

Time-based Magnetic Flux Leakage Assessment of SAE1045 Steel for Biaxial Fatigue Failure

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Abstract

In this study it is aim to investigate behaviour of magnetic metal memory, MMM signal the stress concentration zone of ferromagnetic material using magnetic flux leakage under cyclic axial-torsional loading and later estimating the life of the specimens. Specimen in this study made from SAE 1045 steel prepared according to ASTM E466-01 for cyclic testing. In this study, it is proposed to take the signal using time based method during experiment. Load in axial and torsional direction is given and two types of sensors attach to the specimen; the strain gauge and the MMM sensor. Data is collected in time-based for both sensors. Trend of data from both sensors were then tabulation. It shows that both sensors has similar trend along the experiment when each signals shows important event during experiment such as at loading and at fracture. After that the estimated life from the MMM sensor, the T_{life} was then compared to numbers of cycle to failure from the experiment. It shows that this proposed method has the ability to estimated fatigue life with better accuracy when the specimens have higher number of cycle.

Keywords: biaxial fatigue, magnetic flux leakage, stress concentration zone

1. Introduction

Any component subjected to dynamic loading could experience fatigue failure. In order to prevent metals from failure due to fatigue, evaluating fatigue damage and predicting the remaining life is an important role. Recent studies have shown that the fatigue cracks occur on ferromagnetic material surfaces are initiated and induced spontaneously fluctuation of magnetic signals. Propagation of the cracks to its critical size promotes stress concentration zones (SCZ) or micro defects until the components fails. Stress concentration zones are the main factors that affect the development of fatigue fractures [1, 2]. By taking these SCZ as a variable, the metal magnetic memory (MMM) method can be used to detect SCZ by referring to the Self-Magnetic Leakage Field (SMLF) distribution on metal surfaces.

The fundamental parameter for identifying the SCZ is the SMLF segments. This parameter can be utilized to locate the plausible imperfection area due to different types of loading. The tangential segment $H_p(x)$ and the normal part $H_p(y)$ of the SMFL signals are estimated on the surface of the segment. At the point when the most extreme SCZ happen, $H_p(x)$ has the maximum value and it gives the $H_p(y)$ effect to change the polarity [3]. Several application have been known to utilized the MMM strategy for diagnosing gas and oil pipelines, rails, turbine wheels, weight vessel [4]. The benefits of the MMM technique are it has very fast scanning speed it is easy to operate and it does not require any removal of surface coating or insulation for up to 50 mm in thickness [4]. The sole disadvantages of the MMM techniques contrasted with other NDT method, for example, ultrasonic testing, acoustic emanation, swirl current

testing and so forth, is merely can be utilised for ferromagnetic material.

Apart from SCZ, the MMM method can also detect macroscopic cracks and defects at early stage. MMM has shown capability in positioning crack due to cyclic loading [5]. Fatigue crack by Ahmad in 2015 [6] and fatigue failure characteristics is current research applying MMM. In fact, the MMM method has also the potential for fatigue damage evaluation and remaining life prediction [2, 7, 8]. Chen [9] in 2017 has shown defect classification in metal using enhance MMM method. A development of magneto mechanical model by Shi [10] in 2017 to establish quantitative relationship between the shape and size of defect and the surface of magnetic memory signals.

This paper discussed an experimental research on the Magnetic Metal Memory (MMM) method under biaxial fatigue loading. The objective of this study is to characterise the profile of signal gathered from both strains histories and the signal from metal magnetic memory method. After that, similarity of both signal will be analyse to be used as potential method to evaluate fatigue life of specimen. If the MMM signals shows similar profile as strain histories taken from strain gauge, so the MMM have a potential to evaluate fatigue life of the specimen. In this study it is proposed to use time based signal to monitor signal from biaxial testing. The second objective is to estimate the number of life gathered from the MMM signal and compared to number of life gathered from the experiment. There is a lot of spaces can be explore to gain better knowledge relating to this method. Although research relates to metal magnetic memory and fatigue has been carried out, those research gave more focus on uniaxial loading and using length based signals from metal magnetic memory. By carrying this early stage research towards time-based MMM method for biaxial

fatigue, it is hoped that this study can channel new method for fatigue life evaluation of a component.

