Detection of Fatigue in Structural Steels by Magnetic Property Measurements

M.K. Devine, D.A. Kaminski, L.B. Sipahi, and D.C. Jiles

The magnetic properties of ferromagnetic materials are sensitive to the mechanical and microstructural condition of the material. Fatigue can affect the magnetic properties due to microstructural changes, primarily dislocation production. Magnetic hysteresis measurements have been used to monitor the changes in the parameters due to low cycle fatigue, with the overall objective of developing a new tool to enhance the present NDE techniques for detecting failure. The magnetic measurements were performed using the Magnescope, a portable magnetic inspection system. Materials for fatiguing included plain low carbon steel and samples of quenched and tempered AISI 4340. The coercivity and remanence of the low carbon steel samples increased during the early stages of fatigue, reflecting strain hardening. As cycling progressed, the magnetic parameters leveled off and dropped sharply shortly before failure. The coercivity and remanence of the 4340 samples decreased during the initial stages of cycling, reflecting fatigue softening. The parameters plateaued, then decreased shortly before failure. The amount of change in the magnetic parameters was found to depend on the strain amplitude of the cycling.

1 Introduction

THE magnetic properties of ferromagnetic materials are sensitive to the mechanical and microstructural condition of the material. For example, if the material is subjected to an external elastic stress, the magnetic hysteresis loop/Fig. 1/will change as a result of the stress. This change in the hysteresis loop will depend on the amount of elastic stress, its sign (tensile or compressive), and angle relative to the magnetic field. Microstructural variations will also change the hysteresis signature, but in different ways. Other mechanical effects that are known to influence the hysteresis loop are plastic deformation, corrosion, and creep. This paper will focus on the changes in the hysteresis loop arising from fatigue.

Fatigue has long been a problem for components in service that experience cyclic stresses. It is not always properly accounted for in the design stage of components and is usually discovered after failure of the component during service. Many nondestructive techniques have been developed to detect fatigue in components, but so far they have had limited success. One area that has not been explored thoroughly is monitoring the changes in the magnetic parameters due to fatigue. This paper will focus on a three-phase experiment concerned with detecting fatigue damage and impending failure of various materials. The overall objective of this work is to develop a new nondestructive evaluation tool to enhance the present nondestructive evaluation techniques for detecting fatigue.

The magnetic properties of ferromagnetic materials are affected by fatigue due to the microstructural changes caused by fatigue, primarily dislocation production (see Fig. 2). The dislocations interfere with the movement of magnetic domains in response to a magnetic field. A domain that is favorably aligned with an applied magnetic field will grow, whereas the opposite is true for domains aligned unfavorably. The growth and reduction of domains are accomplished by movements of the domain boundaries. The presence of dislocations and other microstructural features of differing magnetic characteristics will affect the energy requirements for domain wall motion. Dislocations increase the energy required, and they are known to provide pinning sites for domain walls. A larger applied magnetic field is required to move the domain walls. This will manifest as a change in the shape of the hysteresis loop and its parameters, for example, the hysteresis loss and coercivity. Hysteresis loss is a measure of the total energy required for one magnetic hysteresis cycle. The coercivity is the average pinning force on the boundaries. These parameters will both increase if the domain wall requires more energy to move.

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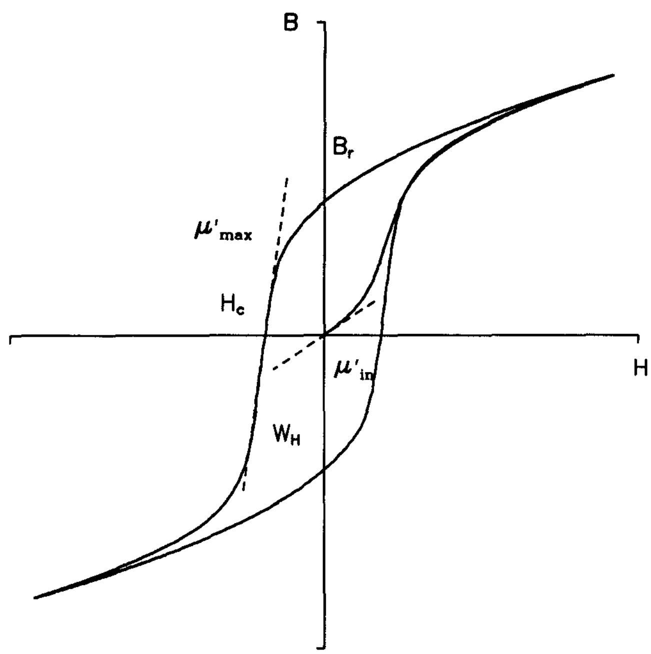

