Study on Magnetic Memory Method (MMM) for Fatigue Evaluation

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Abstract:

In lab experiments to evaluate the fatigue, the surface magnetic field on specimens would be changed with different cycle numbers (N). Good correlation between resulting fatigue level and MMM signals has been demonstrated. In the M (magnetic)N (cycle) curve derived from the experimental data, three stages corresponding to the fatigue process can be clearly distinguished. A similar situation was found in the practical inspections of train axles in service. This technique could be used for fatigue evaluation.

Key Words: MMM; Fatigue; M-N Curve, Nondestructive Evaluation

1 introduction

Stress concentration which is able to lead to failure of a work piece occurs in dangerous regions due to the accumulation of fatigue damages during operation of the work piece subjected to periodic loading. Accompanying with the applications of stress, fatigue develops with the loading of cycle stress, in this process, glide of crystals generates firstly, and then micro-cracks which eventually grows into macro-cracks causing failure of the work piece. Fatigue of train axles, which may play part in train derailment, got more and more attention because of the speed-up railway transport. Analysis for train axle defects represents that apart from defects due to friction; approximately 70% of the defects are brought about by fatigue, 90% of which are due to the present of stress concentration. Traditional nondestructive test (NDT) methods can hardly carry out effective evaluation of earlier damage caused by the concentration of mechanical stress. Recent studies are focused on how to detect concentration of stress and to evaluate fatigue stats and accordingly fatigue life of a work piece [1-3].

In the past century, various NDT methods, such as X-ray [4], ultrasonic [5], laser[6], Barkhausen effect and magnetic emission[7] and so on, are proposed for investigation of earlier fatigue stats. As changes in density and glide of dislocation would affect
magnetic properties of ferromagnetic material, magnetic measurements has nature advantages in the evaluation of ferromagnetic material.

Metal magnetic memory (MMM) method [8] is a novel magnetic NDT means which determines stress concentration stats according to a weak change of magnetic field due to concentration of stress at the region with stress concentration. Prior study [9–15] indicates that MMM signal is sensitive to micro-structure and local stress of ferromagnetic material, both of which are closely associated with fatigue stats of the material. Hence, MMM method may be a potential method for NDT of fatigue stats.

In this paper, MMM method is attempted for fatigue evaluation of ferromagnetic samples and proved to be extraordinary effective on fatigue evaluation and Fatigue life assessment of ferromagnetic material. The M-N curve derived from the experiment data can be clearly distinguished to three stages which are corresponding to three stages of fatigue process respectively. Furthermore, field examination are also carried out, in which magnetic field distribution of real train axles are measured and analyzed.

2 Fatigue experiment

2.1 experiment design

Selected samples have a rectangular cross-section and are loaded in three-point bend manner. As shown in Fig.1, fatigue test was carried out on Instron1603 Electro-Magnetic Resonator which is able to apply a maximum load of 100kN and loading frequency range from 50 to 250Hz, with average load \( F_{average} = 18 \text{kN} \), load amplitude \( F_{amplitude} = 9 \text{kN} \) under load frequency of 130Hz. A micro-magnetic measurement system, as shown in Fig.1, was used to test magnetic field vertical to the surface of the specimen along the lines indicated in fig2 with a lift-off of 2mm. The magnetic sensor controlled by a three-dimensional scanning system so as to facilitate
the comparison of the resulting data has a measuring range from 20nT to 6Gs. If there is no special explanation, the surface magnetic field in this paper means magnetic field perpendicular to the surface of sample.

The specimen used in the experiment is a medium carbon steel bar with rectangular cross-section as shown in Fig.2.

An arc-shape recess with depth of 1mm and radius of 14mm are formed in the middle portion of the specimen so as to control the generation of initial crack at a load cycle number $N < 10^7$.

For the study of the variation of surface magnetic field of ferromagnetic material under loading with high frequency and high cycle number, surface magnetic field of the specimen under various loading and various outside magnetic field. In addition, all parts which is brought into contact with the specimen in the fatigue test are replace with parts of stainless steel so as to minimum the influence of the adjacent parts in the experiment. Some of the specimens are demagnetized so as to analyze effects of initial magnetization of ferromagnetic specimen.
2.2 Result of fatigue experiment

Fig. 3 is a typical graph of surface magnetic field under different loading cycles.

Fig. 3 surface magnetic field versus loading cycle number N with respect to specimen without demagnetization

Results of fatigue experiment (as shown in Fig 3) shows that the sample got demagnetized in the first several cycles, and then the distribution of surface magnetic field changes slightly along with loading cycles of stress. Although, in most cycles, variation of surface magnetic field is relative small, in the enlarged view of the central portion of surface magnetic field which corresponding to the medium portion of the specimen, i.e. where the arc-shape recess locates, variation of magnetic field along stress loading cycles are found to be much greater than other portions. Hence, the magnitude of the central portion are derived and plotted in Fig 4 and 5 in connection with loading cycles N.