2. Theoretical of Magnetic Metal Memory Life Estimation

The MMM technology was introduced by Professor Dubov, a Russian scholar in the field of power engineering [8]. This technology was a current approach in the field of non-destructive testing. It is based on detection of residual magnetism at localised position in any ferromagnetic material. The parameter in the MMM method is the magnetic leakage field H_p , gradient (dH_p/dx) or field variation intensity factor, K_{in} . Research relation of energy between the magnetic and mechanical parameters of specimen under static and cyclic loads [11] given by Equation (1),

$$m = \frac{K_{in}^t}{K_{in}^y} = \left(\frac{\sigma_t}{\sigma_y}\right)^2 \tag{1}$$

where K_{in}^t and K_{in}^y are values of the magnetic field gradient of conditional yield strength and ultimate strength respectively. The magnetic parameter K_{in} characterised the magnetic energy density W_m conditioned by the mechanical deformation energy due to force action W_f as shown in Equation (2),

$$K_{in} = \frac{W_m}{W_f} = \frac{2E}{\sigma^2} \tag{2}$$

where E is modulus of elasticity. The energy relation obtained in Equation (2) then proposed to estimate the lifetime in SCZ based on the actual maximum K_{in}^{act} and the actual service hours of a specific unit of the date of inspection, T_{act} and the period of specimen operation, T_{lim} given as in Equation (3). Therefore, the residual lifetime of the inspected with SCZ estimated by Equation (4),

$$T_{lim} = \frac{K_{in}^t}{K_{in}^{act}} (T_{act}) \tag{3}$$

$$T_{life} = T_{lim} - T_{act} \tag{4}$$

The lifetime estimation is based on the accepted assumption of linear time dependence of the process plastic strain and metal fatigue accumulation.

3. Methodology

Since the sensor is using magnetic flux leakage principle, the selected material is a ferromagnetic material where it could induce magnetic flux. Steel grade SAE 1045 material was used because it has excellent mechanical properties and widely used as structural component [12]. Its chemical composition and mechanical properties are shown in Table 1 and Table 2 respectively. It has

been machined according to ASTM 466-07 and then polished to get mirror like surface to decrease stress concentration zone. The gauge parts of the specimen were divided to eight positions with 10 mm distance from point 1 to point 9 as shown in Figure 1.

Table 1: Chemical Composition of SAE 1045 steel (wt. %)

	Fe	C	Mn	P	S
Min	98.51	0.42	0.60	0.010	0.020
Max	98.98	0.50	0.90	0.040	0.050

Table 2: Mechanical properties of SAE 1045

Steel	Yield Strength (MPa)	Ultimate Strength (MPa)	Young Modulus (GPa)
SAE 1045	392	710	190.5

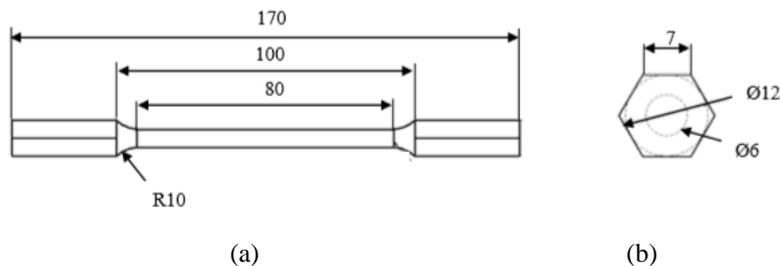
The axial-torsion fatigue test has been conducted using a servo-hydraulic machine. The specification for the fatigue testing shown in Table 3. During the testing, magnetic flux leakage signals are collected using a stress concentration test device. Simultaneously, strain histories also were collected during the experiment using a strain data acquisition system. Three magnetic flux sensors $H_{p1}(y)$, $H_{p3}(y)$ and $H_{p4}(y)$ were attached to the specimens at two different positions; (position 1 and position 8) to capture flux leakage at potential fatigue crack position. Figure 2 shows the positions of the flux sensors on the specimen, where two sensors positioned at each location. At position two, a strain gauge also has been glued to the specimen. The purpose of putting the strain gauge is to study the similarity between strain signal and magnetic flux signal.

