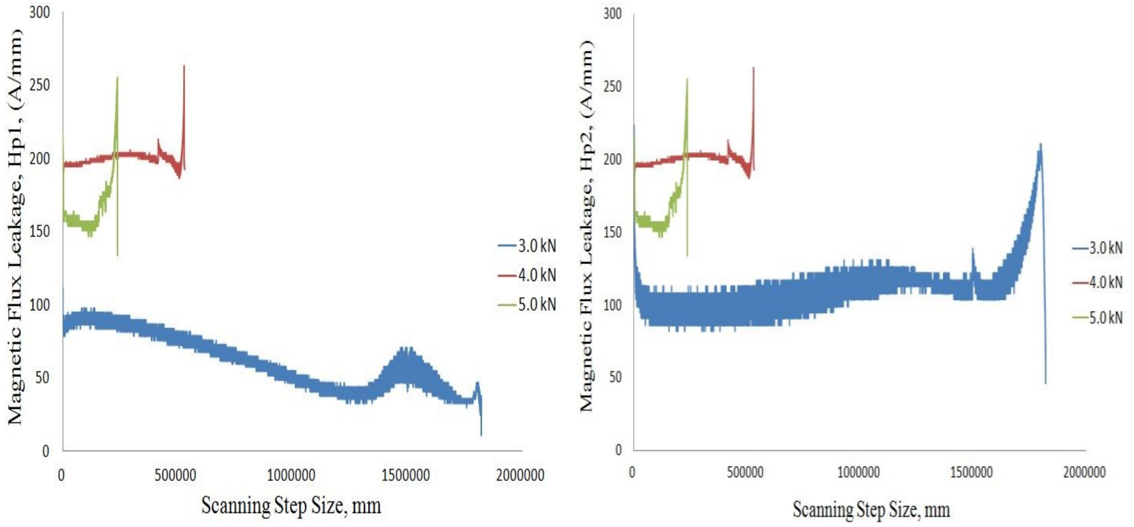

Figure 2. Magnetic signals pattern.

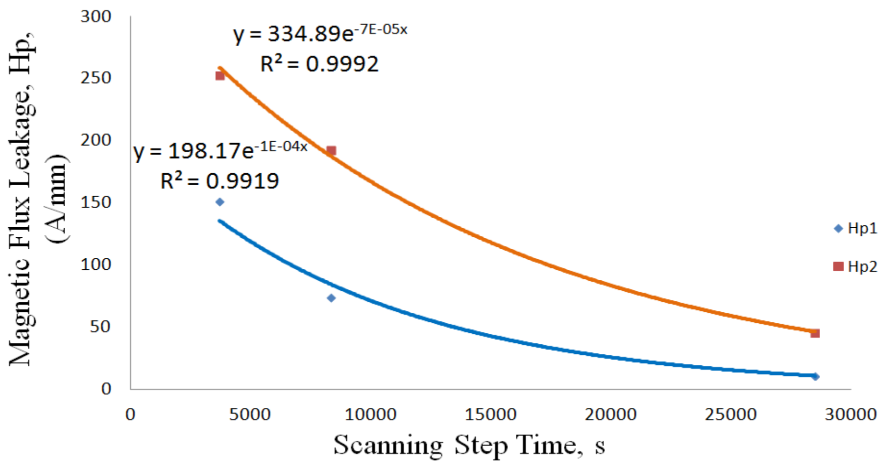

Figure 3. Correlation curve of magnetic signals.

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, *da/dN* value will increase with the increase of *ΔK* value with the R-Squared values in the range of 0.83-0.92. This plot of *da/dN* versus *ΔK* has formed a sigmoidal shape that can be divided into three major regions [16]. Firstly, in region I, the specimen starts to initiate their crack with a very low *da/dN* value. Next, in region II, the relationship follows Paris formula, which yields a straight line on the logarithmic coordinates, followed by in region III, which has high values of *ΔK* that promote rapid crack growth rate.

