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Evaluating the contraction value of ferromagnetic material at early fatigue loading stage using magnetic flux leakage signature

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Abstract. This work focuses on the investigation to evaluate a material parameter, namely a contraction value *ψ*, at failure in estimating the fatigue life of ferromagnetic steel based on magnetic metal memory method. It begins with specimen preparation made from mild carbon steel and it was machined as specified in the ASTM E467-01 standard. These cyclic tests were performed using the 25-kN servo-hydraulic machine with the applied axial loading levels were at 60% UTS and 70% UTS. The magnetic flux leakage was then measured at every hour of the load applied, and the nature of change of magnetic leakage intensity H_p over the surface of the specimen. A further analysis on the collected signals or pattern was carried out based on the H_p distribution and its gradient at dH_p/dx, and both parameters were later being used to estimate total loading time before specimen failure. A further analysis on the collected signals or pattern was carried out based on the H_p distribution and its gradient at dH_p/dx, and both parameters were later being used to estimate total loading time before specimen failure. At every hour of loading cycles, the fatigue life of the specimen is estimated using the specific calculation of this MMM approach.

1. Introduction

Critical location of the component made from ferromagnetic materials, such as steel and cast iron can be potentially monitored using magnetic state for their degradation failure process. Magnetic measurements are a Non-Destructive Test (NDT) technique that can be used to evaluate fatigue damage on ferromagnetic materials due to the modification of density and lattice dislocation patterns, and the formation of continuous sliding bands causing changes in magnetic properties. Major magnetic techniques that have the potential to detect fatigue damage include the effect of Barkhausen (Barkhausen Noise), magneto-acoustic emission (Magneto-acoustic Emission), magnetic flux leakage and magnetic hysteresis. Barkhausen Noise and Magneto-acoustic Emission Signals are derived from the non-continuous magnetization process that occurs during the hysteresis cycle, and both are greatly influenced by stresses and deformations [1]. However, the disadvantage of this technique in NDT applications is that the Barkhausen Noise and Magneto-acoustic Emission signal is generally weak and, therefore, highly sensitive measurement equipment is needed and the effect on noise interference is high and the eddy current method, need an external excitation to detect crack.

To overcome disadvantages of previous method, a Russian scholar, introducing Metal Magnetic Memory-MMM. This method is a passive non-destructive testing method developed based on magneto-mechanical effects. It is a method of advanced magnetics flux leakage, in which the mechanism is like the magnetic flux leakage method but does not require artificial excitation. Due to the impact of the load and the earth's magnetic field, spontaneous magnetic signal changes may occur on the surface of the ferromagnetic material during manufacturing or operation [2]. Fracture due to fatigue usually occurs in areas where significant stress concentration zones microscopic exist, which became a key resource in the development of defect. Recent studies have shown that the fatigue cracks occur on ferromagnetic material surfaces are initiated and induced spontaneously fluctuation of magnetic signals.

Using metal magnetic memory methods, the obtained magnetic signal distribution can be used to evaluate the stress concentration conditions that occur and provide an early indication of the potential failure. Based on the concept of metal magnetic memory, two parameters used to measure the free magnetic signals in stress concentration area are normal component signals, $H(y)$ and tangent component signal, $H(x)$ [3]. The stress concentration level on the specimen can be determined by the maximum value of the normal components gradient, $\mathrm{d}H(y)/\mathrm{d}x$. This $\mathrm{d}H(y)/\mathrm{d}x$ value has the potential to be an indicator in monitoring fatigue crack growth [4]. Signals $H(x)$ and $\mathrm{d}H(y)/\mathrm{d}x$ show different characteristics at different stages of growth of cracking. Therefore, the characterization of MMM signals at different levels of fatigue crack growth can be implemented [5]. MMM has shown capability in positioning crack due to cyclic loading [6]. Chen et al. [7] in 2017 has shown defect classification in metal using enhancement MMM method. A development of magneto mechanical model by Shi et al. [8] in 2017 to establish quantitative relationship between the shape and size of defect and the surface of magnetic memory signals. This method also has potential in estimating residual life of a component in service base on the magnetic flux leakage based on static loading condition [9]. (Dubov & Kolokolnikov, 2008).