Fig. 1 Hysteresis loop showing the hysteresis parameters such as coercivity (H_c), remanence (B_r), initial differential permeability (μ'_{in}), maximum differential permeability (μ'_{max}), and hysteresis loss (W_H, which is the area enclosed by the loop).

2 Materials and Experimental Procedure

The magnetic measurements were performed using the Magnescope, a portable magnetic inspection system.[1] This consists of a personal computer, gaussmeter, fluxmeter, and a bipolar programmable power supply. Both the meters and the power supply are controlled by and send input to the computer. An inspection head, which is connected to the Magnescope, measures both the magnetic induction, B, and the magnetic field, H, in the specimen. The Magnescope uses the inspection head to first demagnetize the region of interest. It then magnetizes this region through one hysteresis cycle by sweeping the magnetic field first in one direction to an amplitude H_m, fully reversing it to a field strength $-H_m$ and then restoring it to H_m again. The Magnescope then analyzes the resultant hysteresis loop and calculates the following magnetic parameters: coercivity, hysteresis loss, remanence, maximum differential permeability, and initial differential permeability. The investigation into fatigue damage reported in this paper was carried out in three phases. For clarity, materials description, results and discussion for each will be kept together.

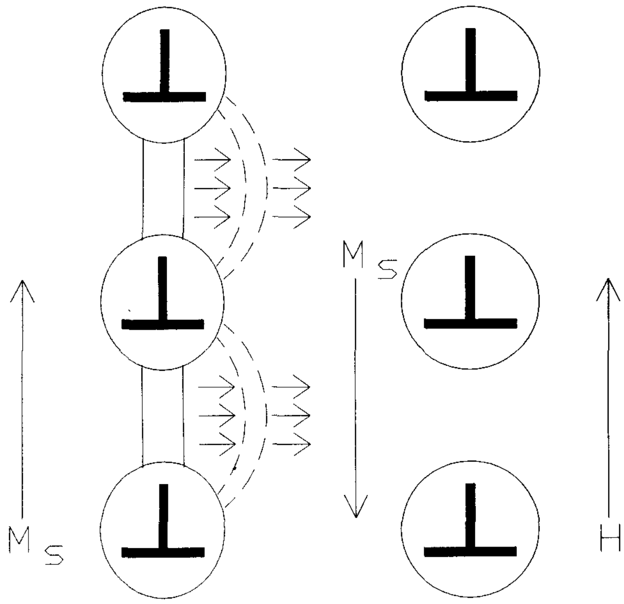

Fig. 2 Schematic of a domain wall attempting to move past a series of dislocations.

3 Phase I

3.1 *Materials and Procedure*

The materials for this phase consisted of 45 samples of plain low-carbon steel. The exact chemical composition was unknown, although they should be similar to the composition of AISI 1030 steel. The samples came from three eyebar sections (identified as A, B, C) of a service-aged railroad bridge. Optical microscopy revealed a pearlitic microstructure in all three groups. The samples were machined to cylindrical bars 100 mm in length with a 6-mm gauge diameter. The samples in this phase were fatigued to a predefined number of cycles without reaching failure. Samples were removed from the fatigue machine and magnetic measurements taken. As the approximate number of cycles to failure, N_f, was known, the percentage of expended fatigue life was calculated. None of the samples in this phase was fatigued to failure, so the percentages calculated were only estimates of expended fatigue life. The specimens were fatigued under a constant total axial strain amplitude. Strain control was performed by an extensometer. During this phase, the samples were fatigued at a strain amplitude of either 0.002 or 0.005. The frequency of the cycling was changed so that the strain rate remained constant.

