Magnetic Detection of Microstructural Change in Power Plant Steels

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This dissertation is submitted
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at the University of Cambridge

PREFACE

This dissertation is submitted for the degree of Doctor of Philosophy at the University of Cambridge. The research described herein was conducted under the supervision of Professor H. K. D. H. Bhadeshia and Dr M. G. Blamire in the Department of Materials Science and Metallurgy, University of Cambridge, between October 1999 and April 2003.

Except where acknowledgement and reference are made to previous work, this work is, to the best of my knowledge, original. This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text. Neither this, nor any substantially similar dissertation has been, or is being, submitted for any other degree, diploma, or other qualification at any other university. This dissertation does not exceed 60,000 words in length.

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In loving memory of
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5 Barkhausen Noise Modelling 95

ABBREVIATIONS

b.c.c. Body-centred cubic

ppm Parts per million

ABBM Alessandro, Beatrice, Bertotti and Montorsi model

AQ As-quenched

BN Barkhausen noise

CSL Coincidence site lattice

EBSD Electron backscatter diffraction

FEG Field emission gun

FWHM Full width half maximum

IQ Image quality

MAE Magnetoacoustic Emission

NDT Nondestructive testing

ODS Oxide-dispersion strengthened

OIM Orientation imaging microscopy

PHD Pulse height distribution

RMS Root-mean-square

SEM Scanning electron microscope

TEM Transmission electron microscope

VSM Vibrating sample magnetometer

NOMENCLATURE

Note: Two SI systems for magnetics nomenclature exist, but the Sommerfeld system has been used throughout; equations not conforming to this system have been converted. A comparison table including the two SI systems and the cgs system can be found in Jiles (1998).

General

d Grain diameter

E Efficiency

M Magnification

M_f Martensite-finish temperature

M_s Martensite-start temperature

P Larson-Miller parameter

t Time

T Absolute temperature

T_1 Absolute heat source temperature

T_2 Absolute heat sink temperature

T_M Absolute melting temperature

Magnetics

$\mathbf{B}$ Magnetic induction

B_S Saturation induction

B_R Remanent induction

E_a Anisotropy energy

E_{area} Area reduction energy (Kersten model)

E_d Demagnetising energy

E_{demag} Inclusion demagnetising energy (Néel model)

