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Evaluation of fatigue damage in steel structural components by magnetoelastic Barkhausen signal analysis

Madhav Rao Govindaraju
Iowa State University

Andrew Strom
Iowa State University

David C. Jiles
Iowa State University, dcjiles@iastate.edu

S. B. Biner
Iowa State University

Z. J. Chen
Iowa State University

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Abstract

This paper is concerned with using a magnetic technique for the evaluation of fatigue damage in steel structural components. It is shown that Barkhausen effect measurements can be used to indicate impending failure due to fatigue under certain conditions. The Barkhausen signal amplitude is known to be highly sensitive to changes in density and distribution of dislocations in materials. The sensitivity of Barkhausen signal amplitude to fatigue damage has been studied in the low-cycle fatigue regime using smooth tensile specimens of a medium strength steel. The Barkhausen measurements were taken at depths of penetration of 0.02, 0.07, and 0.2 mm. It was found that changes in magnetic properties are sensitive to microstructural changes taking place at the surface of the material throughout the fatigue life. The changes in the Barkhausen signals have been attributed to distribution of dislocations in stage I and stage II of fatigue life and the formation of a macrocrack in the final stage of fatigue.

Keywords

CNDE, Barkhausen effects, Materials modification, Materials properties, Magnetic materials, Material fatigue

Disciplines

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M. R. Govindaraju, A. Strom, D. C. Jiles, S. B. Biner, and Z.-J. Chen
Ames Laboratory and Center for NDE, Iowa State University, Ames, Iowa 50011

This paper is concerned with using a magnetic technique for the evaluation of fatigue damage in steel structural components. It is shown that Barkhausen effect measurements can be used to indicate impending failure due to fatigue under certain conditions. The Barkhausen signal amplitude is known to be highly sensitive to changes in density and distribution of dislocations in materials. The sensitivity of Barkhausen signal amplitude to fatigue damage has been studied in the low-cycle fatigue regime using smooth tensile specimens of a medium strength steel. The Barkhausen measurements were taken at depths of penetration of 0.02, 0.07, and 0.2 mm. It was found that changes in magnetic properties are sensitive to microstructural changes taking place at the surface of the material throughout the fatigue life. The changes in the Barkhausen signals have been attributed to distribution of dislocations in stage I and stage II of fatigue life and the formation of a macrocrack in the final stage of fatigue.

I. INTRODUCTION

This paper reports on recent investigations to evaluate fatigue damage in steels using a Barkhausen effect measurement technique. When a ferromagnetic material is magnetized the resulting hysteresis plot appears smooth, but close inspection reveals that the magnetization changes occur in a discontinuous, steplike manner called the Barkhausen effect.[1-4] The micromagnetic Barkhausen effect is attributed to irreversible Bloch wall motion. As domain walls move they encounter pinning sites, such as grain boundaries, dislocations, precipitates, microcracks and other inhomogeneities in the microstructure. In an attempt to move past these pinning sites the walls initially bend in reversible manner like an elastic membrane. With further increase in magnetizing field the domain walls break away irreversibly when their curvature exceeds the critical value causing a Barkhausen emission.[5] The nature of the Barkhausen signal amplitude, which is detected as voltage pulses in an induction coil, depends on the type and distribution of defects in the material. The advantages of the micromagnetic Barkhausen effect inspection are that the method is relatively simple, rapid, requires minimum material preparation, and is nondestructive in nature. Due to its sensitivity to microstructural changes the Barkhausen effect has been used to study many metallurgical properties, such as microstructure,[6] residual stress,[7] grain size,[8] and applied stress.[9] However, the Barkhausen signal that is detected in these measurements comes exclusively from the surface of the material.

When a material is fatigued its microstructure changes although no macroscopic plastic deformation may be evident. Dislocation tangles are broken up, slip lines appear on the surface, and eventually microcracks form. It is envisaged that the Barkhausen effect can be used to predict impending failures in structural components due to fatigue because Barkhausen signals are sensitive to the kinds of structural changes that occur in materials as a result of fatigue deformation.

II. EXPERIMENTAL PROCEDURE

The material used in this investigation was a medium strength structural alloy steel (ASTM code A533B) whose mechanical properties are given in Table I. The composition of the steel given in weight percentages is 1.5% Mn, 0.7% Ni, 0.6% Cr, 0.6% Mo, 0.2% C, 0.2% Si, and 96.2% Fe.

The samples were subjected to low cycle fatigue with constant strain amplitude of ± 0.003. Generally in low-cycle fatigue, the amplitude of strain should be greater than the elastic limit, and consequently the sample undergoes microscopic plastic deformation in each fatigue cycle and generally reaches failure between 10^4 and 10^5 cycles. Fatigue testing was carried out using a computer controlled, 10 kN, servo hydraulic MTS system. Magnetic Barkhausen signal amplitudes were measured using Stresscan™ on the specimens under zero load at predetermined intervals throughout the fatigue life, using a measurement frequency that detected Barkhausen events at nominal depths of up to 0.20 mm below the surface.