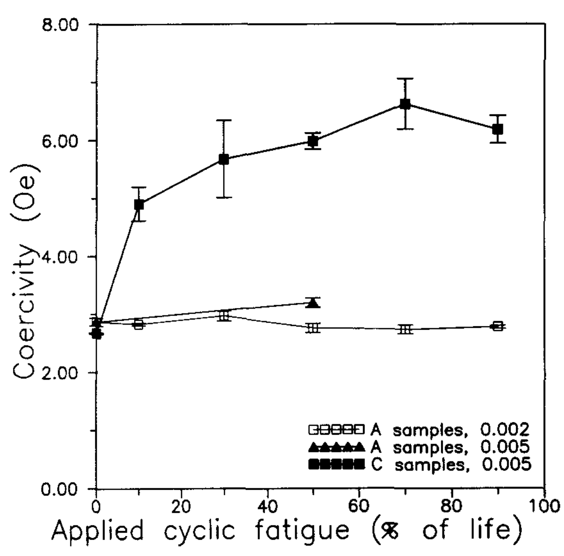

Fig. 3 Coercivity versus estimated expended fatigue life for specimens from eyebars A and C.

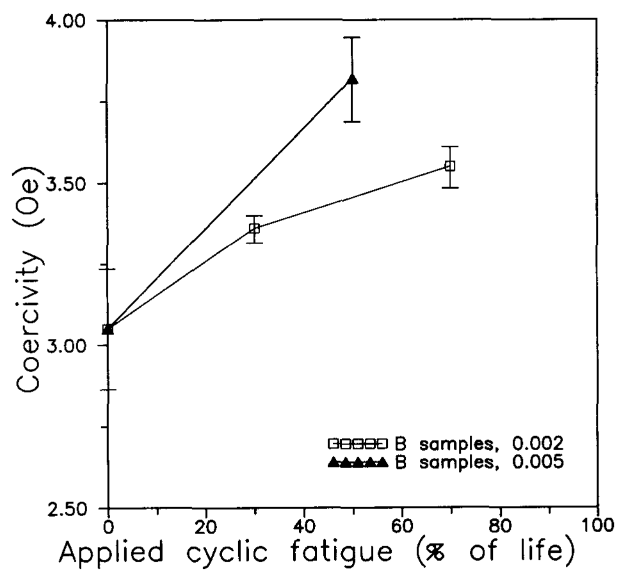

Fig. 4 Coercivity versus estimated expended fatigue life for specimens from eyebar B.

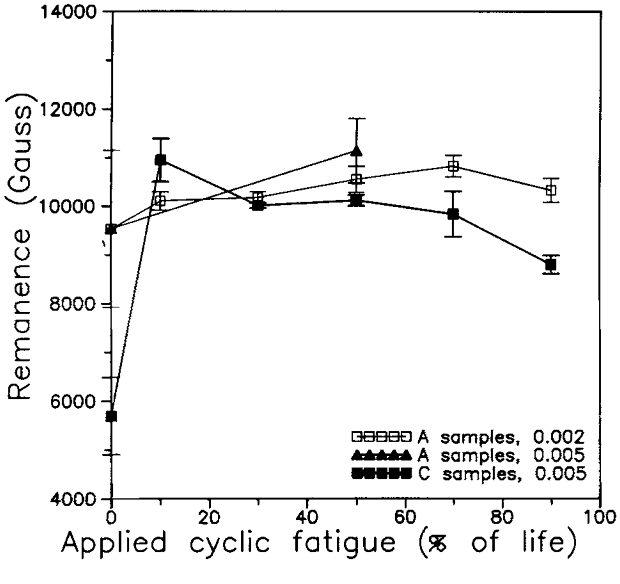

Fig. 5 Remanence versus estimated expended fatigue life for specimens from eyebars A and C.

