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Estimation of fatigue exposure from magnetic coercivity

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Abstract

An investigation of the effects of fatigue on A533B steel under constant load amplitude is reported in this paper. It was found that the plastic strain of the sample accumulated logarithmically with the number of stress cycles after initial fatigue softening. Based on the fact that plastic strain is often linearly related to the coercivity of material, at least for small changes of H_c, a phenomenological relationship has been developed and tested to correlate the number of stress cycles to this magnetic parameter. This result represents the first successful attempt to relate the fatigue exposure directly to a magnetic parameter.

Keywords

CNDE, Coercive force, Magnetic materials, Materials modification, Stress strain relations

Disciplines

Electromagnetics and Photonics | Engineering Physics

Comments

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Estimation of fatigue exposure from magnetic coercivity

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An investigation of the effects of fatigue on A533B steel under constant load amplitude is reported in this paper. It was found that the plastic strain of the sample accumulated logarithmically with the number of stress cycles after initial fatigue softening. Based on the fact that plastic strain is often linearly related to the coercivity of material, at least for small changes of H_c, a phenomenological relationship has been developed and tested to correlate the number of stress cycles to this magnetic parameter. This result represents the first successful attempt to relate the fatigue exposure directly to a magnetic parameter.

I. INTRODUCTION

Metallic fatigue failure is a very difficult and serious problem due to its insidious nature. It has been estimated that fatigue failure is the primary cause of at least 90% of all service failures due to mechanical causes. Magnetic nondestructive evaluation techniques, such as magnetic hysteresis measurements and Barkhausen effect measurements have been proven to be powerful methods of detecting changes in mechanical properties.[1,2] However, due to the fact that so many external factors can influence the magnetic properties, quantitative characterization of fatigue damage remains a very difficult problem.

In this paper, a phenomenological relationship relating coercivity to the number of stress cycles has been developed through the study of the results of fatigue tests under constant load amplitude. One of the significant results of this relationship is that, for the first time, the number of stress cycles was shown to be related directly to the magnetic parameter of coercivity and therefore the measurement of coercivity provides a way to estimate fatigue damage.

II. EXPERIMENTAL PROCEDURE

The material used in this investigation was a medium strength structural steel alloy (ASTM code A533B) whose mechanical properties are given in Table I. Fatigue tests were carried out on smooth tensile specimens with constant load amplitude, using a computer controlled, 10 kN, servohydraulic MTS system. Magnetic hysteresis parameters, such as coercivity, remanence, and initial permeability were measured by the Magnescope, a computer controlled magnetic inspection system.[3] These measurements were made at predetermined intervals throughout the fatigue life under zero load.

TABLE I. Mechanical properties of ASTM A533B steel.

Young's modulus	0.2% Yield stress	UTS	Hardness, R_b
170 Gpa	369 Mpa	536 Mpa	88.0

III. TEST RESULTS AND PREDICTIONS

Fatigue damage is a progressive effect, during which the microstructures of material, such as dislocation density, plasticity, and density of vacancy undergo continuous change before final catastrophic failure. Under cyclic stress at constant load amplitude, it was found that the maximum tensile and compressive strain increased continuously throughout the whole fatigue life, after the initial few hundred stress cycles which caused fatigue softening. A linear relationship between the magnitude of the strain amplitude and number of stress cycles was observed on a semilog graph, as shown in Figs. 1 and 2. This result indicated that the plastic strain accumulated logarithmically with the number of stress cycles.

