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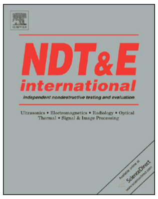

Velocity effect analysis of dynamic magnetization in high speed magnetic flux leakage inspection

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ABSTRACT

The investigation described in this paper focuses on the velocity effect of dynamic magnetization and magnetic hysteresis due to rapid relative motion between magnetizer and measured specimens in high-speed magnetic flux leakage (MFL) inspection. Magnetization intensity and permeability of ferromagnetic materials along with the duration of dynamic magnetization process were analyzed. Alteration of the intensity and distribution of magnetic field leakage caused by permeability of specimen were investigated via theoretical analysis and finite-element method (FEM) combined with the actual high-speed MFL test. Following this, a specially designed experimental platform, in which motion velocity is within the range of 5 m/s–55 m/s, was employed to verify the velocity effect and probability of a high-speed MFL test. Preliminary results indicate that the MFL technique can achieve effective defect inspection at high speeds with the maximum inspection speed of about 200 km/h being verified under laboratory conditions.

1. Introduction

Magnetic flux leakage testing is an efficient electromagnetic non-destructive testing (NDT) [1] technique that has been extensively used for defect inspection and characterization of ferromagnetic materials such as pipelines, pressure vessels, rail tracks and wheels, ropes or cables, etc. Magnetic flux lines generated by a magnetizer are coupled into test specimens with air coupling. Any geometrical discontinuity or local anomalies are manifested as an abrupt change of magnetic permeability [2–4] and force magnetic flux to leak out of the specimen in the poles of yoke in the air. Leakage magnetic field which contains information of defect is collected by magnetic field sensors and used to evaluate the defect dimensions and structural performance. For the advantages of its simplicity, low cost, air coupling and non-contact application, MFL testing is extremely suitable for the automated in-line and real time defect inspection. Some advancing works such as 3-D sensing of magnetic field [5–7], pulsed electromagnetic method (PMFL/PMR) [8–10] and orthogonal magnetization [11] are currently under different stages of development and application for description of the shape and dimensions of defect.

Although this method has a high probability of defect inspection, it still fraught with problems associated with the sensitivity and interpretation of MFL signals to many factors, such as the condition of magnetization, inspection velocity, the B–H curves [4] of a specimen, lift-off, etc. Additionally, a conventional magnetostatic model is unsuitable for the high-speed MFL test. Eddy current distributed in conductors induced by relative movement between the MFL probe and a specimen will alter the profile and intensity of magnetic field leakage and distort the profile of MFL signals [12–17]. It also brings about difficulty in the signal interpretation and description of the defect. The target of improving the probability and accuracy of defect inspection has been attempted in previous work. Many numerical simulations based on 2-D or 3-D transient FEM models were carried out to simulate the distribution of motion-induced eddy currents and analyze their effect on MFL signals [13–20]. In addition, some methods on compensation and velocity invariance of MFL signal to minimize the velocity-induced eddy current effect have been introduced in previous papers [3,17–19]. Motion-induced eddy currents have also been utilized in the description of stress corrosion cracks in terms of measuring perturbation fields [21].

The magnetic flux lines flowing into a test specimen and the magnetization intensity are very important for the sensitivity of MFL signals and the defect inspection ability [2–4]. However, numerical simulation in previous work of the velocity effect only concentrated on the motion-induced eddy current and their influence on MFL signals; the factors of dynamic magnetization and the hysteresis effect during the high speed MFL test were

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neglected. The hysteresis effect exists in the dynamic magnetization process accompanying the magnetic domain rotation and domain wall movements which shows Barkhausen noise (BN) and magnetic hysteresis loop. The duration of the magnetization process decreases with the increase of inspection velocity because of the constant distance between sensor and the starting point of magnetization. If the higher inspection velocity and shorter time of the magnetization process bring about impact on the dynamic magnetization process, magnetization intensity and permeability of specimen as well as leakage magnetic field will be altered. This paper addressed the problem on the velocity effect of dynamic magnetization and magnetic hysteresis during high speed MFL inspection. In dynamic magnetization process, the distribution of magnetic resistance around defect and the velocity effect on specimen permeability and detection signals during the high speed MFL inspection have been analyzed, and verified in FEM simulation and actual high speed test. The rest of this paper is organized as follows: Section 2 describes the theoretical analysis of the dynamic magnetization and its effect on magnetic resistance and field distribution. Section 3 presents FEM simulation on magnetic field leakage along with the permeability of specimen on the basis of magnetization due to velocity effect. Section 4 elaborates on the experimental study with a specially designed high-speed MFL inspection platform. And then, derived conclusions will be given in Section 5.