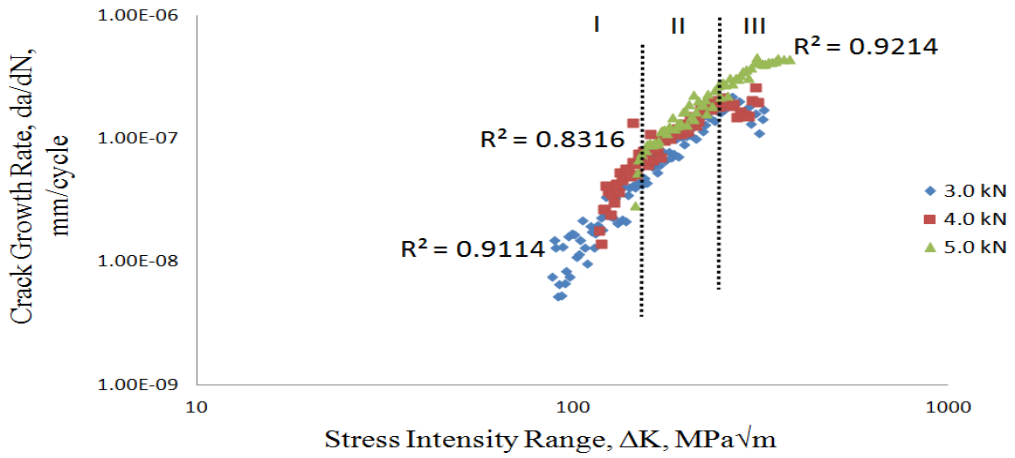

Figure 4. Crack growth rate curve (*da/dN* versus *ΔK*).

In order to see the relationship between *ΔK* and *Hp(y)*, the graph of *Hp(y)* with *da/dN* is identified in advance and it is shown in Figure 5. It can be observed that the pattern of the curves for *Hp(y)*1 showed identical trend with the curve in Figure 4, but the curves for *Hp(y)*2 were not really consistent for every load applied. It happens because of a certain effect on the position and accuracy of sensors that are used in this experiment that influenced the accuracy of magnetic data [17]. From Figure 5 also, a modified power law equation for fatigue crack growth analysis was introduced in the equation below.

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

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

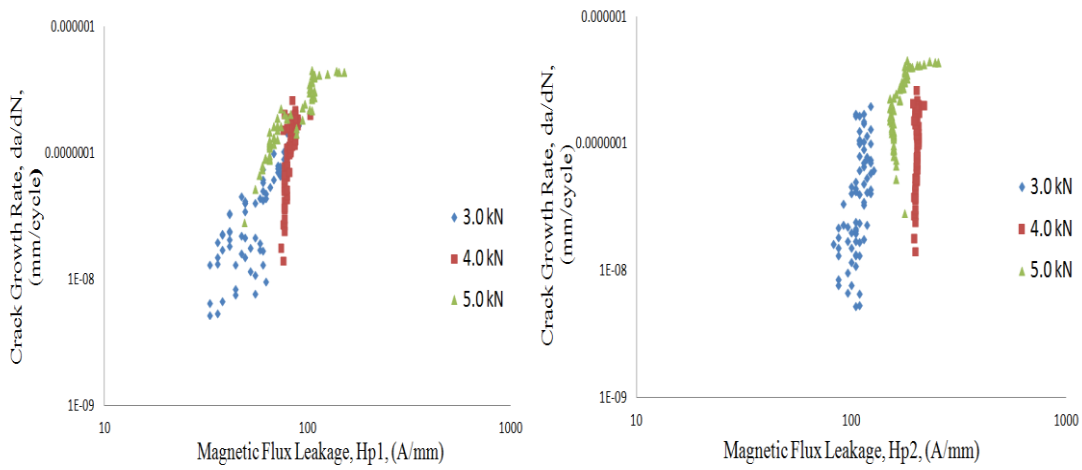

Figure 5. Crack growth rate curve (*da/dN* versus *Hp(y)*).

