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Advanced Techniques for the Measure of Microstructure and Residual Stress in Components Subject to Rolling Fatigue

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ABSTRACT

Demands on loaded, rotating components, e.g., bearings, shafts & gears continue to escalate. Modern manufacturing strategies require improvements in traditional measurements and process control tools.

Traditionally residual stress examination in bearings was accomplished with depth profiles obtained using X-Ray diffraction (XRD) and electrochemical layer removal. More recently Barkhausen Noise Analysis (BNA) has proven itself in the evaluation of microstructure as well as surface residual stress in ferromagnetic materials. Traditional BN analysis parameters have been used for fixed measurement depths, usually near the surface.

This study is an examination on a set of as-hardened and ground bearing rings manufactured with variations in processing. The Barkhausen signal was analyzed to yield information about a range of depths. XRD & BNA depth profiles were gathered and they correlate well. This allows a calibration of the BN signal to the residual stress. It is proposed that BNA can be used for quick, non-destructive assessment of residual stress depth profiles.

INTRODUCTION

Current manufacturing processes for rotating components, specifically those subject to rolling fatigue, often include multiple instances of surface grinding and heat treatment. These processes introduce a multitude of complex changes to the microstructure of the component, including residual stresses.

Residual stresses impact the fatigue life of components as they play a role in the total stress exerted on the component. The total stress exerted on a component is the sum of all external and internal stresses, including internal residual stress. Traditionally, surface residual stresses can be evaluated non-destructively using XRD methods or BNA. In order to measure stresses below the surface and through the depth XRD must be complemented by electrochemical layer removal, thus destroying the component. It is possible, however, using advanced techniques in BNA, to estimate subsurface stress features non-destructively.

MAIN SECTION

RESIDUAL STRESS MEASUREMENTS VIA X-RAY DIFFRACTION – X-ray diffraction uses two well known principals to effectively use the inter-atomic spacing between a specific crystallographic plane as a strain gauge and allow the calculation of the planar residual stress stored in the surface using linear elastic values.

The first such principal is Bragg's law that relates the diffracted peak position (θ) to the inter-atomic spacing (d) as well as the wavelength of the incident radiation (λ).

$$n\lambda = 2d \cdot \sin\theta$$

The values of the wavelength and peak position are known for the selected crystallographic plane. In this

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case CrKα radiation and the Fe 211 plane at a 2θ value near 156°. This allows for small changes in the peak position to reflect changes in the d-spacing in the surface plane as measurements are taken in the positive and negative directions relative to normal (ψ); effectively measuring the strain.

The second principal is Hooke's law that relates the Modulus of Elasticity (E) and the strain (ε) to the stress (σ) by assuming that the stress normal to the plane is zero ($\sigma_z = 0$) and that the d-spacing can be used as a measure of strain. The relationship between d-spacing and stress uses the Modulus of Elasticity, Poisson's Ratio (ν) and (m) the slope of $d \text{ vs } \sin^2\psi$ plot.

$$\sigma_\varphi = \left(\frac{E}{1+\nu}\right)m$$

This equation in conjunction with cross correlation methods to determine peak translation and multiple exposures through the positive and negative ψ range allows for the precise and repeatable measurements of residual stress on nearly any crystalline material.

FUNDAMENTALS OF THE BARKHAUSEN EFFECT – The Barkhausen Effect is a micromagnetic phenomena observed in ferromagnetic materials undergoing magnetization. As a ferromagetic sample is magnetized and demagnetized the net magnetization of the sample changes in relation to the applied external magnetizing field; this process is hysteretic in nature. The Barkhausen Effect occurs during this hysteretic process as the magnetization of the sample changes with respect to the applied magnetic field in discrete "steps" as opposed to a smooth, continuous transition (see Figure 1).