E_{ex} Exchange energy

E_m Magnetostatic energy

E_{pin} Energy dissipated against pinning

E_{supp} Energy supplied

$\mathbf{H}$ Magnetic field

H_C Coercive field

H_d Demagnetising field

H_e Weiss mean field

H_{max} Maximum applied field

H_S Field at which $M = M_S$

K_1 Anisotropy constant

$\mathbf{M}$ Magnetisation

$\mathbf{m}$ Magnetic moment

M_R Remanent magnetisation

M_S Saturation magnetisation

N_d Demagnetising constant

P Barkhausen noise power

T_C Curie temperature

V Voltage

W_H Hysteresis energy loss

α Mean field constant

β Term characterising nearest-neighbour interactions

γ Domain wall energy

δ Domain wall thickness

λ_{UVW} Magnetostrictive strain along $< UVW >$

λ_{si} Ideal magnetostrictive strain

μ_0 Permeability of free space

μ' Differential permeability

μ'_{max} Maximum differential permeability

σ Electrical conductivity

χ'_{in} Initial differential susceptibility

χ'_{max} Maximum differential susceptibility

Φ Magnetic flux

$\omega*$ Surface pole density

$\mathcal{J}$ Term characterising nearest-neighbour interactions

Modelling: existing models

A, B Amplitude of fluctuations in ABBM

k pinning parameter

M_{an} Anhysteretic magnetisation

M_{JS} BN jump sum

M_{rev} Reversible magnetisation

$< M_{disc} >$ Average BN event size

v domain wall velocity

W noise term in ABBM

$< \epsilon_\pi >$ Pinning energy for 180° wall

$< \epsilon_{pin} >$ Pinning enrgy for wall at arbitrary angle

ξ Correlation length

Modelling: new model

A_i Total number pinning points of ith type per unit volume

$\mathbf{A}_w$ Wall surface area

C Constant

E Fitting error

E_0 Electric field amplitude

$\mathbf{l}_w$ Wall jump distance

$l\{H\}$ Distance between pinning sites at field H

$< l > \{H\}$ Domain wall mean free path

$N\{H\}$ Number of pinning sites of strength $\geq H$

$n\{S\}$ Number pinning sites of strength S

S Pinning site field strength

S_b Field at which unpinning first occurs

$< S >_i$ Mean value of S for ith type of pinning site

$V\{H\}$ BN voltage at field H

$V_r\{H\}$ Real $V\{H\}$

$V_p\{H\}$ Predicted $V\{H\}$

$< x >$ Mean value of $ln\{S\}$ for log-normal distribution

β Parameter depending on angle between adjacent domains

ΔS_i Standard deviation of S for ith type of pinning site

Δx Standard deviation of $ln\{S\}$ for log-normal distribution

Orientation Imaging Microscopy

$\mathbf{c}_c$ Crystal coordinate system

$\mathbf{c}_s$ Sample coordinate system

d Planar spacing

$\mathbf{G}$ Rotation matrix

$\mathbf{M}$ Misorientation matrix

$< UVW >$ Misorientation axis

ν_0 Brandon ratio proportionality constant

ν_m Maximum allowable deviation from ideal coincidence

λ Radiation wavelength

θ Misorientation angle

θ_B Bragg angle

ABSTRACT

Power plant components are expected to withstand service at high temperature and pressure for thirty years or more. One of the main failure mechanisms under these conditions is creep. The steel compositions and heat treatments for this application are chosen to confer microstructural stability and creep resistance. Nevertheless, gradual microstructural changes, which eventually degrade the creep properties, occur during the long service life. Conservative design lives are used in power plant, and it is often found that components can be used safely beyond the original design life. However, to benefit from this requires reliable monitoring methods. One such technique involves relating the microstructural state to measurable magnetic properties.

Magnetic domain walls interact energetically with microstructural features such as grain boundaries, carbides and dislocations, and are 'pinned' in place at these sites until a sufficiently large field is applied to free them. When this occurs, the sudden change in magnetisation as the walls move can be detected as a voltage signal (Barkhausen noise). Previous work has suggested that grain boundaries and carbide particles in power plant steels act as pinning sites with characteristic strengths and strength distributions.

In this study, the concept of pinning site strength distributions was used to develop a model for the variation of the Barkhausen noise signal with applied field. This gave a good fit to published data. The modelling parameters characterising pinning site strengths showed good correlations with grain and carbide particle sizes.

New Barkhausen noise data were obtained from tempered power plant steel samples for further model testing. The Orientation Imaging Microscopy (OIM) technique was used to investigate the grain orientations and grain boundary properties in the steel and their possible role in Barkhausen noise behaviour. The model again fitted the data well, and a clear relationship could be seen between the pinning strength parameter and the severity of tempering (as expressed by the Larson-Miller tempering parameter) to which the steel was subjected.

The experimental results suggest that the Barkhausen noise characteristics of the steels investigated depend strongly on the strain at grain boundaries. As tempering progresses and the grain boundary dislocation density falls, the pinning strength of the grain boundaries also decreases. A clear difference in Barkhausen noise response could be seen between a $2\frac{1}{4}$Cr1Mo traditional power-plant steel and an 11Cr1Mo steel designed for superior heat resistance.

A study of an oxide dispersion strengthened ferrous alloy, in which the microstructure undergoes dramatic coarsening on recrystallisation, was used to investigate further the effects of grain boundaries and particles on Barkhausen noise. The findings from these experiments supported the conclusion that grain boundary strain reduction gave large changes in the observed Barkhausen noise.