Lastly, to verify the results above, the relation of *ΔK* and *Hp(y)* is investigated and shown in Figure 6. The linear relation is represented in which 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 a 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 parameter to be analyzed together by developing the knowledge of fatigue crack growth to a new stage.

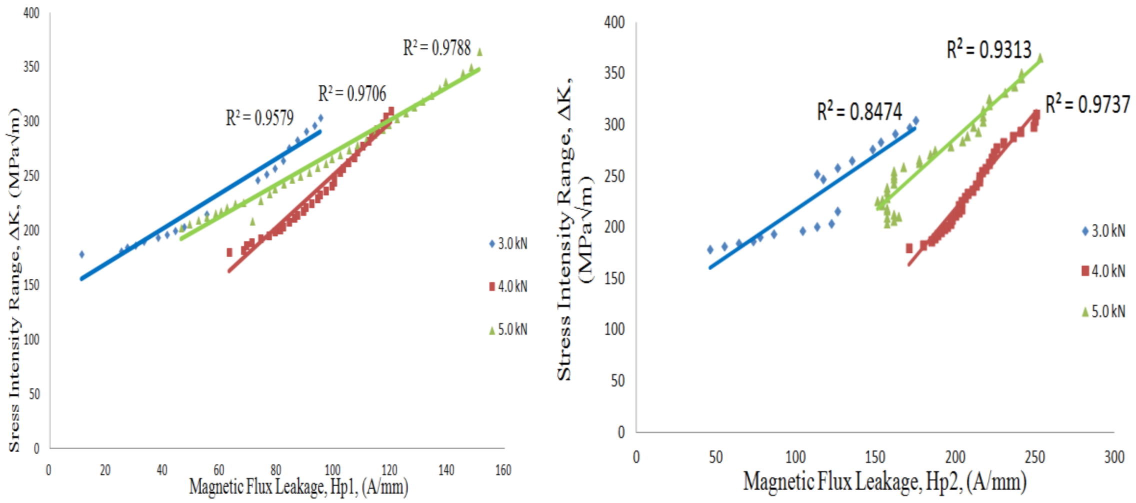

Figure 6. Correlation of stress intensity range, *ΔK* and magnetic flux leakage, *Hp(y)*.

CONCLUSIONS

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 one mathematical model has been 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 investigated and formed a result of sigmoidal shape that obeys the concept of 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 *ΔK* and *Hp(y)* graph with the R-Squared values in the range of 0.84-0.98. Therefore, a good correlation obtained between the *Hp(y)* and *ΔK* gives a new achievement for developing the magnetic knowledge concept for a new solution of application problem in fatigue crack growth. For future study, in order to develop a MMM knowledge, some correlations will be taken into account, such as evaluating the relation between the MMM signals and strain signals in fatigue crack growth analysis of specific components.

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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; 217-218:504-9.

[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(7): 67-70.

[4] Wang Z, Yao K, Deng B, Ding K. 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. 2007; 353-358:2293-6.

[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] 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 and Fracture of Engineering Materials and Structures. 2012;35:595-605.

[11] 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.

[12] Standard A. Annual book of ASTM standards. American Society for Testing and Materials Annual, Philadelphia, PA, USA. 2004;4.

[13] Beden S, Abdullah S, Ariffin A. Review of fatigue crack propagation models for metallic components. European Journal of Scientific Research. 2009;28:364-97.

[14] 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.

[15] Yao K, Wang Z, Deng B, Shen K. Experimental research on metal magnetic memory method. Experimental mechanics. 2012;52:305-14.

[16] Wu DB, Xu MQ, Xing HY. Detection of crack growth rate in 45 steel by metal magnetic memory. Applied Mechanics and Materials. 2010; 34-35:855-8.

[17] 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;190:415-8.