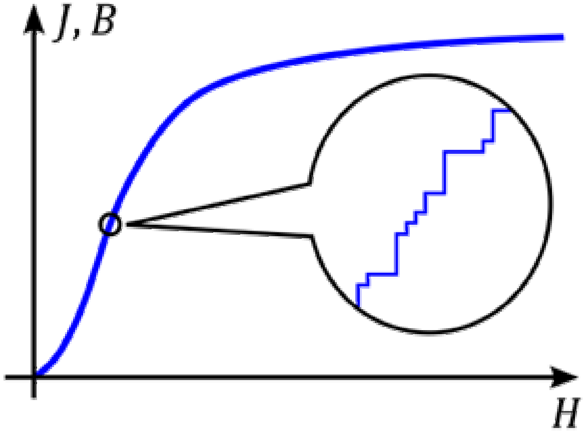

Figure 1[a] – Magnetization (J) or Magnetic Flux Density (B) with respect to applied field strength (H)

It is the presence of these discrete steps in the magnetization-applied field (J,B-H) relationship that result in Barkhausen noise. These jagged steps are the product of rapid discontinuous changes in the magnetization of the sample which is a consequence of changes in the size and orientation of magnetic domains [1].

The net magnetization of a ferromagnetic material is the sum of the magnetization of all its magnetic domains. Magnetic domains are small sections or patches within a sample that contain billions of magnetic dipoles oriented in the same direction [2]. Each magnetic dipole is essentially an atom acting as a bar magnet. Ordinarily magnetic domains are randomly oriented, resulting in zero net magnetization. In the presence of an applied field (or a permanent magnet), however, these bar magnets begin to align with the direction of the applied field. Entire domains align rapidly (see Figure 2) and, sometimes, assimilate into neighboring domains. When all domains have been assimilated into one the sample is magnetically saturated.

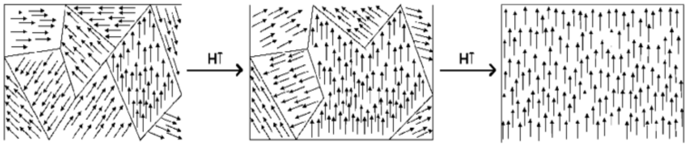

Figure 2[a] – Resizing and reorienting of domains as a result of applied field H

Each rapid change in domain magnetization is a result of the rapid change in the magnetization of billions of atoms, thus producing the aforementioned steps or jumps in the net sample magnetization. The consequence of these jumps is a burst of electromagnetic noise, or Barkhausen noise.

Barkhausen noise can be analyzed by inductively measuring the changing magnetization of a sample, usually while applying an alternating magnetic field. When an alternating magnetic field is applied the sample emits a stream of Barkhausen noise bursts as the applied field continuously changes.

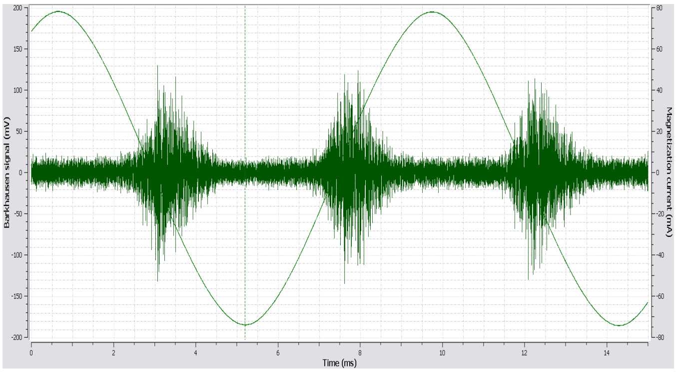

Figure 3 – Driving current for magnetizing yoke and resulting Barkhausen noise bursts

The noise bursts in Figure 3 are the result of measuring and filtering the sample magnetization via a probe/sensor and central processing unit. The probe/sensor includes both a magnetizing yoke and an inductive pickup. The central processing unit provides magnetizing power to the probe and filters the signal from the pickup. The pickup signal is run through a bandpass filter that removes the low frequency magnetizing wave and any high frequency noise which may be a result of electromagnetic interference (EMI).