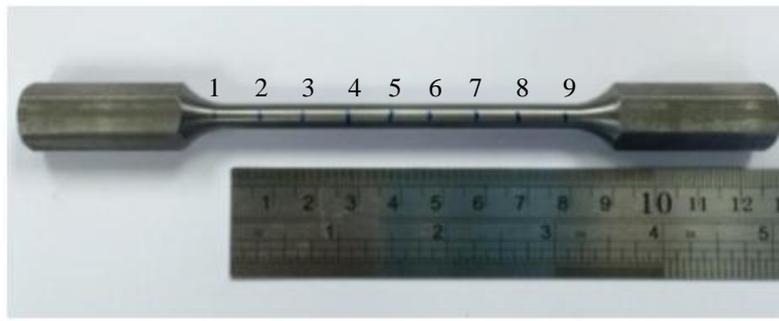
Table 3: Specification for the biaxial cyclic testing

Loading	Load (MPa)	Frequency (Hz)	Angle of rotation (°)
Axial	0.5UTS	1	-
Torsion	-	1	3 and 15

4. Results and Discussion

Tabulation of signals gathered from the strain gauge show in Figure 3. In Figure 3a the strain time histories from the beginning until half of the experiment is shown. Another half fracture shows in Figure 3b. Following the same manner, tabulation of magnetic flux signals gathered using the MMM sensor shown in Figure 3c for first half and 3d for the second half. These histories divided into two segments due to limitation of MMM sensor which unable to store data in longer time. From the strain histories it can be seen that when the machine starts to loading, strain signals starts to decrease and become steady when experiments continued. Decreasing trends value of the microstrain in the histories due to loading step from machine which brings the specimen to zero position before cyclic loading begin. At the same time magnetic flux signals gathered from the MMM sensor showing same trends as gathered from the strain time histories; the decreasing trends followed by the steady state condition onwards. As the time increased, the signals have achieved steady state condition because loading is given in





(c)
Figure 1: Geometry for the specimen a) side view b) front view, c) actual specimen used in experiment and point on the gauge length

constant amplitude along the loading condition. The same trends also give by all three signals gathered from the MMM sensors. When the specimens fracture, increasing in both strains time histories and magnetic flux signals were detected. Figure 4 shows the strain time histories signal collected from the experiment. In the histories variation of microstrain ($\mu\epsilon$), values vary from 3124 microstrain in the beginning to 3200 microstrain towards end of the experiment. It seen can be seen that increasing in strain value using strain gauge with $\Delta\mu\epsilon$ is 76 microstrain. Figure 5 shows the signal gathered from the MMM sensor 1, $H_{p1}(y)$ which is the critical point to the fracture position on the specimen. Variation values of magnetic flux leakage, $\Delta H_{p1}(y)$ detected ranged from the beginning where $\Delta H_{p1}(y)$ is 13 A/mm and $\Delta H_{p1}(y)$ at the end is 20 A/mm. Difference of the $\Delta H_{p1}(y)$ value gathered from the MMM sensor is 7 A/mm.

Results given by the number of cycles to failure from the experiment and estimated from the magnetic flux signal, called T_{Life} that indicate period of specimen operation tabulated in Table 4. From the Table 4 it can be seen that when applied axial load was $0.5\sigma_{UTS}$ and rotation angle of 15° , the specimen failed at 2.215 hours and the T_{Life} value estimated at 3 hours of life. While when the same axial load applied at smaller rotation angle, 3° , the specimen has longer life where it fails at 32.670 hours and the estimated T_{Life} is 33 hours. The MMM method estimate fatigue life value of tested specimen using integer number. Due to this limitation, it has estimated longer fatigue life value for Specimen 1. However, when higher number of cycles to failure gathered, as given by Specimen 2, the T_{Life} value is almost same as service operation hours from the experiment.