This paper discussed an experimental research on the Magnetic Metal Memory (MMM) method under uniaxial fatigue loading. The objective of this study is to determine stress concentration zone of the specimen at early stage. After stress concentration being detected, residual life of the specimen is estimated. The materials properties called contraction at failure was evaluated to analyse the effect of contraction value with fatigue life estimated. The estimated fatigue life were than compared with experimental value and analytical calculation. In this study length-based signals were used to monitor signal from uniaxial cyclic testing. There is a lot of spaces can be explored to gain better knowledge relating to this method. Although research relates to metal magnetic memory and fatigue has been carried out, those researches gave more focus on positioning and sizing the crack. By carrying this early stage research towards MMM method life time estimation, it is hopes that this study can channel new method for fatigue life evaluation of a component.

2. Theoretical background

2.1 Fatigue failure

Fatigue is a dangerous phenomenon because it can cause sudden failure due to microscopic scale changes, which is the dislocation of the atomic lattice on the material structure after having been in service for many years [10]. Knowledge of fatigue failures in metal materials, components and structures is less clear and incomprehensible, where it is difficult to predict by engineers due to the complex nature of this failure mechanism [11]. Proper prediction of fatigue is crucial to ensuring component safety and reliability. To control the quality of ferromagnetic materials, it is important to monitor the timidity of fatigue in a timely manner to detect the beginning and propagation of fatigue cracking, and to estimate the remaining life.

The fatigue damage for each loading cycle D_i can be calculated as follows:

$$D_i = \frac{1}{N_f} \tag{1}$$

The Palmgren-Miner rule is then used to calculate the cumulative fatigue damage D of a loading block, and it is defined as follows:

$$D_i = \sum \frac{n_i}{N_f} \tag{2}$$

where n_i is the number of applied cycles. Fatigue damage has a range of zero to one, where zero indicates no damage (infinite cycles to failure) and one is assumed as failure (one cycle to failure) [12].

2.2 Magnetic Metal Memory Method

MMM inspection using natural magnetization and-after effects, which succeeded in the form of magnetic memory of the metal to actual strains and change of metal structure with no preparation operation. As loads applied, ferromagnetic material tends to change the dimension of the materials in a microstructure scale. Magnetic domain change from original condition when load applied. This phenomenon called magneto-mechanical effect, introduced by Jiles in 1995 [13]. It is based on magneto elasticity and magneto-mechanical characteristics of materials. During operation or loaded, the magnetic domain will dislocate and be irreversibly reoriented.

Two parameters used to measure the stress concentration zone are $H_p\,(x)$ to measure the intensity of the magnetic field parallel to the surface material while $H_p\,(y)$ to measure the intensity of magnetic field perpendicular to surface material. Figure 1 shows the reaction components of $H_p\,(x)$ and $Hp\,(y)$ in the zone stress concentration. $H_p\,(x)$ will form a peak and the polarity $H_p\,(y)$ changes from negative to positive at stress concentration zone. The tangent component of the magnetic leakage $H_p\,(x)$ shows the maximum value, while the normal component value of the magnetic leakage $H_p\,(y)$ is zero.

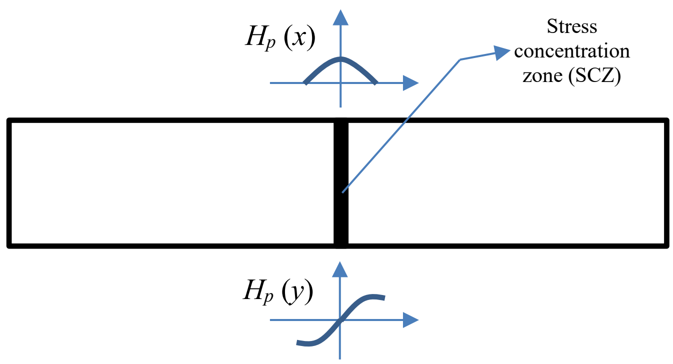


Figure 1: Reaction of component $H_p(x)$ and $H_p(y)$.