3.2 *Results and Discussion*

Figure 3 shows the coercivity of the samples versus estimated expended fatigue life. At 0% applied cyclic fatigue, the specimens had a coercivity ranging from 2.7 to 2.8 Oe. After fatiguing began, the coercivity increased substantially for the eyebar C samples fatigued at strain amplitude 0.005. This increase in coercivity at the start of fatiguing is believed to reflect fatigue hardening of the material. The coercivity is known to give an indication of the hardness of the material and generally the harder the material, the higher the coercivity. The specimens from eyebar A strained at an amplitude of 0.002 did not show any significant changes in coercivity throughout the fatiguing process. It is possible that the strain amplitude was small enough so that no significant amount of hardening occurred. The three specimens from eyebar A that were fatigued at 0.005 had a slightly larger coercivity (3.2 Oe) than the same group fatigued at 0.002. From this figure, it appears that the larger the strain amplitude, the larger the increase in coercivity.

Figure 4 shows the coercivity measured on samples from eyebar B. Here, as in Fig. 3, there is an increase in the coercivity with increasing fatigue. The coercivity increased from 3.05 Oe

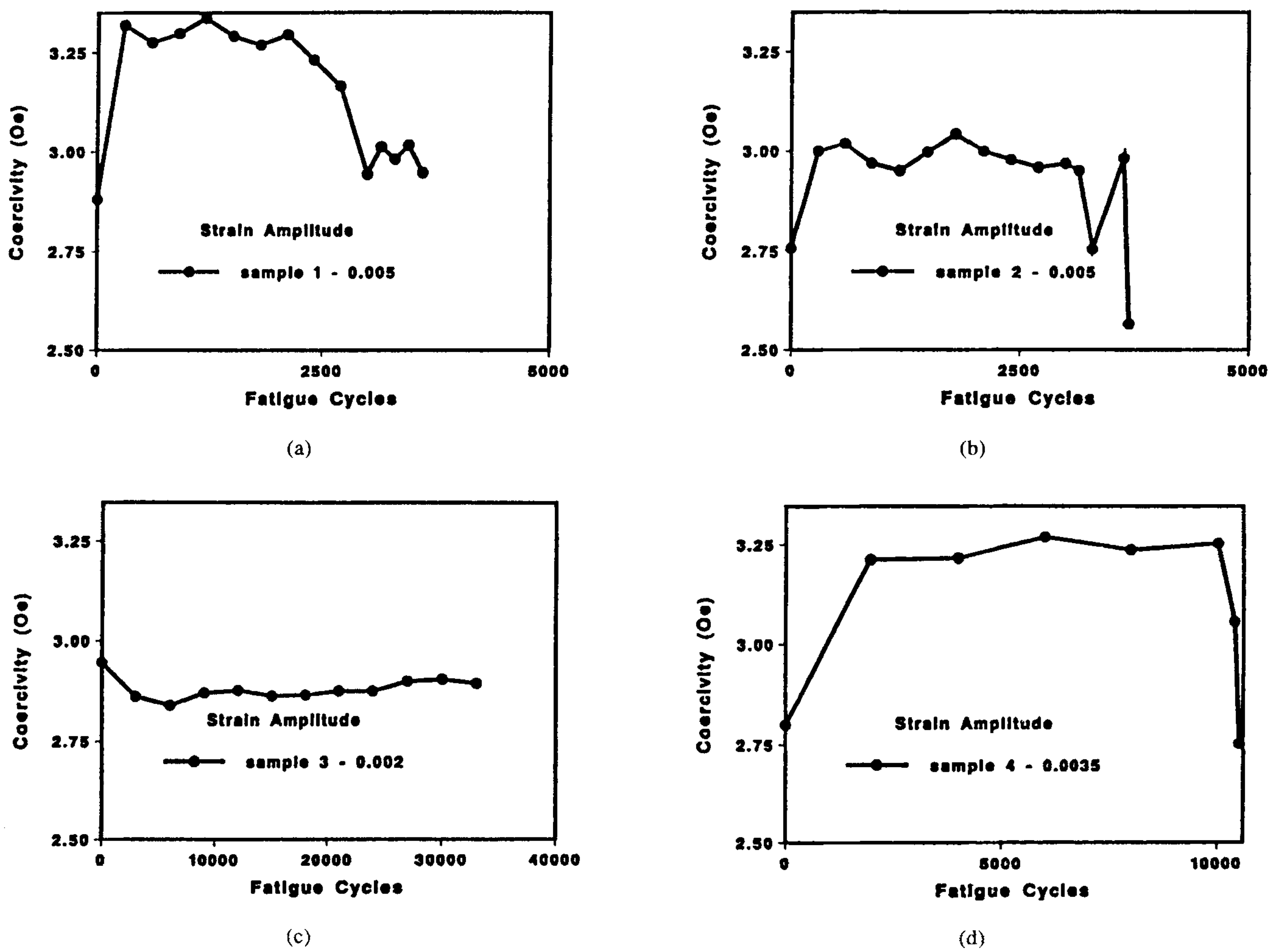

Fig. 6 Coercivity versus number of cycles for specimens fatigued at various strain amplitudes.

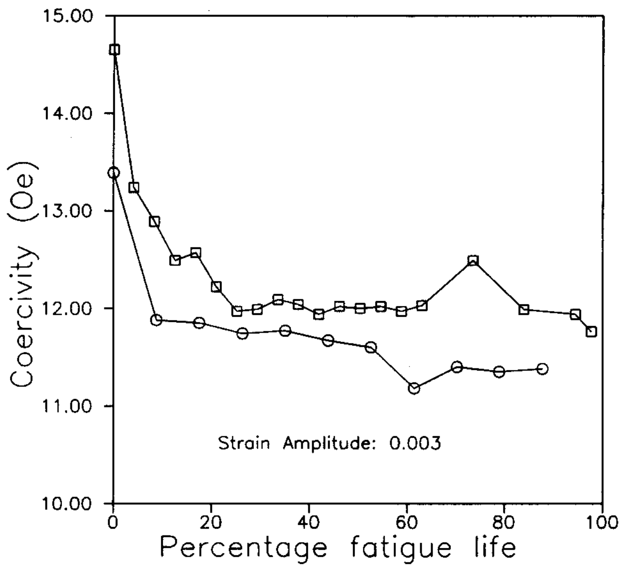

Fig. 7a Coercivity measured on AISI 4340 specimens cycled at strain amplitude 0.003.

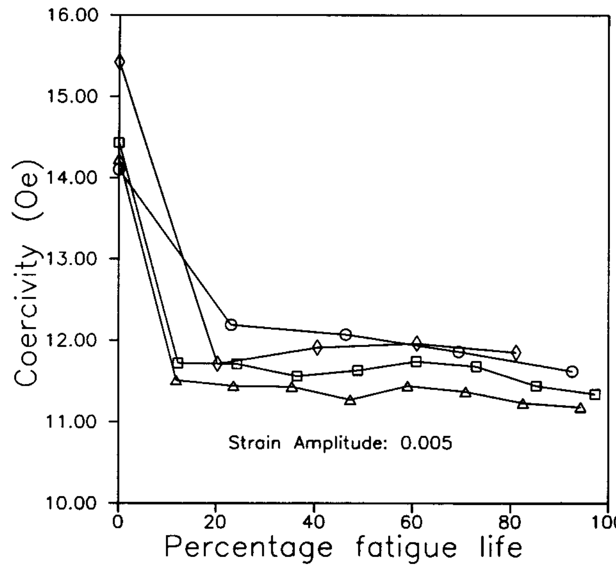

Fig. 7b Coercivity measured on AISI 4340 specimens cycled at strain amplitude 0.005.

at 0% expended fatigue life to 3.55 Oe at approximately 70% expended fatigue life. Also, the samples fatigued at a strain amplitude of 0.005 had a larger coercivity at 50% expended fatigue life than any of the samples fatigued at 0.002. If this group of samples also had an initial coercivity of 3.05 Oe, there is a 0.75 Oe change at 50% expended fatigue life.