BARKHAUSEN NOISE ANALYSIS AS A MEASURE OF MICROSTRUCTURE – Barkhausen noise is sensitive to any sample properties affecting magnetic domain size or wall movement. In ferromagnetic materials, like steels, microstructural properties related to hardness, alloy content, and residual stress affect magnetic domain wall movement. The consequence of a change in microstructure is a change in the properties of the noise burst, most notably the amplitude. There are, however, a number of properties of the noise burst which are sensitive to variations in microstructure. Evaluating microstructure using these parameters is known as Barkhausen Noise Analysis.

The amplitude of the noise burst is quantified by calculating the root mean square (RMS) of the filtered noise signal. This value is referred to as the magnetoelastic parameter in reference to the “magnetoelastic interaction”, the phenomenon of elastic properties interacting with domain structure and magnetic properties [3].

It has been observed that the magnetoelastic parameter increases with surface residual stresses (see Figure 4) and decreases with gains in hardness. As a result BNA has been successfully used to detect stresses induced by aggressive grinding, softness and other heat treatment defects, and other near surface microstructural properties and/or defects.

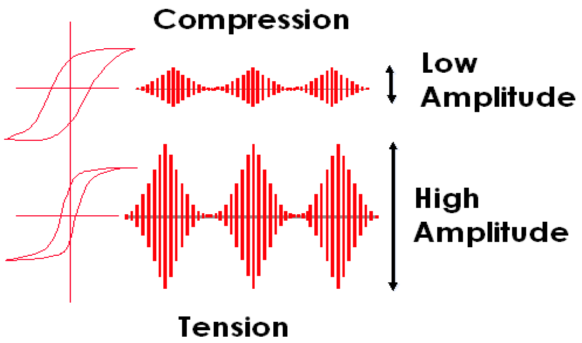

Figure 4 – As tensile residual stresses increase the amplitude of the Barkhausen noise bursts also increase.

BNA AND RESIDUAL STRESSES – A sample set of ground 52100 steel bearing rings was examined non-destructively using BNA and XRD.

This sample of four rings includes both well ground and abusively ground parts with varying residual stresses as seen in Table 1.

Bearing Ring Sample Set		
Sample	**Ground Condition**	**Surface Stress Condition**
Ring 1 Edge	Abusive	High
Ring 1 Middle	Abusive	Moderate
Ring 3 Middle	Good	Low
Ring 4 Middle	Abusive	High
Ring 5 Middle	Good	Low

Table 1 – Sample set grinding and surface stress conditions.

BNA was conducted using a Microscan 600 central processing unit and a standard handheld outside diameter (OD) sensor magnetizing in the circumferential direction[b], as seen in Figure 5. All rings were measured with the sensor centered on the long axis. Ring 1, which exhibited an edge effect, was also measured on the edge. XRD was conducted using the Xstress 3000 stress analyzer and the G3 goniometer[b]. XRD measurements were made in compliance with SAE HS-784[c] and ASTM E915.

Figure 5 – Handheld testing of bearing ring using OD sensor.

The resulting surface stress measurements correlate with the magnetoelastic parameter measured via BNA as seen in Figure 6. As surface stresses increase into tension the magnetoelastic parameter also increases.

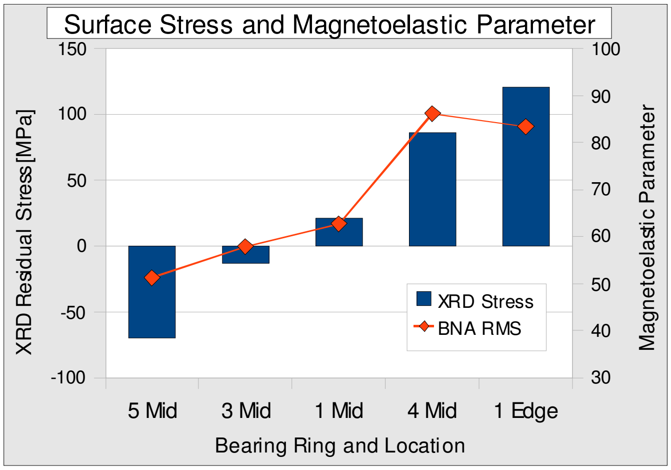

Figure 6 – Surface residual stresses as measured by XRD and magnetoelastic parameter measured by BNA

There is a clear correlation between surface residual stresses and the magnetoelastic parameter for this sample set, but examination of residual stress through the depth via XRD with electrochemical layer removal shows other interesting features (see Figure 7).

