Breaking Barriers with Grain-level Non-Destructive Evaluation

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The extensive application of steel in diverse engineering systems has heightened the demand for reliable inspection methods in both pre-service (PSI) and in-service (ISI) scenarios. Among the various non-destructive testing (NDT) methods, Electromagnetic-based NDT techniques, particularly Magnetic Flux Leakage Testing (MFLT) and Eddy Current Testing (ECT), are vital for assessing ferromagnetic materials, offering high sensitivity and non-invasiveness. Various study delves into the operational principles of MFLT and ECT, emphasizing the significance of precise magnetic flux density (MFD) evaluation. While classical electromagnetism describes MFD, magnetic field $\vec{H}$, and magnetization $\vec{M}$ in linear, isotropic media, this model often doesn't align with real-world conditions. Variables like external excitations such as operational stress and temperature variations affect magnetic susceptibility χ_m and can lead to a scenario where $\vec{M}_{eqv}\neq0$ even when $\vec{H}=0$. Neglecting these variations results in substantial errors in NDT measurements. Furthermore, the internal microstructure of a metal influences MFD due to the presence of grain clusters with unique crystallographic lattice orientations. This microstructure, coupled with the alignment of magnetic domains, introduces fluctuations in MFD distribution. While state-of-the-art 2D and 3D imaging techniques are capable of providing precise visualization of MFD within a grain, their utilization in NDT for ISI inspection is impractical. This limitation prompts the development of a new measurement system that can provide a 3D distribution of MFD. To address this need, this study introduces an innovative approach using a three-axis Tunneling Magnetoresistive (TMR) sensor to map the 3D distribution of MFD on a material's surface. By combining TMR data with microscope images, our goal is to visualize the MFD distribution within individual grains. This method offers a comprehensive understanding of the spatial arrangement of the magnetic field before testing, which is expected to provide valuable noise information on the material surface. In addition, it promises to contribute significantly to our comprehension of the fundamental principles governing MFD distribution in ferromagnetic materials.