III. RESULTS AND DISCUSSION

The amplitude of the Barkhausen signal generated during domain wall movement depends on the distance between pinning sites and the strength of the pinning sites. The variation of the Barkhausen signal amplitude with fatigue, shown in Fig. 1, can be explained by a three-stage fatigue sequence. Stage I: The initial increase in Barkhausen signal amplitude that occurs in the first 30%

TABLE I. Mechanical properties of the material used in the investigation.

Young's modulus GPa	170
0.2% yield stress, MPa	369
Ultimate tensile strength, MPa	536
Hardness R_b	88

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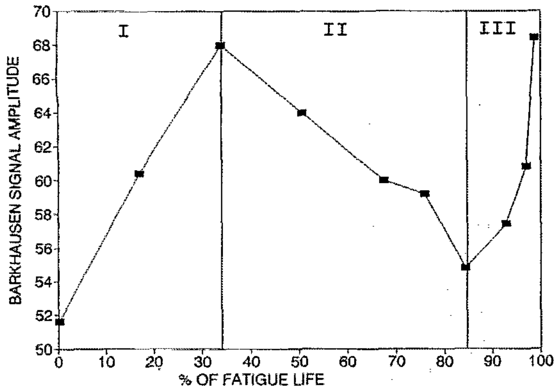

FIG. 1. Variation of Barkhausen signal amplitude due to fatigue in a medium strength structural steel; measurements taken at 0.2 mm below the surface.

of fatigue life is due to fatigue softening. This causes an increase in the mean distance between dislocations which act as domain wall pinning sites. Softening is evident from a decrease in load necessary to reach 0.3% strain, as shown in Fig. 2 and is called the Bauschinger effect.[10] The Bauschinger effect is characterized by a decrease in flow stress of a material in compression, when it was initially stressed beyond the elastic limit in tension. If the material is then stressed again in tension, the flow stress will be even lower. This softening process continues in the initial stages of fatigue, until an equilibrium state is achieved, at which point the flow stress does not change between subsequent cycles.

Orowan explained the Bauschinger effect by examining the motion of dislocations.[11] During the plastic portion of deformation dislocations move causing slip until they pile up at grain boundaries or precipitates, forming dislocation tangles. With reversed loading, the dislocations at the trailing edges of the tangles move away from the grain boundaries and precipitates more easily causing an apparent softening.

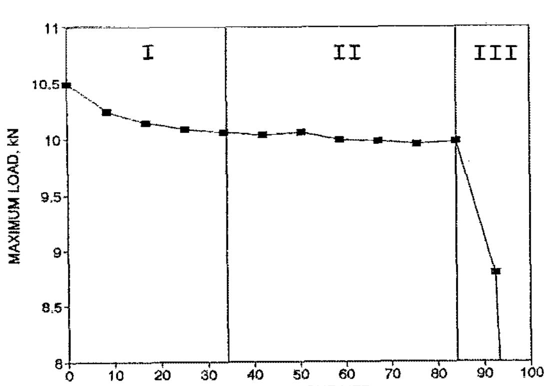

FIG. 2. Maximum load per fatigue cycle necessary to achieve 0.3% strain.

The Barkhausen measurement technique indirectly measures this phenomenon of dislocation movement. As dislocation tangles are broken up, the dislocations are dispersed more evenly throughout a material, thus their mean separation distance will increase. A larger separation distance between pinning sites gives rise to a larger discontinuous change in magnetization when a domain wall breaks away from a dislocation. Therefore the Barkhausen signal amplitude increases in stage I.

Stage II: Fatigue in stage II, is marked by the appearance of slip lines that often occur on free surfaces due to fatigue.[12] As loads necessary to reach 0.3% strain stabilize, existing dislocations move and generally accumulate at the surface,[13] eventually causing slip lines. As this happens, mean separation distance between dislocations decreases, causing a decrease in Barkhausen signal amplitude from the surface seen in stage II.

Stage III: The Barkhausen signal is observed to increase rapidly in stage III of fatigue deformation (Fig. 1) which corresponds to macrocrack propagation stage. When a macrocrack is produced, closure domains are created at the surface of the crack leading to a higher domain density, higher domain wall density and consequently a higher Barkhausen signal. As the crack grows, the numbers of these domains grow and the Barkhausen signal amplitude increases as seen in Fig. 1.

IV. CONCLUSIONS

The Barkhausen measurement technique appears to be a viable method for detecting the fatigue damage in steel structural components. Significant changes were observed in the Barkhausen signal amplitude in the first 30% and the last 20% of fatigue life. These changes are associated with the nature of domain wall–dislocation interactions. The changes in the surface sensitive Barkhausen signals during fatigue have been described by a three stage sequence. In stage I, the increase in Barkhausen signal amplitude has been attributed to the fatigue softening which causes a break-up of dislocation bundles and a resulting increase in the mean separation distance between dislocations acting as domain wall pinning sites. The decrease in Barkhausen signal in stage II is caused by the migration of dislocations towards the surface leading to a smaller mean distance between dislocations. In stage III, the creation of closure domains at the surface of a macrocrack results in a higher domain density and hence an increase in Barkhausen activity.

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