2.2.1 Contraction at Failure, ψ.

The mechanical characteristics values depend on dimension and shape of the test specimen as well as the method of measurements. The values of limiting mechanical characteristics for materials embodied in specific shapes of parts or objects may considerably differ from references. Limiting values mechanical characteristics of the same material called extension strain ε_t and contraction ψ at failure. These two characteristics are the characteristics of the plasticity of the materials. Combined with limiting values of conditional specific load or strains, giving characteristics of energy or fracture energy. Correlation between the extension strain and contraction value, making these characteristic interchanges.

Contraction is determined in the neck region and extension strain is an average elongation on a certain base, the dimension of which strongly influences the result-the extension strain amount. To reduce the longitudinal strain assessment error, the concept of the true strain was introduced and determined as $\varepsilon_{true} = \ln\,(1 + \varepsilon_{long})$. However, for description of plastic deformability of material as a function of strain variation due to conditional load, changing from minimum to destructive values, it is possible and appropriate to use extension strain since this characteristic agreed with other strain characteristics. As for contraction, this characteristic is very important already for failure conditions evaluation and for determination of the role of the very longitudinal and transverse linear strains during failure. Correlation of extension strain and contraction, which with extension strain ε_t and contraction at failure ψ characteristics for various steels and alloys reveal their correlation as

$$\varepsilon_t = f(\psi) \quad (3)$$

2.2.2 Magnetic metal memory life estimation. 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 [12] given by Eq. (4),

$$m = \frac{K_{in}^t}{K_{in}^y} = \left(\frac{\sigma_t}{\sigma_y}\right)^2 \quad (4)$$

where K_{in}^t,K_{in}^y, σ_t and σ_y are values of the magnetic field gradient of conditional ultimate strength, gradient of conditional yield strength, ultimate tensile strength and yield 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 Eq. (5),

$$K_{in} = \frac{W_m}{W_f} = \frac{2E}{\sigma^2} \quad (5)$$

where E is modulus of elasticity. The energy relation obtained in Equation (2) then proposed to estimate the lifetime in stress concentration zone (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 Eq. (6). Therefore, the residual lifetime of the inspected with SCZ estimated by Eq. (7),

$$T_{lim} = \frac{K_{in}^t}{K_{in}^{act}}(T_{act}) \quad (6)$$

$$T_{life} = T_{lim} - T_{act} \quad (7)$$

3. Methodology

In this study, the material used is the ferromagnetic material. Table 1 show the chemical composition of the specimen. The magnetic flux leakage sensor was used in this study. Due to that, steel grade SAE1045 has been chosen because it is ferromagnetic material with ability to induce magnetic flux for crack detection and evaluation. SAE 1045 steel has excellent mechanical properties and widely used as structural component [14].

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

	Composition (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

Tensile test has been carried out to gather the mechanical properties of the specimen. Material has been prepared according to ASTM E8-01 (Standard Test Method for Tension Testing of Metallic Materials). Figure 2 show stress-strain curve generated from tensile test and mechanical properties of the specimen tabulated in Table 2.

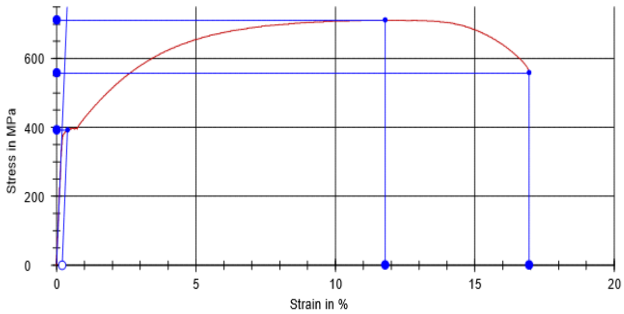
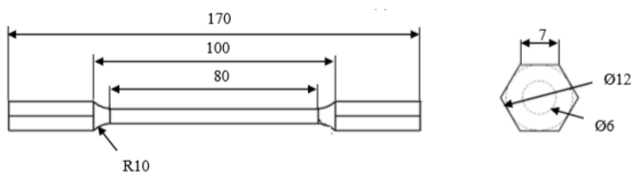


Figure 2: Stress-strain curve of SAE 1045 steel

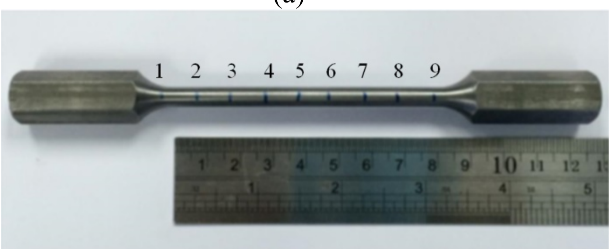
Table 2. Mechanical properties of SAE 1045.

