Detection of surface cracks in ferromagnetic materials by C-scan mapping of residual stresses using Barkhausen emissions

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Abstract
Surface cracks can develop in components due to residual stresses, fatigue, stress corrosion cracking, corrosion fatigue, etc, during service exposure. Different non-destructive testing (NDT) methods are employed to detect and monitor such cracks. Magnetic Barkhausen Noise (MBN) analysis is one such technique that is used for in situ examination of microstructural anomalies or stress patterns. In the present work, we study the applicability of MBN for the detection of surface cracks. A part through surface crack was created by controlled fatigue loading of a martensitic stainless steel plate. The surface of the sample was scanned for BN emissions in incremental steps parallel and perpendicular to the crack. Measurements of MBN signal strength were recorded and assessed. Localized peaks in the MBN values observed whilst scanning sample surface can reveal the presence of flaws. Furthermore, the remnant stress pattern ahead of the crack tip as well as in the wake of the crack can get reflected in the measured MBN values. The observations carried out show that the surface scan carried out with MBN measurements can be a good non-destructive method for in situ NDT to detect and characterize surface cracks.

Disciplines
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ABSTRACT
Surface cracks can develop in components due to residual stresses, fatigue, stress corrosion cracking, corrosion fatigue, etc., during service exposure. Different non-destructive testing (NDT) methods are employed to detect and monitor such cracks. Magnetic Barkhausen Noise (MBN) analysis is one such technique that is used for in situ examination of microstructural anomalies or stress patterns. In the present work, we study the applicability of MBN for the detection of surface cracks. A part through surface crack was created by controlled fatigue loading of a martensitic stainless steel plate. The surface of the sample was scanned for BN emissions in incremental steps parallel and perpendicular to the crack. Measurements of MBN signal strength were recorded and assessed. Localized peaks in the MBN values observed whilst scanning sample surface can reveal the presence of flaws. Furthermore, the remnant stress pattern ahead of the crack tip as well as in the wake of the crack can get reflected in the measured MBN values. The observations carried out show that the surface scan carried out with MBN measurements can be a good non-destructive method for in situ NDT to detect and characterize surface cracks.

I. INTRODUCTION
Surface cracks constitute a type of flaw that can grow to critical size during service of an equipment and therefore can become precursors to premature failures. For timely corrective action, such flaws need to be detected, characterized, evaluated and repaired to ensure continuing safety of installations. Cracks are associated with characteristic stress patterns that depend on their size, configuration, location, loading regime and material properties. Residual stresses are present in the wake of the crack as well as ahead of the crack front even in unloaded condition. Non-destructive testing techniques employed in laboratories and in the field employ X-ray diffraction, eddy currents, Barkhausen emissions, ultrasonics etc. Barkhausen emissions are also sensitive to microstructure, stress environment, chemical inhomogeneity, grain size, surface or near surface stresses resulting from static or dynamic loading. Stress measurements require appropriate calibration of the equipment used. In this work, Barkhausen noise measurements will be used to detect and characterize residual stress patterns in the plastic zone of a part through crack in a steel sample.

A. Barkhausen effect
Barkhausen noise (BN) measurements are susceptible to local chemical inhomogeneity, lattice strain and imperfections that result from thermal or mechanical processing, static or dynamic loading, etc. Residual stresses resulting from stable or unstable crack
growth during fatigue cycling or fracture processes can be evaluated in ferromagnetic materials using BN methods.

The Barkhausen effect, first observed by Heinrich Barkhausen in 1919, is described as sudden magnetization changes that occur when a ferromagnetic material is magnetized using an alternating magnetic field. This phenomenon occurs due to domain level mechanisms such as domain translation and rotation. Domains aligned in the direction of magnetic field, tend to grow favorably in that direction. On encountering pinning sites or at grain boundaries, magnetic domains can undergo translation or rotation, often described via the irreversible and reversible components of magnetization, Fig. 1.

Magnetic domain walls get temporarily immobilized when they encounter defects such as dislocations necessitating higher magnetization field intensities for overcoming the pinning effect. The BN count thus changes in the presence of such pinning sites associated with plastic deformation and accompanying stresses.

B. Plastic deformation and BN mapping

Fatigue cracks get initiated as surface damage accumulates during cyclic loading of components and continue to grow during service. During this growth process, plastic yielding takes place as a result of high levels of stress intensities along the crack front. As cracks continue to grow, plastically deformed zones form in the wake of the growing cracks and remain in the material even after unloading. Bands of plastically deformed material with relatively elevated dislocation density are found on either side of a crack and persist as plastic zones as shown in the schematic, Fig. 2.