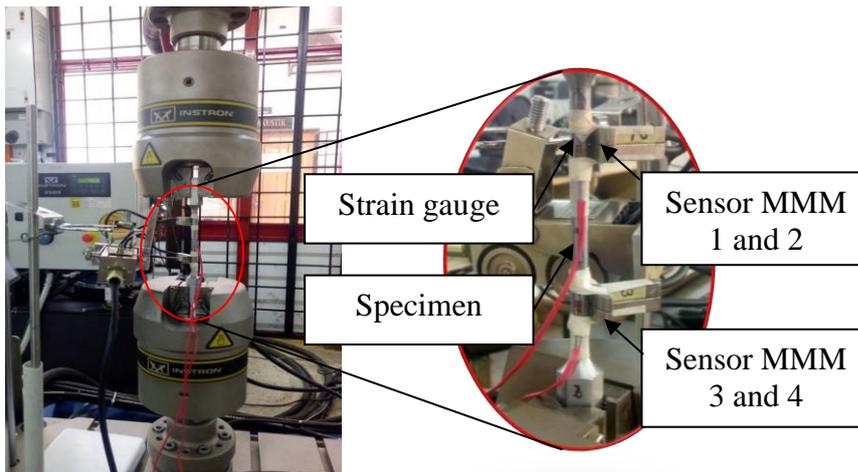
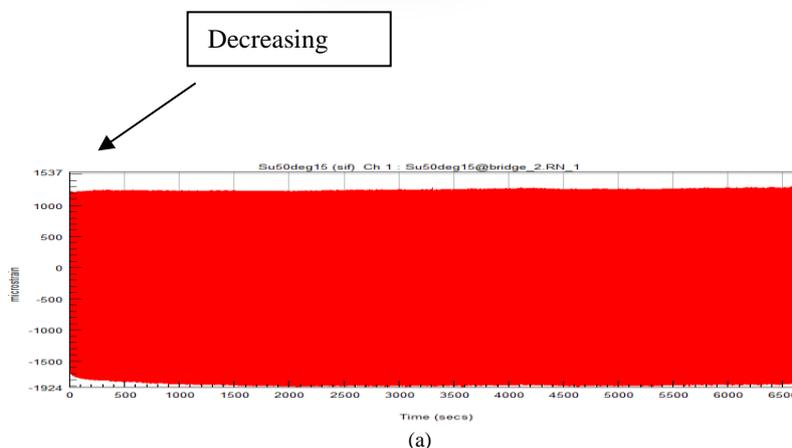
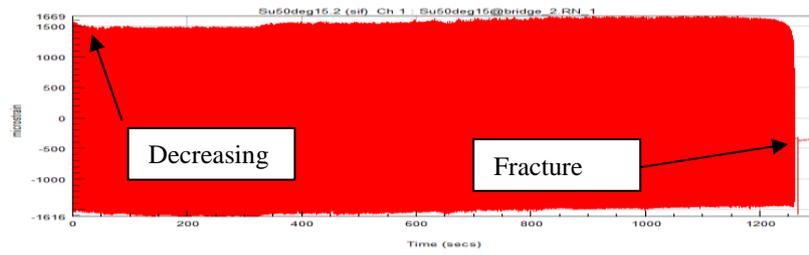