Material	Mechanical properties		
	Yield Strength (MPa)	Ultimate Strength (MPa)	Young Modulus (GPa)
SAE 1045	392	710	190.5

For the cyclic testing, specimen has been prepared according to ASTM E466-07 (Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Test of Metallic Materials). Specimen has been polished to mirror like surface to decrease stress concentration that lead to crack initiation during fatigue testing. 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 3. This is to facilitate the detection of stress concentration location after signal processing is performed on the observed magnetic flux leakage signal. Electromagnetic signals observed offline, in which the machine is stopped at an interval of every hour of loading to get the relation between fatigue life of the experiment and fatigue life prediction using the metal magnetic memory and stress concentration changes with increasing time.



(a)



(b)

Figure 3 Specimen for cyclic testing a) specimen draft b) actual specimen used in experiment and point on the gauge length

Purpose of cyclic testing is to determine fatigue life of metallic specimen. The test conducted using a servo-hydraulic machine with capacity of 25 kN in room temperature. Figure 4 shows the servo-hydraulic machine with specimen attached to the machine. The loading capacity used for the uniaxial cyclic testing is 0.7 of ultimate tensile strength (UTS) and 0.75 UTS with frequency of 1 Hz.

Figure 4: The servo-hydraulic machine used in the study

During the testing, magnetic flux leakage signals are collected using a stress concentration test device. This device is capable of recording data that is a magnetic signal on the memory card. Magnetic changes influenced by stress concentration, can be seen on the display screen on the device in the form of magnetic graphs against the distance as shown in Figure 5. The advantage of this device is its ability to detect stress concentration zones on small structures and equipment that are in a difficult area. The device also features two transducer flux channels and wheel distance calculations. To facilitate the process of observing magnetic signals on specimens, aluminium runways are used. Figure 6 shows how the magnetic signal is observed during the test. Stress concentration test device are connected to a computer data acquisition system to process data in obtaining stress concentration locations due to cracking in the specimen. From the analysis, the residual life of the specimen can be estimated.

Figure 5: Stress concentration test device and display of the stress concentration graph on screen

Figure 6: Method of observing magnetic signal offline using aluminium platforms

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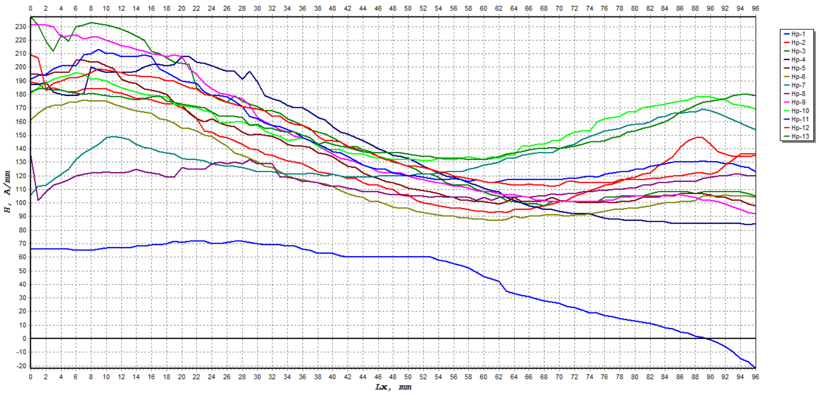
4. Results and Discussion