The presence of dislocations thus interferes with the domain wall movements in response to applied external magnetic field. The intensity of the Barkhausen emissions that get generated can be related to the level of the dislocation density which in turn depends on the extent of local plastic deformation and corresponding levels of local residual stresses which can be compressive or tensile. Residual stress mapping of the sample surface using Barkhausen noise (BN) measurements can thus help in the detection of plastically deformed material in the shape of narrow bands that accompany fatigue cracks. Once a crack is detected, further analysis of the BN measurements can be carried out to determine the stress profile and characterize the crack further.

In essence, the presence of localized high/low Barkhausen Noise (BN) counts in relation to the background values should make it possible to detect the presence of surface cracks. The conventional methods such as Dye Penetrant Testing, Magnetic Particle Inspection, Ultrasonic A-scan or surface waves have limited effectiveness in detection of small cracks. Barkhausen emission method is amenable to surface stress mapping in C-scans and is cost effective. Through BN measurements depths comparable to the size of shallow surface cracks can be reached. Localized Barkhausen noise measurements can be made with reference to a suitably designed grid in small steps for different directions of magnetization. Anomalies in otherwise uniform MBN values covering the sample surface can be detected in the C-scan representation thereby revealing the presence of the bands of plastic zone and thus of the surface cracks.

II. MATERIAL, MEASUREMENTS AND RESULTS

A. Material properties

A 13% Cr-0.1% C, martensitic stainless steel plate (12 × 80 × 165 mm) in quenched and tempered condition was chosen for the present work. A part through surface crack was introduced by subjecting the sample to fatigue loading on a 100 KN MTS in a three point bend mode to generate a crack about 10 mm long in the center of the sample surface. A thin surface layer was ground off and the
surface was further polished taking care that no additional stresses were introduced. Figure 3, is a micrograph of the steel sample in quenched and tempered condition showing lath martensites with chromium carbide precipitates.

B. Measurement process and results

A schematic of the measurement setup is shown below in Fig. 4. Barkhausen noise measurements were performed at a frequency of 20 Hz using a sinusoidal wave with an amplitude of 6.5 V. The measured signal was filtered using a bandpass filter of 10–1000 kHz.

First, the sample was measured along different directions of magnetization in order to confirm the detectability of the crack presence and examine the corresponding signatures of the MBN patterns.

While assessing the data, several parameters including the BN counts, and other related parameters such as magnetic permeability, coercivity and remanence were examined. As in Ref. 16, the BN count is known to be proportional to the Barkhausen voltage. Thus, the MBN voltage measurements were performed along directions longitudinal and transverse to the crack orientation. A close examination of the BN count, Fig. 5, on approaching and traversing the crack line shows significant change reflective of the presence of the plastic band. Therefore, the crack location, orientation and extremities of a crack can be identified from the BN voltage measurement.

A transverse scan shows uniform values of MBN count typical of a stress-free material until the probe approaches the crack location, Fig. 6, with magnetization perpendicular to the crack plane (transverse).

Scans in radial direction from crack tip outwards show variations in the intensities of BN indicative of corresponding variations in the stress field that the magnetic field encounters, Fig. 7.
III. DISCUSSION AND CONCLUSIONS

MBN measurements in C-scan mode in the plane of the sample surface, covering the area of interest, can reveal the presence of residual stress patterns indicative of the presence of surface opening or near surface cracks. A transverse scan of a parameter perpendicular to the crack plane showed a sharp peak over the crack location.

Further ahead of the crack tips the scans showed varying intensities in transverse, longitudinal and radial scans. The radial scans are indicative of variable stress patterns. The width of the plastic band cover on either sides of the crack within which a sharp MBN peak could be detected indicates that the plastic zone and residual stress effects present in the wake of a crack are spread out over a much wider width compared to the crack thickness and contribute to the intensity of MBN signals and thus its detectability.

The observations indicate that the in situ MBN measurements and examining their 2D patterns and contours in the plane of the sample surface is an excellent tool amenable for detecting surface cracks particularly in the early stages of their development.

The observations made with the help of a typical ferromagnetic material for a known surface crack has thus shown that MBN mapping of a sample surface in C-scan mode can reveal presence of tightly closed small surface cracks and allow their characterization. The method provides a tool for in situ damage assessment of components and equipment in service.

IV. FUTURE WORK

This work was carried out on a crack produced by controlled fatigue loading that was characterized by other methods. It is seen that the MBN measurements and examining them in C-scan representation can provide a novel and cost effective method for experimental detection and characterization of surface cracks. In view of the presence of plastic zone along the crack flanks which actually occupies much larger width than the actual crack thickness, the probability of small surface crack detection gets enhanced. An assessment of the smallest size crack that can be detected through this technique in relation to parameters like distance that separates magnetizing electrodes on the sensor surface, fineness of the grid, intensity of magnetic pulse, etc. may have to be made and verified experimentally. Suitable sensor developments can facilitate scanning, and improved data management can enable effective interpretations thereby making crack detection more effective.

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