Despite the fact that the middle of Ring 1 had the median surface residual stress and magnetoelastic parameter, it had the greatest maximum subsurface residual stress. This feature, along with others like crossing points in the residual stress depth profiles, are important in metallurgical evaluation and process control.

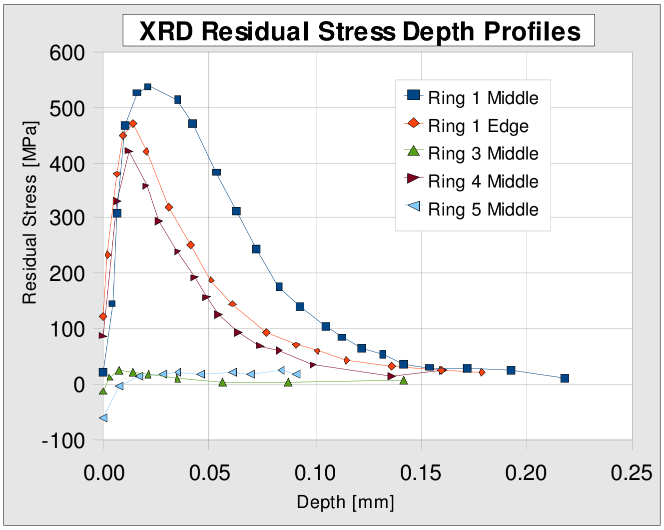

Figure 7 – Residual Stress through the depth measured with XRD.

This is an important factor when using simple BNA for evaluation, as it is effective at measuring the aggregate of emissions through a fixed, near surface depth. This depth can be affected by many factors including, but not limited to, magnetizing field strength, alternating field frequency, analysis frequency pass band, and material properties such as permeability and conductivity.

ADVANCED TECHNIQUES – Subsurface stress features, such as those in this sample set, are easily seen with XRD and electrochemical layer removal; unfortunately this method is a destructive evaluation. Simple non-destructive measurements using BNA cannot resolve the aforementioned features; however, using advanced signal processing techniques to analyze the Barkhausen noise bursts, these features can be resolved non-destructively. By utilizing the signal processing and data capture capabilities of the Microscan 600 it is possible to capture and analyze the Barkhausen noise signal in more complex ways.

An advanced algorithm and modeling method can estimate the residual stress of a sample through a limited depth range, thus allowing for non-destructive evaluation of subsurface stress features. The details of this method will be described in future publications.

Residual stresses estimated via BNA through the depth and corresponding XRD residual stress measurements are illustrated in Figure 8. Two samples, Sample Ring 5 and Ring 1 Edge, data are used for model calibration. Model calibration is required as changes in permeability, conductivity, and geometry with respect to depth affect the frequency response of the sample and the relationship between Barkhausen noise and residual stress. These non-linear variations can only be accounted for by using measured sample data (XRD residual stress and Barkhausen noise) as a reference. In larger sample sets more samples can be used for calibration to increase the accuracy of the residual stress calculations. The accuracy of these estimations, as well as the range of predictable depths, are limited by material properties in this sample set; high carbon content in 52100 steel decreases sensitivity to changes in microstructure. Also, as all noise signals measured are the aggregate of signals through the maximum depth of emission, sensitivity is lost with increasing depth [4].

