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The effect of temperature on the average volume of Barkhausen jump on Q235 carbon steel

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ABSTRACT

On the basis of the average volume of Barkhausen jump (AVBJ) $\bar{v}$ generated by irreversible displacement of magnetic domain wall under the effect of the incentive magnetic field on ferromagnetic materials, the functional relationship between saturation magnetization M_s and temperature T is employed in this paper to deduce the explicit mathematical expression among AVBJ $\bar{v}$, stress σ, incentive magnetic field H and temperature T. Then the change law between AVBJ $\bar{v}$ and temperature T is researched according to the mathematical expression. Moreover, the tensile and compressive stress experiments are carried out on Q235 carbon steel specimens at different temperature to verify our theories. This paper offers a series of theoretical bases to solve the temperature compensation problem of Barkhausen testing method.

1. Introduction

It has been widely accepted that when incentive magnetic field is applied to ferromagnetic materials, the rotation of magnetic moments and the irreversible displacement of magnetic domain wall (90° and 180° wall) will appear within the ferromagnetic materials [1,2]. These can generate a series of discontinuous irreversible jumps at the steepest position of the hysteresis loop of ferromagnetic materials, known as Barkhausen effect, which was firstly discovered by Heinrich Barkhausen in 1919 [3]. As early as in the 1930s, the Barkhausen irreversible jump had been studied by Bozorth et al. who measured the average volume of Barkhausen jump (AVBJ) $\bar{v}$ in several kinds of metals and alloys, for example, the maximum value of AVBJ $\bar{v}$ in the 50% Fe-50% Ni alloy and the iron is respectively 4×10^{-8} and 10^{-9} cm^3 [4]. On the basis of these researches, we have studied the mathematical relationship between AVBJ $\bar{v}$ and stress σ [5]. It is found that the maximum value of AVBJ $\bar{v}$ monotonously increases with the increasing of tensile stress but decreases with the increasing of compressive stress [6,7] and a tiny stress can already cause to change Barkhausen jump.

However, it is found in practice that the AVBJ $\bar{v}$ is not only influenced by stress σ, but also closely related to temperature T [8]. So far, nevertheless, there are not many researches on how temperature T influences Barkhausen jump and the explicit mathematical expressions for the relationship between AVBJ $\bar{v}$ and temperature T are still lacking.

In this paper, AVBJ $\bar{v}$ and the functional relationship between saturation magnetization M_s and temperature T are adopted to study the theoretical correlation between AVBJ $\bar{v}$ and temperature T. Then an explicit mathematical expression among AVBJ $\bar{v}$, stress σ, incentive magnetic field H and temperature T is derived.

2. Research on the theoretical relationship

In previous researches, the permeability that exists in the process of irreversible displacement of magnetic domain wall was deduced as follows [5],

$$\mu_{irr} = 1 + \chi_{irr} = 1 + \frac{2M_s}{H_0} = 1 + \frac{4\mu_0 M_s^2 l'}{3\pi\lambda_s\sigma\delta} \tag{1}$$

where M_s is saturation magnetization; H_0 is the critical magnetic field of the irreversible displacement; μ_0 represents the space permeability; λ_s denotes the saturation magnetostriction constant of isotropic material; σ is the maximum stress (amplitude) of ferromagnetic materials, including internal and external stress; l' is the displacement distance of magnetic domain wall; δ is a constant and can be expressed as $\delta = \sqrt{A_1/K_1}$, here A_1 and K_1 denote respectively the exchange integral constant and magnetocrystalline anisotropy constant.

According to formula (1) and the research on discontinuous

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irreversible Barkhausen jumps by Bozorth et al., the mathematical expression among AVBJ $\bar{v}$, stress σ and incentive magnetic field H is obtained [5], given as follows,

$$\bar{v} = \frac{0.2l\mu_r \overline{i^2}}{A^2\rho B_S\{1 + [4\mu_0 M_s^2 l'/3\pi\lambda_s\sigma\delta]\}dH/dt} \tag{2}$$

where l is the length of induction coil influenced by Barkhausen jump in ferromagnetic specimen, the induction coil is used to receive the Barkhausen jump signal; A denotes the line constant of experimental apparatus; ρ is the resistivity of ferromagnetic specimen; $B_S = 4\pi I_S$, here I_S denotes the spontaneous magnetization; dH/dt represents the change rate of incentive magnetic field; μ_r is the reversible permeability of ferromagnetic specimen. According to magnetic theory [9], μ_r is related to inductance L as follows,

$$\mu_r = \lim_{\Delta H \to 0} \frac{\Delta B}{\mu_0 \Delta H} = \frac{Ll}{\mu_0 s N^2} \tag{3}$$

where ΔH and ΔB respectively denotes the variations of magnetic field and magnetic flux; s is the cross-sectional area of ferromagnetic specimen; N is the number of turns of induction coil. So the reversible permeability μ_r can be measured indirectly through the corresponding inductance L.