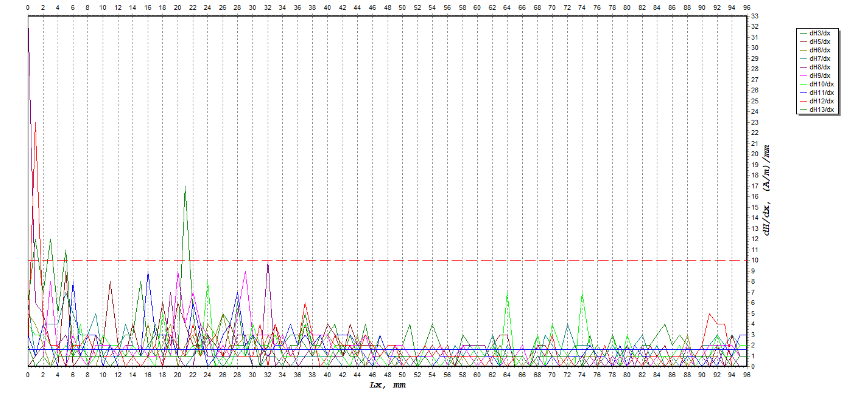
Through metal magnetic memory sensing devices used, two magnetic flux leakage signals are obtained namely normal component signals, H(y) and normal component gradient signals, dH (y) / dx. Figure 7 shows the graph of the signal H(y) against the length of the runway track and signal d*H*(*y*)/d*x* against the length of the observation track, *Lx* for 70% UTS cyclic loading. Figure 7 (a) for normal component signals and Figure 7 (b) for gradient of normal component signals. Magnetic signals are shown by combining signals obtained from different cycles of life. Cycle load at 70% UTS produces fatigue life of about 11 hours 36 minutes equivalent to 41760 cycles. Signal was taken at an hour interval. The signal, *H*(*y*) starting from before the clamp, clamping, the first hour until the 11 hours of loading. The lowest value of the *H*(*y*) given by signal before clamping, followed by signal during clamping at servo-hydraulic machine. At the moment of the testing begin, tabulation of stress concentration increases rapidly. This increment due to early stages of fatigue failure, the decrease in *H*(*y*) is due to hardening or softening of the strain, causing changes in the placement structure. In the next fatigue cycle the structure of the dislocation cells becomes stable and the magnetic surface intensity decreases until there is no change. At the last stage micro-crack growth was followed by macroscopic crack propagation resulting in a significant increase in magnetic signals [15].

Analysis by the normal component gradient signals, d*H*(*y*)/d*x* as shown at bottom of Fig. 7(b) is more appropriate in assessing the extent of damage or failure experienced by the specimen [16]. Accordingly, further analysis in this study focuses on the signal change value of d*H*(*y*)/d*x*. In Fig. 7(a), the change shown by signal d*H*(*y*)/d*x* at 0 to 4 mm for all cyclic intervals value is more pronounced than the *H*(*y*) signal. The height of signal curve value of d*H*(*y*)/d*x* shows the gradient value of *H*(*y*) signal. Significant stress concentrations can be seen at 0 to 4 mm with a higher altitude of the signal curve than at other distances. Through the indicated signal there is a high stress concentration at 0 to 4 mm which is potentially a fatigue failure position. Visual examination from the fractured specimen, the fracture position was matched with the high peak given by d*H*(*y*)/d*x* distribution. Position of fracture specimen shows in Figure 8. For 60%UTS cyclic load, gradient signals d*H*(*y*)/d*x* in Figure 9 shows concentration of distribution is at distance of 16 to 22 mm. Many high peak gradient d*H*(*y*)/d*x* can be seen clearly from the figure. This signal show that, at that position is the potential of fatigue failure position.

Value of contraction at failure, ψ for certain loading hours were assessed to study the effect of this value in estimating total loading hours for the specimen. From Table 3 and Table 4, it is found that the value of ψ is vary from 0.33 to 0.8 to achieve similar fatigue life as the experiment. At early loading hours, the maximum value is 0.8 but this value is unable to achieve total service hours as gathered from experiment. As the loading hours increase, the value of ψ is decrease. The optimum contraction value to achieve total loading hours is in between of 0.77 to 0.79 as shown in Table 3 and Table 4 for 60% UTS and 70%UTS cyclic loading respectively. For lower cyclic loading, the contraction, ψ value variation is bigger compared to lower cyclic loading. Estimation of total loading hours shows the influence of contraction value in estimating total loading hours for each specimen. Figure 10 shows the tabulation of the contraction towards specimen failure in time that showing decreasing value of contraction as loading hours increased. The decreasing value in contraction showing the influence of this magnetic signature towards the life of the specimen. Again, it shows that the MMM methods proposed in this study have strong potential in estimating fatigue at early stage loading.