Figure 5 shows the remanence measured on samples from eyebars A and C. The specimens of eyebar C fatigued at strain amplitude 0.005 showed a large initial increase in the first 10% of fatigue life then a slight downward trend as fatiguing progressed. Between 70% and 90% fatigue life, the downward trend accelerated, this could indicate the approach of failure. The specimens of eyebar A fatigued at strain amplitude 0.002 did not show an abrupt change at the start of fatigue and only a slight upward trend as fatiguing progressed. However, there is also a downward trend between 70 and 90% in the measurements on eyebar C. One could interpret a decrease in the remanence as an indicator of impending fatigue failure. The effect of changing strain amplitude on the remanence can also be seen in this figure. For eyebar A, the samples fatigued at 0.005 have larger remanence values than the samples fatigued at 0.002.

4 Phase 2

4.1 *Materials and Procedure*

The materials used in this phase were the same as in Phase 1. The sections were machined into cylindrical bars 100 mm in length with a 6-mm gauge diameter. This phase involved fatiguing the specimens to failure at various strain amplitudes. Fatiguing was interrupted at various times, generally every 100 cycles, to take a magnetic hysteresis measurement. Failure was defined as the cycle at which the applied load dropped 50% from its plateau value. The magnetic measurements were made while the samples were in the tensile test machine, but with the specimen under zero strain. The samples were fatigued at strain amplitudes of 0.002, 0.0035, and 0.005. As in Phase 1, the frequency of the strain cycling was changed so that the strain rate was kept constant at all strain amplitudes.

4.2 *Results*

Figure 6 shows the coercivity measured on the samples fatigued to failure. It is important to emphasize that measurements taken in this phase of the investigation involved stopping the test, taking the measurement, and restarting the fatigue cycling. Magnetic measurements were taken while the samples were in the grips, and the parameters were plotted as a function of the number of cycles experienced. Figures 6(a) and 6(b) show measurements taken on samples fatigued at strain amplitude 0.005. As shown in the measurements from Phase 1, there is an initial increase in coercivity at the start of fatiguing, followed by a plateau period, and finally a sharp decrease in coercivity shortly before failure. Sample 1 (shown in Fig. 6a) exhibited a plateau at a coercivity of 3.25 Oe, 0.25 Oe more than sample 2 (shown in Fig. 6b). This could possibly be due to differing values of maximum magnetic field applied to the specimens. Figure 6(c) shows the effects of fatiguing at a strain level of 0.0035. The initial increase in coercivity is still present. The plateau region lasts until approximately 90% of the fatigue life. Figure 6(d) shows the coercivity during fatiguing a specimen at strain amplitude 0.002. This sample did not have an initial large increase in coercivity. This is consistent with the samples fatigued at 0.002 strain amplitude in Phase 1. It is believed that this material does not fatigue harden at the lower strain amplitude. Note also that this sample did not show any appreciable drop in coercivity before failure. This also happened in the samples in Phase 1 fatigued at this strain amplitude.

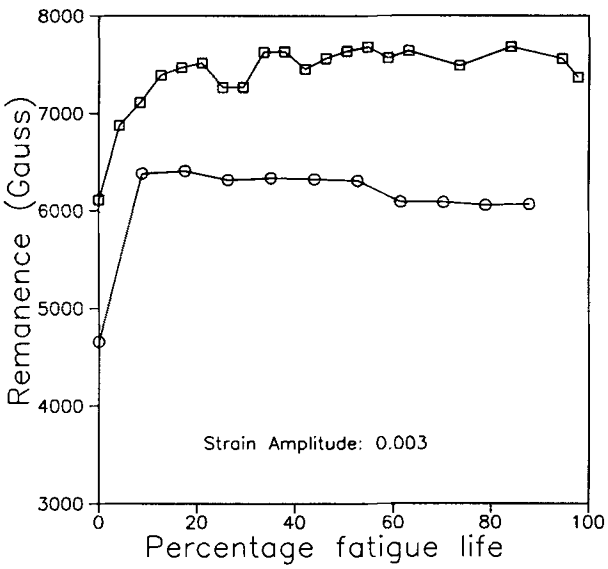

Fig. 8a Remanence measured on AISI 4340 specimens cycled at strain amplitude 0.003.

