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Current Perspectives

Measuring stress variation with depth using Barkhausen signals

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A B S T R A C T

Magnetic Barkhausen noise analysis (BNA) is an established technique for the characterization of stress in ferromagnetic materials. An important application is the evaluation of residual stress in aerospace components, where shot-peening is used to strengthen the part by inducing compressive residual stresses on its surface. However, the evaluation of the resulting stress-depth gradients cannot be achieved by conventional BNA methods, where signals are interpreted in the time domain. The immediate alternative of using x-ray diffraction stress analysis is less than ideal, as the use of electropolishing to remove surface layers renders the part useless after inspection. Thus, a need for advancing the current BNA techniques prevails. In this work, it is shown how a parametric model for the frequency spectrum of Barkhausen emissions can be used to detect variations of stress along depth in ferromagnetic materials. Proof of concept is demonstrated by inducing linear stress-depth gradients using four-point bending, and fitting the model to the frequency spectra of measured Barkhausen signals, using a simulated annealing algorithm to extract the model parameters. Validation of our model suggests that in bulk samples the Barkhausen frequency spectrum can be expressed by a multi-exponential function with a dependence on stress and depth. One practical application of this spectroscopy method is the non-destructive evaluation of residual stress-depth profiles in aerospace components, thus helping to prevent catastrophic failures.

1. Introduction

Barkhausen jumps are discontinuous changes in magnetization which occur in a ferromagnetic material subjected to a time-varying magnetic field. These local magnetization changes give rise to an electromagnetic noise-like signal which is termed the *Barkhausen noise*, after the discoverer, Heinrich Barkhausen, who noticed a crackling noise while subjecting a ferromagnetic material to an applied field [5]. Owing to the coupling between magnetic and mechanical properties of ferromagnetic materials, the Barkhausen signal can be used to evaluate the specimen under test [54,40,42,59], revealing material parameters such as grain size, microstructure and stress state.

Theoretical models of Barkhausen noise, such as the ABBM [1,3,2], have found little application in the technological domain due to their fundamental nature. Despite their extensive account of magnetization dynamics, they address aspects of practical Barkhausen noise measurement only over a limited scope, for particular specimen geometries (such as thin films) and, in some cases, single crystal structures. Also, a homogeneous material is usually assumed and there is no attempt to determine depth-specific material properties. The multitude of parameters and the mathematical complexity prevents these models from direct translation into more practical applications where specimens are heterogeneous.

Therefore, it follows that in the technological domain, and particularly when it comes to magnetic material characterization, heuristic models dominate. However, despite their good performance in some cases, such as in production lines where parts of the same geometry and composition have to be characterized, they lack the physical insight necessary to advance fundamental understanding.

Barkhausen noise analysis is typically used to determine average stresses in a structure. Compared to other stress evaluation methods such as hole drilling and sectioning [39,43] and even XRD combined with electropolishing [44], it offers the advantage of being entirely non-destructive, rapid and cost-effective. However, the current inability to extract depth-specific information has imposed a limitation on its popularity. To achieve this, one needs a good understanding of domain wall dynamics as well as of the practical measurement techniques which involve the electromagnetic propagation of the Barkhausen signal from the point of its origin to the surface where it is measured.

In previous works, a parametric frequency domain model was

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developed [27,30,29,30,32,31,26] which expresses the measured Barkhausen signal in terms of the contributions from different depths inside the material. The capability of the model to estimate stress-related parameters from a uniaxially stressed specimen was recently demonstrated, by expressing the main equation in terms of one homogeneous, uniformly stressed layer of ferromagnetic material [31]. In the latest rendition of the model [32], the measured frequency spectrum at the surface was expressed as a linear combination of the Barkhausen spectra originating in volumetric regions below the surface.

The aim of the present paper is to present (1) an introduction to the theory and practice of Barkhausen noise, using the depth-profiling model as a connecting example, (2) an overview of magnetization dynamics, solid mechanics theory, as well as a description of signal analysis techniques commonly used in the field, and (3) a series of experiments for the proof of concept conducted by the authors, which show that by considering both the domain wall dynamics and propagation characteristics of the Barkhausen signal one can obtain a depth-specific stress estimate.

1.1. Evaluation of residual stresses

Stress is defined as the force per unit area. Applied stress manifests when a component is actively loaded, while residual stress is what remains when that loading is removed. Residual stresses have a ”balancing” effect, in the sense that they cancel out over the entire volume of the material.

Consider the example of a shot peening process, where a metallic surface is blasted with small ceramic pellets. Compressive stresses are formed on the surface, in what is essentially a plastic deformation. In order to balance the forces within the entire volume of the specimen, elastic tensile stress forms in the part below the compressed region. The expected stress-depth profile is illustrated in Fig. 1.