(a)



(b)

Figure 7: (a) Distribution of magnetic leakage field intensity, H_p and (b) distribution of magnetic leakage field intensity gradient, (dH_p/dx) along the specimen gauge length for 70% UTS loading.

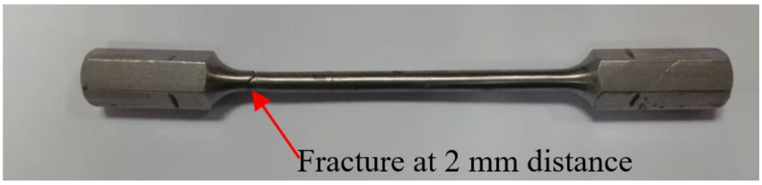


Figure 8: Fracture position on the specimen at 70%UTS cyclic loading

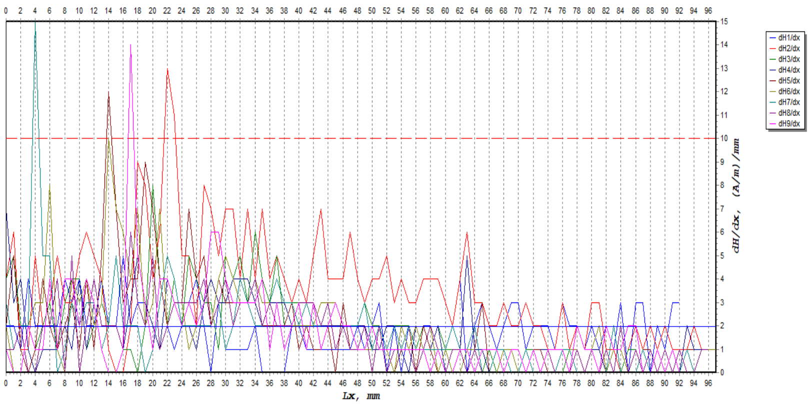


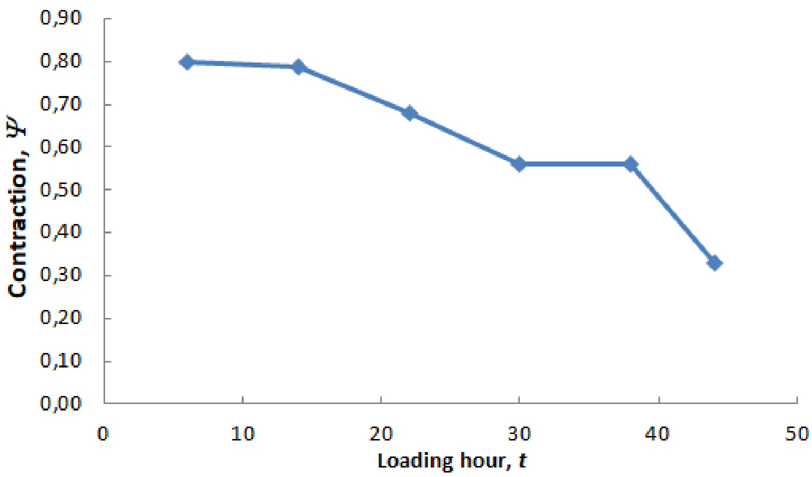
Figure 9: (a) Distribution of magnetic leakage field intensity gradient, (dH_p/dx) along the specimen gauge length for 60% UTS loading.