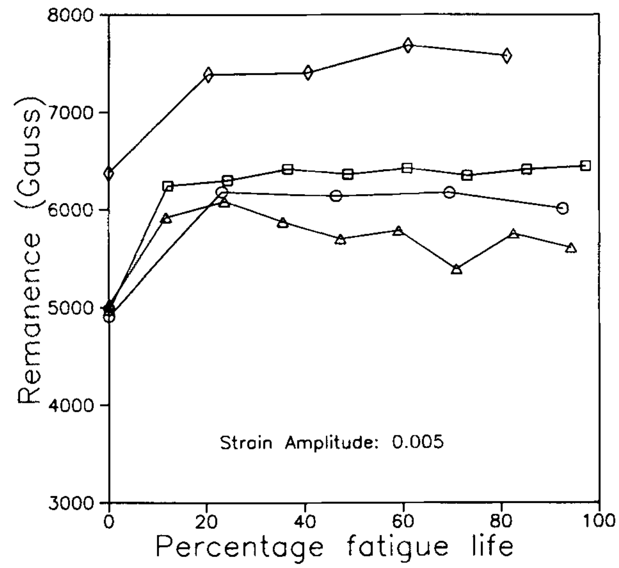

Fig. 8b Remanence measured on AISI 4340 specimens cycled at strain amplitude 0.005.

5 Phase 3

5.1 *Materials and Procedure*

The specimens used during this phase were samples of AISI 4340, quenched and tempered according to the following schedule: austenitized at 850 °C for 1 hr, oil quenched, tempered at 400 °C for 1/2 hr, then oil quenched again. Optical microscopy revealed a martensitic microstructure. The samples were machined into cylindrical bars 70 mm in length with a 6-mm gauge diameter. Samples in this phase were fatigued to failure at various strain amplitudes. The fatiguing was interrupted at various times, generally every 100 cycles, to take a magnetic hysteresis measurement. As in Phase 2, failure was defined as the cycle at which the applied load dropped 50% from its plateau value; the magnetic measurements were made while the samples were in the test machine, but with the specimen under zero strain. The specimens were fatigued under a constant total axial strain amplitude either 0.003 or 0.005, and the frequency of the cycling was changed so that the strain rate was kept constant.

5.2 *Results*

Figures 7 and 8 show the results from fatiguing samples of AISI 4340. Figure 7 shows the measured coercivity versus the percentage of expended fatigue life. There is a large initial drop in the coercivity in the first 15% of fatigue life. This corresponds to fatigue softening, which the samples underwent in the early stages of fatigue. The microstructure has a considerable number of dislocations moving around that are annihilated during this stage. The plateau region for the coercivity lasted until failure for most of the specimens. There is no sharp decline before failure as seen in the previous two phases.

Figure 8 shows the remanence measured as a function of expended fatigue life. There is a large initial increase in the first 15% of expended fatigue, reflecting the fatigue softening. The plateau region then extends for most of the rest of fatigue life. A few samples show a slight decline near the end of fatiguing. Larger drops in the remanence, indicating impending failure, were not observed, probably because measurements were not taken close enough to failure.

6 Conclusions

The magnetic hysteresis parameters have been shown to vary with fatiguing in some ferromagnetic materials. Some of the parameters have been shown to decrease sharply near the end of fatigue life. The strain amplitude appears to affect the magnitude of the change in the hysteresis parameters. The parameters have been shown to reflect either the strain hardening or strain softening during fatiguing.

Acknowledgment

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Reference

1. D.C. Jiles, S. Hariharan, and M.K. Devine, *IEEE Trans. Mag. 26*, p 2577 (1990).