Fig. 4 and 5 shows that field magnitude signals change along with stress cycles N and there is a leap of magnetic signal before fracture. A primary conclusion can be drawn that the magnetic signals of the concentration location is sensitive to fatigue evaluation. From these two figures, three stages of M value are clearly distinguished. During the early stage of fatigue process, the amplitude of magnetic field increases and then reaches a flat roof. The flat roof continues in the middle stage of fatigue, the change of magnetic field in this stage is slow and neglectable.
After coming into the last stage, the amplitude of magnetic field raises rapidly. The flat roof initials at 10% of fatigue life and terminates at 90% of fatigue life, which is highly consistent with three stages of fatigue development.

Fig. 4 magnitude of magnetic field in the central portion M as a function of loading cycles N of specimens without demagnetization

Fig. 5 magnitude of magnetic field in the central portion M as a function of loading cycles N of specimens with demagnetization

Surface magnetic field of specimen with demagnetization and variation thereof due to stress cycles are significantly smaller than that of specimen without demagnetization. However, the M-N curve still indicates three stages mentioned above with their boundaries mixed up which makes distinction of these stages more difficult.

2.3 Discussion
According to principal of ferromagnetism $^{[16]}$, magnetic elastic energy (Ems)
associated with magnetostriction in Ferro magnets is obtained by following equation:

\[ E_{ms} = B_1 \sum e_{ii} (\alpha^2_i - 1/3) + 2B_2 \sum e_{ij} \alpha_i \alpha_j \]

In which, \( B_1 \) and \( B_2 \) indicates magnetic elastic couple factors
\( \alpha_i, \alpha_j \) — cosine of the included angle between a direction of magnetization and crystal axle
\( e_{ii}, e_{ij} \) — components of deformation

As can see from above equation, displacement of magnetic domain walls is induced by deformation due to action of stress. Thus the direction of spontaneous magnetization varies and consequently forms fixed nodes of magnetic domains which lead to the increase of magnetic energy. With the application of loadings, stress concentration and residual stress with high stress energy are formed in the specimen, which still exist even after the loading is removed. Hence displacement of magnetic domain walls is induced in the region of stress concentration, forms magnetic poles and thus disturbs surface magnetic field of a specimen. The above described phenomenon is basic principle of MMM method.

Theoretically, it is considered that fatigue initials due to movement of dislocations, which gather together and form initial cracks. Consequently, stress concentration generates again by the cracks, this process is repeated and finally lead to macro cracks [2].

An explanation to the M-N curve derived from fatigue experiment can be drawn on the basis of fatigue theory in combination with MMM principle: during 0-10% of fatigue life, density and configuration of dislocations varies significantly as microstructure of specimen adapted to the present of stress loading, which leads to the increasing of the degree of stress concentration along with loading cycles \( N \) and thus leads to variation of magnitude of surface magnetic field \( M \) at the region of stress concentration; during 10-90%, substructure of dislocations develops slowly and lead to the formation of stable slip bands without macroscopic changes of stress, hence, there is a flat roof in the portion of M-N curve corresponding to this stage of fatigue life; at last stage, a relative large leakage of magnetic field generates due to the occurrence of macro cracks.

The consistence between M-N curve and fatigue life with three stages makes it possible to evaluate fatigue stats of ferromagnetic material by using M-N curves.

3 Field examination

In order to approve above result, a field examination was carried out in Feb. 7th Rolling Stock Works. In the examination, magnetic field distribution of off–load slot
of total of 140 pairs of axles with different time on active service are tested, wherein the time on active service of an axle can partly represents fatigue stats of the axle.

![Diagram](image)

Fig 6 magnitude of circumference magnetic field at off-load slot as a function of time on service

Generally, result of field examination are in consistent with the M-N curve derived in fatigue experiments. The plot of Fig.6 are quite similar to the M-N curve of Fig.4 and 5, which approves the applicability of M-N curve in the evaluation of fatigue life of ferromagnetic specimens.

4 conclusion

According to the results of fatigue experiment, the M-N curve derived from ferromagnetic specimens are found indicating three stages corresponding to the three stages in the development of fatigue, which is also approved by field examination of real axles. MMM method shows great advantages in the evaluation of fatigue stats of ferromagnetic materials.

However, there are still problems, such as how to determine current position of a specimen in the extent of M-N curve without historic data, need to be solved to evaluate fatigue stats effectively by using MMM method.

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