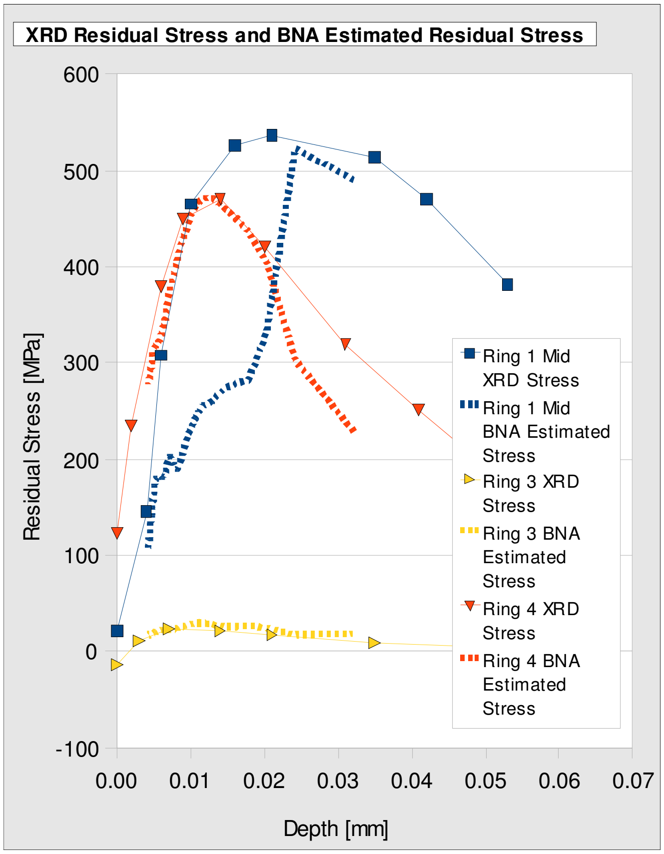

Figure 8 – Residual stress depth profiles measured with XRD and estimated with BNA

Although the exact shape of the stress profile is not preserved in the non-destructive Barkhausen noise estimation the location of features, or peaks in this case, and their magnitudes are estimated to an accurate degree. The estimation via BNA is able to resolve the depth and magnitude of the subsurface stress peak of the Ring 1 Mid sample, thus distinguishing it clearly from the other two samples shown. The BNA stress calculation also correlates well with Ring 3 and Ring 4 XRD residual stress measurements.

CONCLUSION

Barkhausen noise analysis has been an effective tool for evaluating changes in microstructure of ferromagnetic materials, including grinding burn detection, heat treatment evaluation, carburization quality, nitriding case depth, surface residual stresses, and more. Using advanced techniques BNA can also effectively locate and estimate the magnitude of subsurface stress features.

REFERENCES

1. Tiitto, S., Saynajakangas, S. (1975). Spectral Damping in Barkhausen Noise. IEEE Transactions on Magnetics, 11(6)
2. Griffiths, David J., *Introduction to Electrodynamics*, Prentice Hall, New Jersey (1999)
3. Fix, R.M., Tiitto, K., Tiitto, S. (1990). Automated Control of Camshaft Grinding Process by Barkhausen Noise. Materials Evaluation 48(July)
4. Desvaux, S., Gualandri, J., Carrerot, H., Lamare, A., Industrial Application of a Complete Process of Improvement of the High Precision Bearings Service Lif; Pre-stress, Barkhausen Noise. International Conference on Barkhausen Noise and Micromagnetic Testing, 2003.

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ADDITIONAL REFERENCES

[a] Figure from:
http://en.wikipedia.org/wiki/Barkhausen_effect

[b] American Stress Technologies, Inc., Pittsburgh, PA
http://www.stresstechgroup.com

[c] American Stress Technologies, Inc. uses a modern Modified-Psi diffractometer configuration instead of traditional Omega or Psi

DEFINITIONS, ACRONYMS, ABBREVIATIONS

BNA: Barkhausen Noise Analysis

XRD: X-Ray Diffraction

Hysteresis/Hysteretic Process (Magnetic): The lagging of an effect behind its cause, as when the change in magnetism of a body lags behind changes in the magnetic field.

Magnetic Domain: A region in which the magnetic fields of atoms are grouped and aligned.