Residual stresses are typically classified into three different categories, which indicate the length scales over which these stresses manifest. These categories are Type I, II and III [60], and correspond to macro-, micro-[1] and atomic scale residual stresses, respectively. Type I residual stresses, range in the order of millimeters; Type II residual stresses, range in the order of micrometers; Type III residual stresses, range over atomic length scales. The present work is addressing the upper end of Type II stresses overlapping with the lower end of the Type I stresses. A range of measurement techniques, both destructive and non-destructive, may be used to quantify stresses in the aforementioned length scales [55].

Currently, x-ray diffraction is used in conjuction with electropolishing (for surface layer removal) to assess the stress-depth profile of shot-peened components. The need to remove surface layers is not required with magnetic techniques, which can be used to non-destructively probe the near-surface region. A common technique within the realm of magnetic non-destructive evaluation methods is Barkhausen noise. The next sections provide the definition of Barkhausen noise, along with the theoretical models developed so far, and a overview of the utility of the Barkhausen technique in the field of non-destructive evaluation of steels.

1.2. Barkhausen noise

Over the years, studies have shown that magnetic Barkhausen noise is a rather complex physical process [3,2,53,19]. Its manifestation varies depending on the type of ferromagnetic material, defect/inclusion sizes, frequency of applied magnetic field, as well as thermal effects [47,22]. The aim of this section is to provide a description of the theoretical models that have been introduced over the years in order to describe Barkhausen noise. It also aims to provide a summary of developments in the context of non-destructive evaluation applications, particularly how measured signals contain information about the stress state of a material.

1.2.1. Domain wall motion and Barkhausen noise

Theoretical models of Barkhausen noise are based on domain wall dynamics, and usually attempt to describe a complex physical mechanism in one or two mathematical expressions. Barkhausen activity contains a large stochastic component, which creates ambiguity concerning the choice of statistics that need to be used in describing the phenomenon. The physics community has shown great interest in Barkhausen noise due to the fact that Barkhausen *avalanches* (successive Barkhausen jumps) are fractal in nature and thus exhibit scale-invariance [16,13,4,37,46,45,49,41,56,24]. Despite extensive studies that yielded complicated theories, little has been done towards practical application. This is partially demonstrated by the fact that all past attempts to accurately model Barkhausen activity are either too complicated to be used within an applied context or too heuristic to provide insight into the phenomenon. In the engineering world, although they are used in the non-destructive evaluation industry, Barkhausen noise techniques still remain much the same after decades of use, as the complexity of the phenomenon limits understanding. This disconnect between the theoretical and practical realms is what the present work attempts to bridge. The discussion begins with a review of domain wall dynamics, progresses to a description of Barkhausen power spectra, and ends with a review of models of Barkhausen noise geared towards applications in the field of non-destructive evaluation.

Chikazumi [10] invokes the expression for the coercive field that pins a domain wall, by arguing that the domain wall motion is described by a second order differential equation [15] of the form

$$m_{dw}\frac{d^2x}{dt^2} + \eta\frac{dx}{dt} + \lambda x = \nu H, \tag{1}$$

which contains a velocity term dx/dt, and a damping factor, η. In this expression, m_{dw} is the effective mass of the domain walls, d^2x/dt^2 is the acceleration, and λ is the restoring coefficient that arises due to the internal potential. The force per unit area of the domain wall due to the applied field H is νH, where ν is a parameter that specifies the type of domain wall (180 or 90 degree). In the case of an equilibrium, or equivalently, steady-state condition,

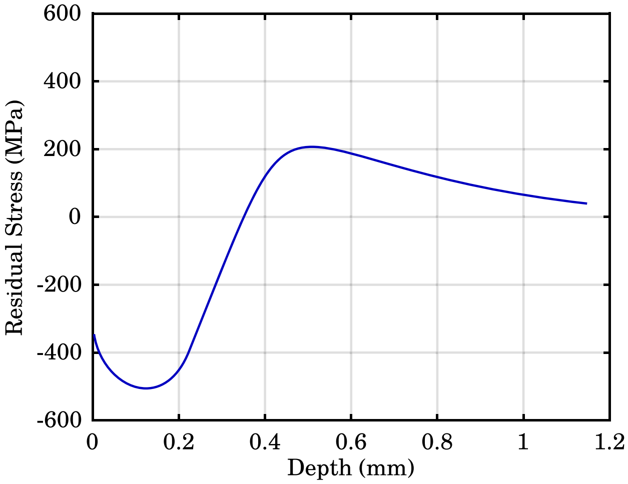

Fig. 1. Expected stress-depth profile due to shot peening.

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[1] At the length scale of grains.

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