Table 3: Contraction value for specimen with 60% UTS cyclic loading

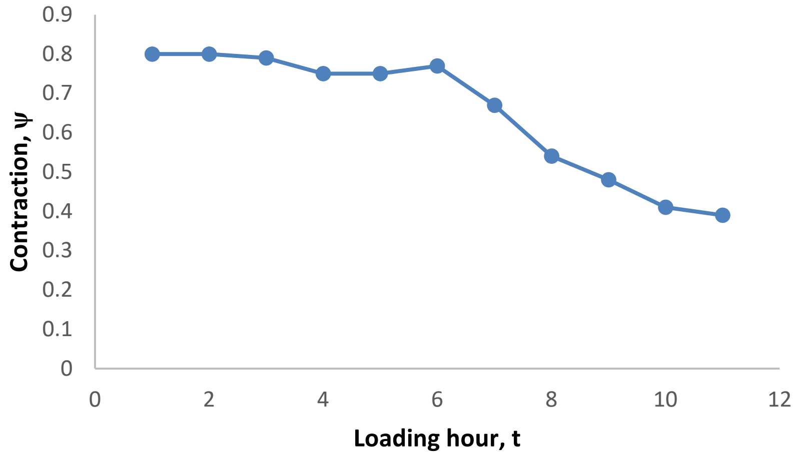
Service Hours	Contraction, ψ	Total loading hours estimated using MMM Life
2	0.80	9
3	0.80	13
4	0.80	15
5	0.80	30
6	0.80	32
14	0.79	70
22	0.68	70
30	0.56	70
38	0.56	70
44	0.33	70

Table 4: Contraction value for specimen with 70% UTS cyclic loading

Service Hours	Contraction, ψ	Total loading hours estimated using MMM Life
1	0.80	2
2	0.80	5
3	0.79	11
4	0.75	11
5	0.75	11
6	0.77	11
7	0.67	11
8	0.54	11
9	0.48	12
10	0.41	12
11	0.39	12



(a)



(b)

Figure 10: Tabulation of contraction, ψ value corresponding with loading hour a) 60% UTS cyclic loading b) and 70% UTS cyclic loading

In order to evaluate the ability of contraction value in estimating life of the specimens, the value of life from the MMM estimation were compared with the value of experiment and analytical calculation. Results given by the number of cycles to failure from the experiment and estimated from the magnetic flux signal, that indicate period of specimen operation tabulated in Table 5. From the Table 5 when applied axial load was 70%$_{UTS}$, the specimen failed at 11 hours 36 minutes or 41760 cycles. The estimated from MMM is 17 hours of life. The value of MMM_{Life} have high different compared to experiment, however this value is almost same as given by analytical calculation which is 16 hours and 15 minutes. Both specimens give almost same trend where experimental life give shorter life compared to MMM_{Life} that is estimated using MMM method and analytical calculation. These discrepancies due actual condition of the specimen that degradation due to manufacturing and processing. However, this estimation shows the potential of MMM method in estimating the fatigue life at early condition before crack.

Table 5: Fatigue life estimation based on MMM method with comparison to experiment and analytical calculation

Loading	Fatigue Life		
	Experiment	MMM Life Prediction	Analytical
60%$_{UTS}$	62 hours and 23 minutes 224580 cycles	70 hours	97 hours and 30 minutes 351000 cycles
70%$_{UTS}$	11 hours and 36 minutes 41760 cycles	12 hours	16 hours and 15 minutes 58500 cycles

5. Conclusion

The evaluation of magnetic flux leakage signature through contraction value at early fatigue loading have shown the capability to estimate fatigue life as similar as value given by the experiment. The gradient of the stress distribution signals d$H(y)$/dx shows the potential fracture position in the specimen. The density of the stress concentration indicate there is defect on that specific position. Evaluation with fractured specimen has confirmed the position with high stress concentration zone (SCZ) tabulated by signal $dH(y)/dx$ was the fractured position. The materials value evaluated in this study, the contraction value shows it relation in estimating the total loading hours before fracture of the specimen. The value varies from 0.33 to 0.8, and optimum value to estimate life is in between 0.77 to 0.79. The estimated value of life using signals gathered from the MMM sensors, MMM_{life} has small differences compared to value of life from the experiment. At cycles to failure of 41760 cycles which equal to 11 hours 36 minutes, the life estimated from the MMM sensors is 17 hours and at cycles to failure of 224580 cycles which equal to 62 hours 23 minutes, the life estimated using MMM method is 70 hours. The estimated value using the MMM method proposed in this study fall within actual number of cycles by experiment and analytical method. This finding shows the capability this method to locate the position of fatigue crack at early stage, as well as estimating fatigue life of the components.

Acknowledgments
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