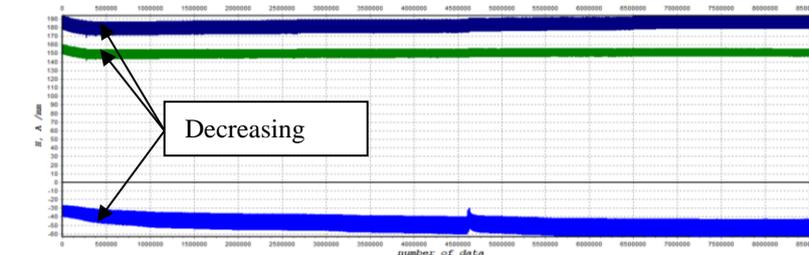
Figure 2: Position of the MMM sensor and strain gauge on the specimen during cyclic testing using servo-hydraulic machine



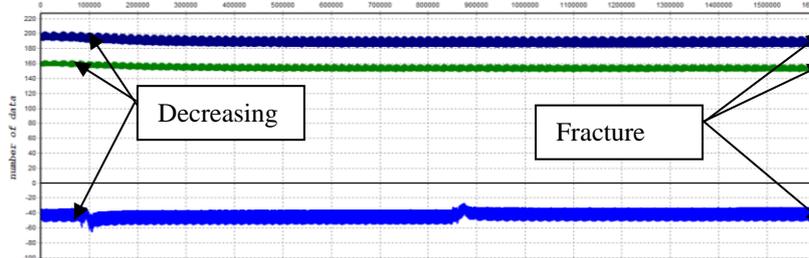
(a)



(b)

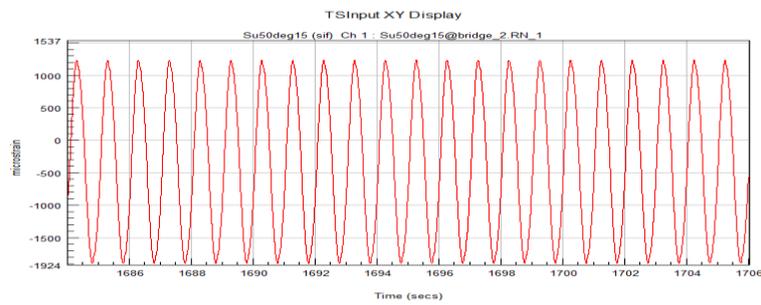


(c)

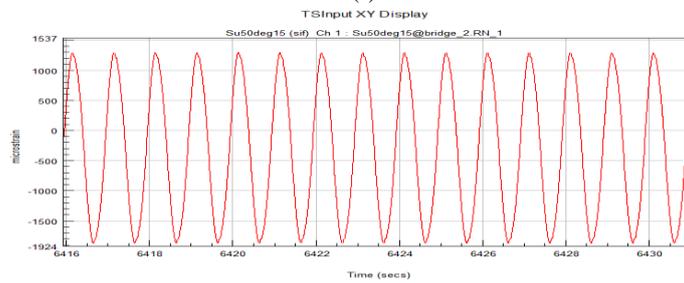


(d)

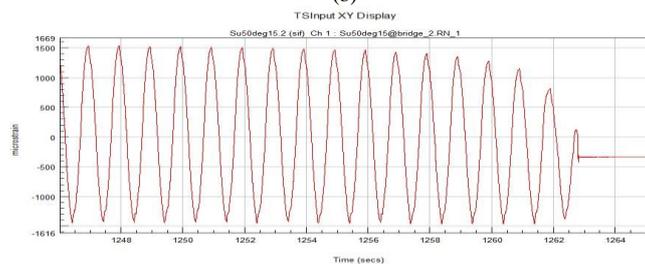
Figure 3: Tabulation of data; (a)to (b) Strain histories and (c) to (d) magnetic flux leakage signal.



(a)



(b)



(c)

Figure 4: Variation on strain time histories a) in the beginning b) in the middle c) in the end of experiment.