Correlations between mechanical properties and magnetic properties have been studied previously.[4,5] It was found for example that the coercivity H_c was generally linearly

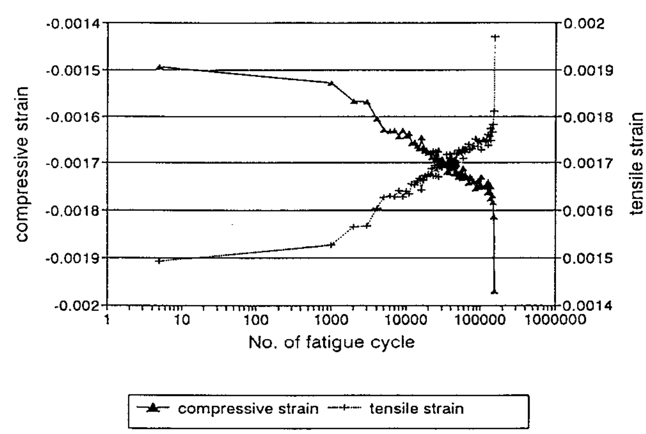

FIG. 1. Maximum tensile and compressive strain as a function of number of stress cycles at a fixed stress amplitude of 272 MPa.

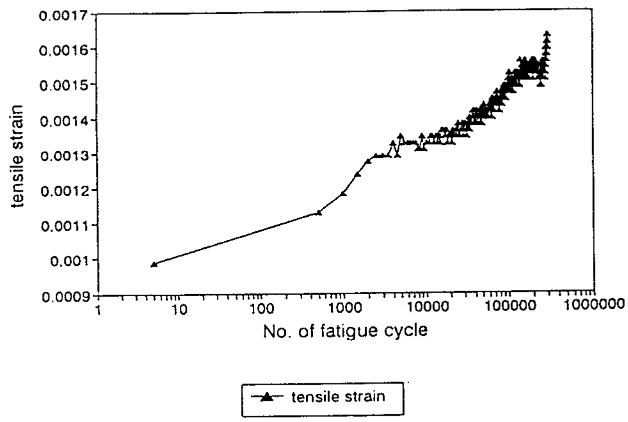

FIG. 2. Maximum tensile strain as a function of number of stress cycles at a fixed stress amplitude of 243 MPa.

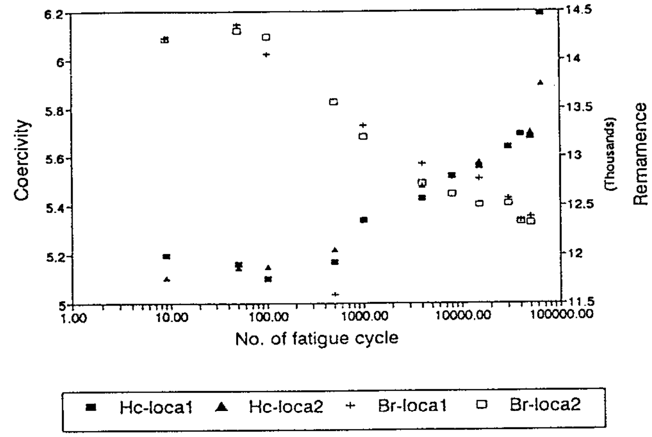

FIG. 4. Magnetic properties as a function of the number of stress cycles.

related to the plastic strain of a material, and this relationship can be understood theoretically because increased plastic strain results in a linear increase in dislocation density, which increases the pinning term k in the theory of hysteresis.[6] If this relation also holds in the fatigue process, then according to the experimental discovery of the logarithmic relationship between plastic strain and number of stress cycles, the same logarithmic relation between coercivity and number of stress cycles should be expected.

From Figs. 1 and 2, the strain amplitude and the number of stress cycles N can be related by following equation:

$$\epsilon-\epsilon_0=a\ \ln(N), \tag{1}$$

where ϵ_0 is the intercept along the strain axis and a is the slope of the line. Assuming the linear relationship between the coercivity and the plastic strain, the following equation is obtained:

$$H_c-H_{c0}=b\ \ln(N), \tag{2}$$

where H_{c0} and b are constants under the specific test condition. Equation (2) can also be expressed as

$$N=c_1\ \exp(c_2H_c), \tag{3}$$

where C_1 and C_2 are determined by H_{c0} and b.

Magnetic measurements were performed under the same test conditions. Results are shown in Figs. 3 and 4. A linear relation between coercivity and number of stress cycles is quite apparent on the semilog graph after the initial few hundred cycles of fatigue softening. This relation matches the prediction described by Eq. (2). Similar results were also found on the fatigue test at different stress amplitudes in the high cycle fatigue regions under constant stress amplitude.

