

Reliability Fatigue Assessment Based on Electromagnetic Features and Stacking Ensemble Learning

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ABSTRACT

Fatigue failure is a common mode of failure in ferromagnetic materials, yet traditional electromagnetic detection techniques and assessment models struggle to accurately estimate fatigue levels. To address this, a reliability method for evaluating the fatigue degree of ferromagnetic materials is proposed in this paper, integrating multi-electromagnetic features with a multi-model stacking ensemble learning approach. Four types of electromagnetic parameters, namely magnetic Barkhausen noise, incremental permeability, tangential magnetic field, and hysteresis loops, are collected as feature parameters. Subsequently, a stacking ensemble learning framework is constructed. Least squares support vector machine models serve as base learners with a multivariate linear regression model serving as the meta-learner. Experimental results on Q345 steel samples demonstrate that the proposed method achieves an average error rate of 7.3% in fatigue degree assessment, enabling early fatigue detection and lifespan prediction for materials.

KEYWORDS

Fatigue Assessment, Ferromagnetic Materials, Multi-Model Fusion, Stacking Ensemble Learning, K-Fold Cross-Validation

INTRODUCTION

Ferromagnetic equipment, subjected to repetitive loads during long-term service, can experience fatigue, leading to sudden fracture failure and catastrophic accidents. Fatigue damage is a common mode of material failure, and conventional non-destructive testing techniques are unable to detect changes in material properties before and during the early stages of fatigue crack formation. Electromagnetic non-destructive testing evaluates changes in the internal microstructure of materials based on variations in their electrical and magnetic properties under the influence of an electromagnetic field. It offers the advantages of convenient implementation and high detection sensitivity (Badyka et al., 2020; Sagar et al., 2022; Silva et al., 2017; Zhang et al., 2023). Currently, common electromagnetic

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non-destructive testing techniques include eddy current testing, magnetic Barkhausen noise (MBN), and magnetic flux leakage (Daniel et al., 2022; Lach et al., 2020; Mustafa et al., 2022).

Currently, scholars have conducted numerous studies on the application of electromagnetic testing techniques for detecting characteristics of ferromagnetic materials. For instance, Faris et al. (2019) proposed a linear scanning method based on scanning feature extraction to detect crack depth and angle and combined it with a back-propagation (BP) network prediction model to establish an evaluation method for outputting crack depth and angle. Gupta et al. (2012) successfully established a constitutive relationship for stainless steel 316 alloy using an artificial neural network model based on thermal stretching tests, accurately predicting the flow stress of 316L stainless steel. Fragassa and Babic (2019) employed three algorithm such as: Random Forest, artificial neural network, and k-nearest neighbors for pattern recognition in the tensile behavior of cast alloys. Kim et al. (2022) utilized ultrasonic technology and machine learning models to classify the thermal aging conditions of stainless steel. Dong et al. (2021) predicted stress in stainless steel materials with high accuracy using a BP neural network algorithm based on MBN signals. Wang et al. (2023) established a machine learning model based on a database of mechanical properties of stainless steel, enabling effective prediction of tensile strength and yield strength. Since various electromagnetic testing methods have their own advantages and disadvantages, reflecting different internal information of materials and yielding distinct electromagnetic characteristics upon measurement, some scholars have also employed multi-feature fusion to obtain more information about the microstructure of materials (Astudillo et al., 2015; Hang et al., 2023), thereby enabling the more accurate prediction of structural damage in materials.

However, the prediction models employed in the aforementioned methods are typically single learning models. While these studies demonstrate the potential of electromagnetic features and machine learning, a significant gap remains in the literature regarding the application of ensemble learning, particularly the stacking framework, for fatigue assessment using multi-electromagnetic features. Single models may not fully capture the complex, non-linear relationships embedded in diverse electromagnetic parameters. The potential of ensemble learning to mitigate model-specific limitations and enhance prediction accuracy and robustness in this specific context remains underexplored. To address this gap, this paper constructs a stacking ensemble prediction model that integrates multiple machine learning algorithms. Utilizing multi-electromagnetic parameters within the stacking ensemble learning framework, the model is specifically designed to assess the fatigue level of ferromagnetic materials. Compared to traditional single-model predictions, the proposed ensemble model demonstrates a significant improvement in prediction accuracy.

Electromagnetic Signal Features Analysis for Fatigue Level Assessment

The microstructure of materials not only determines their electromagnetic properties, but also governs the fatigue damage process (Hu et al., 2023; Kinoshita, 2023). Therefore, electromagnetic characteristics can be utilized to infer the microstructural changes occurring during the fatigue damage process of ferromagnetic materials, enabling early fatigue detection and life prediction of the materials. In our previous study (Wu et al., 2025), by comparing various electromagnetic signals, we found that four parameters, namely MBN, hysteresis loop (BH), magnetic incremental permeability (MIP), and tangential magnetic field (TMF), are closely related to the fatigue level of ferromagnetic materials. These four electromagnetic parameter features were extracted respectively from the MBN signal envelope, BH curve, MIP curve, and harmonic analysis results of TMF, with the respective feature curves illustrated in Figure 1.

MBN is generated by placing a magnetizing coil and a sensing coil on a ferromagnetic material. As the applied current in the magnetizing coil gradually increases, discontinuous changes in magnetic domain walls, which is known as domain wall jumps that can produce transient pulse signals that are captured by the sensing coil. These collected pulse signals constitute what is known as the Barkhausen noise (Nebair et al., 2024). Through the quantitative analysis of MBN signal characteristics, such as

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