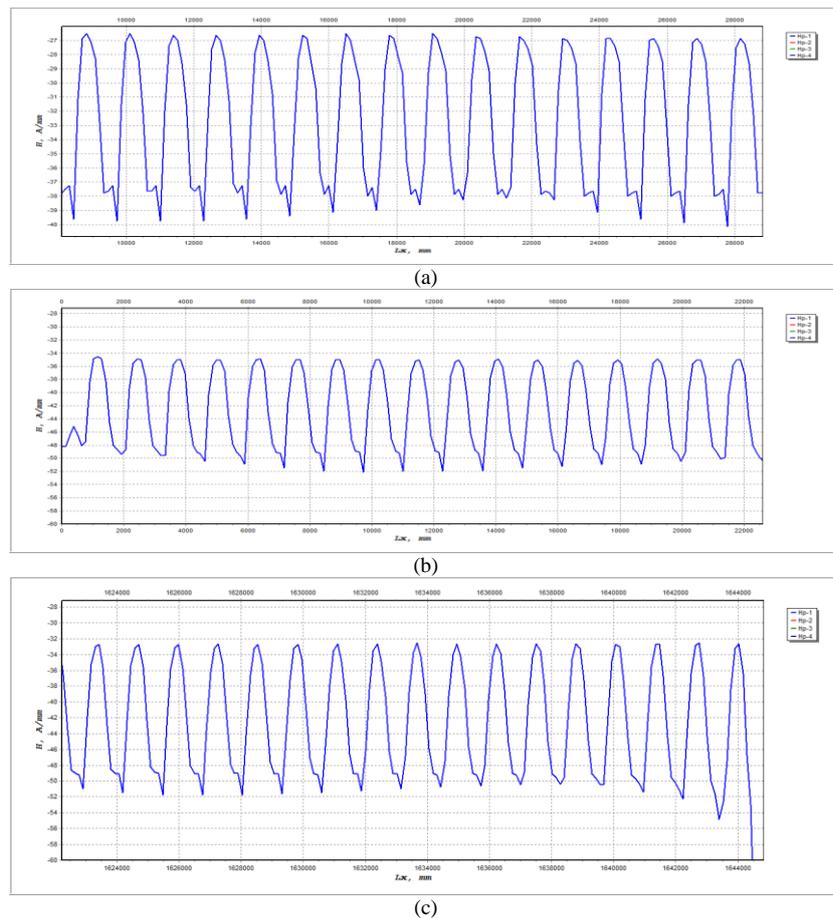


Figure 5: Variation in magnetic flux leakage signals sensor 1, $H_{p1}(y)$ a) in the beginning b) in the middle c) in the ends of the experiment.

Table 4: Results of the cyclic biaxial testing from both experiment and MMM Life

Specimen	Loading	Experiment (Cycles to failure)	Experiment (hours)	MMM Life, T_{life} (hours)
1	$0.5\sigma_{UTS}$, 15°	7977	2.215	3
2	$0.5\sigma_{UTS}$, 3°	117614	32.670	33

5. Conclusion

Fatigue life assessment of SAE 1045 steel using time based magnetic flux leakage method in this study has shown positive results. The collected signal from the MMM device used during the cyclic biaxial testing has similar trend as signal collected from strain time histories. It clearly seen in both signal when the loading events started and specimens fractured, both signal showed changes events. The variation strain value from strain time histories of $\Delta\mu\epsilon$ is 76 microstrain and variation values of magnetic flux leakage, $\Delta H_{p1}(y)$ is 7 A/mm. Low value of $\Delta H_{p1}(y)$ is due to the direction of self magnetic flux leakage is in tangent direction but the sensor is only capable to detect in normal direction. The estimated value of life using signals gathered from the MMM sensors, T_{life} has small differences compared to value of life from the experiment. The higher values of cycles to failure in experiment give better accuracy of T_{life} compared to lower value of cycles to failure in experiment. At cycles to failure of 7977 which equal to 2.215 hours, life estimated from the MMM sensors is 3 hours and at cycles to failure of 117614 which equal to 32.670 hours, life estimated is 33 hours. These results indicate that the MMM time-based method proposed in this study is able to estimated fatigue life with better accuracy for higher service life component.

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