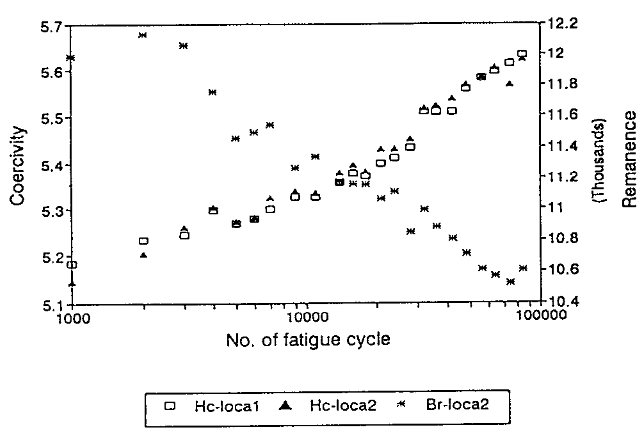

FIG. 3. Magnetic properties as a function of the number of stress cycles.

IV. DISCUSSION

The relationship expressed in Eq. (1) was determined from the fatigue tests under load control. It applies to high cycle fatigue on A533B material. However, the generality of this relation between the accumulated plastic strain and the number of stress cycles should be tested on different materials, and furthermore the dependence of the parameters on the test conditions should also be investigated.

The assumption of a linear relation between plastic strain and coercivity through the theory of hysteresis leads from Eq. (1) to Eq. (2). The linear relationship between plastic strain and coercivity has been observed previously and can be explained by the fact that plastic strain introduces extra dislocations which pin domain walls and therefore increase the hysteresis loss parameter k. In our A533B material, fatigue softening was observed which indicated that there was a decrease in dislocation density. However, the fatigue induced local yielding (and therefore residue stress), and the resulting extra density of vacancies acted as additional wall pinning sites. The overall effect of fatigue can therefore still increase the hysteresis loss parameter k.

The parameters C_1 and C_2 in Eq. (3) can be experimentally determined by three measurements of $(N_0,\ H_{c_1})$, $(N_0+\Delta N,\ H_{c_2})$, $(N_0+\Delta N',\ H_{c_3})$, where ΔN and $\Delta N'$ are two intervals of the number of stress cycles between successive measurement. N_0 is the number of accumulated stress cycles when the first measurement is taken. Practically, N_0 is also an unknown number. Although Eq. (3) does not indicate the final value of fatigue life, it does show how to estimate accumulated fatigue damage by measuring coercivity. If the total fatigue life can be predetermined by an alternative method, then this relationship can be used to monitor fatigue damage.

V. CONCLUSIONS

A relationship for determining the number of stress cycles under constant stress amplitude by magnetic measurement of the coercivity has been presented. This relationship is based on experimental evidence. According to the relationship, the number of stress cycles is logarithmically related to the coercivity of the material. Although the sensitivity of the result so far is not completely satisfactory for practical applications especially during the later stages of fatigue life, the relationship demonstrated in this paper gives a connection between the magnetic properties and fatigue damage. It therefore provides a clue for further development of models for validation of nondestructive evaluation techniques for fatigue based on magnetic property measurements.

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[1] M. K. Devine, S. Hariharan, L. J. H. Brasche, and D. C. Jiles, Rev. Prog. QNDE **10**, 2021 (1991).
[2] S. Titto, M. Otala, and S. Saynajakangas, NDT Int. **9**, 177 (1976).
[3] D. C. Jiles, S. Hariharan, and M. K. Devine, IEEE Trans. Magn. **MAG-26**, 2577 (1990).
[4] D. C. Jiles, Phys. Status Solidi, A **108**, 147 (1988).
[5] D. C. Jiles and D. Utrata, Rev. Prog. QNDE **7**, 1255 (1988).
[6] D. C. Jiles, J. Magn. Magn. Mater. **61**, 48 (1986).