2. Theoretical analysis of the dynamic magnetization effect

2.1. Ferromagnetic magnetization

Ferromagnetic material is composed of many small spontaneous magnetization areas called magnetic domains, and the transition area between adjacent magnetic domains is called the magnetic domain wall. Magnetic domains distributed in the spontaneous magnetization direction and the ferromagnet do not show magnetism outward when the object is not magnetized. When an extra external magnetic field is applied to the specimen, magnetic domains flip and rotate in the direction of the applied magnetic field accompanied with the domain wall movements. Fig. 1 illustrates the initial magnetization curve [22] of the ferromagnetic material with four stages showing the dynamic change during magnetization and the variation of micro-level magnetic domain and domain wall structures [23]. When all the magnetic moments of domains tends to be consistent with applied magnetic field direction and the magnetization intensity no longer increases, it means that the specimen is to be saturation magnetized.

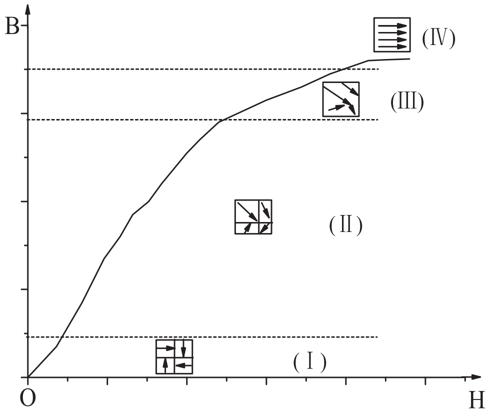

Fig. 1. Initial magnetization curve of the ferromagnetic material, (I) reversible magnetic domain wall motion, (II) irreversible domain wall motion, (III) reversible domain wall motion and domain magnetization rotation, and (VI) only domain magnetization rotation [22].

The magnetization process is governed by the following equations

$$M=\frac{\sum m_0}{V}=\chi_m H \tag{1}$$

$$B=\mu_0 H+\mu_0 M=\mu_0(1+\chi_m)H=\mu_0\mu_r H=\mu H \tag{2}$$

where M, H, B and V, respectively, represent magnetization intensity, magnetic field intensity, magnetic flux density and volume of the magnetized specimen; $\sum m_0$ and χ_m, respectively, are the sum of magnetic moments in a certain volume and the magnetic susceptibility of specimen; μ_0 and μ_r denote the permeability of air and relative magnetic permeability of materials with respect to air, and μ represents the absolute permeability of the medium. During the magnetization process, the variation of magnetic flux density B in a specimen lags behind the applied field H by a phase-shift because of the internal magnetic damping and some energy losses in specimen according to Jiles–Atherton model [24–26] and Landau–Lifshitz–Gilbert (LLG) equation [27,28] which is famous for the description of dynamic magnetization process. After the applied field is revoked, ferromagnetic specimen can still keep part of original magnetism, which is called the magnetic hysteresis phenomenon [29–31]. This phenomenon is the result of irreversible migration of the magnetic domain wall, which is affected by the internal friction of magnetic materials [23], the damping effect of micro eddy currents around a moving domain wall [23], the stress of specimen, material hardness and impurities, lattice defects, and so on. It can cause the resistance of the migration of magnetic domain wall and rotation of magnetic domains. According to the magnetic hysteresis phenomenon, the $\sum m_0$ will be decreased due to the velocity effect of dynamic magnetization. It will lead to the decrease of χ_m and the permeability of magnetized specimen [22–31].

2.2. Dynamic magnetization effect of the high-speed MFL inspection

A conventional MFL testing model [6] using a yoke-electromagnet is illustrated below in Fig. 2. The MFL probe incorporates a magnetizer and the sensor travels on the specimen along the scanning direction at a certain velocity (V). MFL signals are the magnitudes of leakage magnetic field measured by sensors positioned in the middle of the two magnet poles and at a constant distance over specimen (lift-off). The distance between two yoke-electromagnet poles is a constant, represented as L in Fig. 2, which is the valid magnetization distance in MFL inspection. The dynamic magnetization processes during the high speed MFL inspection is like a magnetization with a sinusoidal current of a certain angular frequency $(2\pi)/T$ due to the applied magnetic field induced by a moving yoke-electromagnet. The magnetic field acting on the magnetized specimen first is zero, then increased to the strength of the south-pole, it changes to the strength of the horizontal field between the two poles, and decreases further to the strength of the north-pole before reducing absolutely to zero

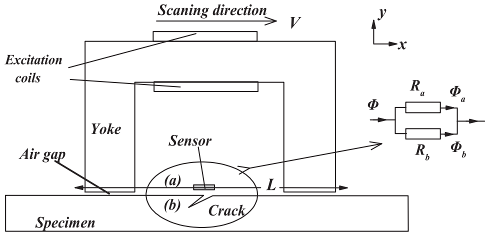

Fig. 2. A conventional magnetic flux leakage testing model [6].