Note that $\overline{i^2}$ represents the average square current generated by Barkhausen jump and it can be measured with the experimental apparatus [5]. It can be presented in the following from,

$$\overline{i^2} = \frac{2n\rho A^2 s}{\mu_r} \cdot \mu_{irr}^2 \overline{(\Delta H)^2} = \frac{2n\rho A^2 s}{\mu_r}\left(1 + \frac{4\mu_0 M_s^2 l'}{3\pi\lambda_s\sigma\delta}\right)^2 \overline{(\Delta H)^2} \tag{4}$$

where n is the number of Barkhausen jump in unit time; $\overline{(\Delta H)^2}$ denotes the average square value of variation of incentive magnetic field. According to ferromagnetism theory [10], the saturation magnetization M_s and temperature T have the following functional relationship,

$$M_s = M_0 B_J(T) \tag{5}$$

where M_0 denotes the maximum value of saturation magnetization; $B_J(T)$ is the Brillouin function [11,12] and it is expressed as follows,

$$B_J(T) = \frac{2J+1}{2J} cth\left(\frac{(2J+1)g_J\mu_B\gamma M}{2\kappa T}\right) - \frac{1}{2J} cth\left(\frac{g_J\mu_B\gamma M}{2\kappa T}\right) \tag{6}$$

where J is the total azimuthal quantum number of atom; g_J and μ_B respectively represent the Landé factor and Bohr magneton; γ represents the molecular field coefficient; κ is Boltzmann constant; M is the spontaneous magnetization of ferromagnetic specimen. Form formula (6) one can see that,

when $T \to \infty$, $B_J(T) \cong 0 \Rightarrow M_S \to 0$,

when $T \to 0$ $B_J(T) \cong 1 \Rightarrow M_S \to M_0$.

Substituting formulas (4) and (5) into formula (2), the relationship among AVBJ $\bar{v}$, stress σ, temperature T and incentive magnetic field H is obtained as follows,

$$\bar{v}(\sigma, T, H) = \omega\left(1 + \psi\frac{B_J^2(T)}{\sigma}\right)\overline{\Delta H^2} \tag{7}$$

Here, ω and ψ are respectively written as follows,

$$\begin{cases} \omega = \dfrac{nsl}{10\pi I_s(dH/dt)} \\ \psi = \dfrac{4\mu_0 l' M_0^2}{3\pi\delta} \end{cases} \tag{8}$$

Formula (7) indicates that the value of Brillouin function $B_J(T)$ decreases with the increasing of temperature T; accordingly AVBJ $\bar{v}$ decreases as well. Conversely, AVBJ $\bar{v}$ increases with the decreasing of temperature T. It should be note that the precondition of above analysis is that the temperature T is less than Curie temperature of ferromagnetic materials. When T equals or exceeds Curie temperature, the ferromagnetic materials will translate into paramagnetic materials [13,14]. Therefore, the corresponding AVBJ $\bar{v}$ closes to zero, because the effect of particle exchange within ferromagnetic materials is completely offset by thermal motion. Formula (7) expresses the relationship between AVBJ $\bar{v}$ and temperature T and offers guidance and reference for the solution of temperature compensation problem of Barkhausen method that is adopted to detect stress in engineering application.

3. The effect of temperature T on AVBJ $\bar{v}$

Without the effect of stress, according to formula (7), the relationship curve between the maximum value of AVBJ $\bar{v}$ and temperature T is drawn in Fig. 1.

Here the critical magnetic of ferromagnetic materials is adopted as the incentive magnetic field. Fig. 1 indicts that the maximum value of AVBJ $\bar{v}$ decreases with the increasing of temperature T. Furthermore, the higher temperature will lead to the more obvious decreasing trend of the maximum value of AVBJ $\bar{v}$, namely the value of $d\bar{v}/dT$ will be enhanced with the increasing of temperature. Utilizing formula (7) to plot the relationship curve between the maximum value of AVBJ $\bar{v}$ and stress σ at different temperature, as shown in Fig. 2.

It can be found that the maximum value of AVBJ $\bar{v}$ monotonically increases with the increasing of tensile stress and monotonically decreases with the increasing of compressive stress. When temperature is 20 °C and tensile stress increases to 100 MPa, the maximum value of AVBJ $\bar{v}$ tends to saturate. Compared with the tensile stress curve, the compressive stress curve is easier to saturate (e.g., the compressive stress curve already saturates under 80 MPa at 20 °C) and the corresponding Barkhausen jump is asymmetric under the effect of tensile and compressive stress. The reason is that the Bauschinger effect occurs during the repetitive tensile and compressive process [15,16]. As shown in Fig. 2, the temperature interval is 20 °C, but the spacings of tensile and compressive stress curves at different temperature are unequal. With the temperature increasing, the corresponding spacing of stress curves will gradually increase.

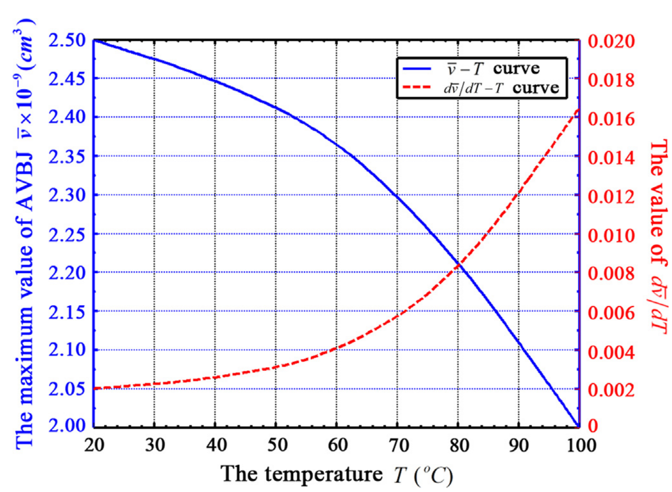

Fig. 1. The relationship curve between the maximum value of AVBJ $\bar{v}$ and temperature T.