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# The effect of stress and incentive magnetic field on the average volume of magnetic Barkhausen jump in iron

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ABSTRACT

The average volume of magnetic Barkhausen jump (AVMBJ) $\bar{v}$ generated by magnetic domain wall irreversible displacement under the effect of the incentive magnetic field $H$ for ferromagnetic materials and the relationship between irreversible magnetic susceptibility $\chi_{irr}$ and stress $\sigma$ are adopted in this paper to study the theoretical relationship among AVMBJ $\bar{v}$(magneto-elasticity noise) and the incentive magnetic field $H$. Then the numerical relationship among AVMBJ $\bar{v}$, stress $\sigma$ and the incentive magnetic field $H$ is deduced. Utilizing this numerical relationship, the displacement process of magnetic domain wall for single crystal is analyzed and the effect of the incentive magnetic field $H$ and the stress $\sigma$ on the AVMBJ $\bar{v}$ (magneto-elasticity noise) is explained from experimental and theoretical perspectives. The saturation velocity of Barkhausen jump characteristic value curve is different when tensile or compressive stress is applied on ferromagnetic materials, because the resistance of magnetic domain wall displacement is different. The idea of critical magnetic field in the process of magnetic domain wall displacement is introduced in this paper, which solves the supersaturated calibration problem of *AVMBJ*$-\sigma$ calibration curve.

## 1. Introduction

In the process of alternating magnetization, the hysteresis loop of ferromagnetic materials is not smooth and the continuously irreversible jumps appear in the steepest position of the hysteresis loop [1,2]. This is known as the Barkhausen effect. According to Faraday's law of induction, the impulse voltage signal can be received by the pick-up coil on the surface of ferromagnetic materials, which is known as the magneto-elasticity noise. Now it has been accepted that the magneto-elasticity noise is generated by the irreversible displacement of $90^0$ and $180^0$ magnetic domain wall and the rotation of magnetic moments [3,4]. As early as in the 1930s, Barkhausen irreversible jump had been studied by Bozorth–Dillinger AVMBJ $\bar{v}$ in several kinds of metals and alloys have also been measured, indicating that the maximum average volume of magnetic Barkhausen jump (MAVMBJ) in the 50% Fe–50% Ni alloy and the iron is $4 \times 10^{-8}$ and $10^{-9}$ cm$^3$, respectively [5].

In recent years, scholars have carried out a series of theoretical study in depth on Barkhausen effect, especially in the field of the metallographic structure analysis of materials, the grain size measurement and the distribution testing of defects and stress, and the using of Barkhausen effect has become research hot issues [6–9]. However, there are still some puzzles in the theoretical model of Barkhausen jump, particularly for the map relation between Barkhausen jump signal and stress within materials. This relation can be adopted as the theory basis of numerical calibration for Barkhausen noise characteristic value and stress change in the engineering application. Moreover, the relation can also provide guidance and reference to obtain the *AVMBJ*$-\sigma$ calibration curve. This relationship is widely used in engineering practice [10–13], but the theoretical relationship is not very clear yet.

In this paper, the relationship among the AVMBJ $\bar{v}$, stress $\sigma$ and incentive magnetic field $H$ has been researched. Utilizing the relationship among irreversible jump critical magnetic field $H_0$, irreversible magnetic susceptibility $\chi_{irr}$ and stress $\sigma$ [14], and introducing the AVMBJ $\bar{v}$ of magnetic domain irreversible displacement, ultimately the theoretical relationship of the AVMBJ $\bar{v}$, stress $\sigma$ and incentive magnetic field $H$ is built to analyze the process of irreversible displacement of domain wall and the production conditions of Barkhausen jump. This theoretical relationship can also be utilized to analyze the effect of stress $\sigma$ and incentive magnetic field $H$ on the AVMBJ $\bar{v}$.

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## 2. Research on the theoretical relationship

According to Bozorth–Dillinger's research results on the Barkhausen irreversible jump, the AVMBJ $\bar{v}$ is expressed as follows [5]:

$$\bar{v} = \frac{0.2 l \mu_r \bar{i^2}}{A^2 \rho B_S \, \mathrm{d}B/\mathrm{d}t} \tag{1}$$

Here,

$$B_S = 4\pi I_S \tag{2}$$

where $A$ denotes the line constant; $\rho$ is the resistivity of specimens; $I_S$ is spontaneous magnetization intensity; $\mathrm{d}B/\mathrm{d}t$ is the change rate of the magnetic induction intensity; $l$ is the length of induction coil that is influenced by Barkhausen jump in specimens; $\mu_r$ is the reversible magnetic permeability; $\bar{i^2}$ is the average square current generated by the Barkhausen jump.

The average square current $\overline{i^2}$ is obtained by measurement in experiment, and the corresponding experimental apparatus is shown in Fig. 1. By gradually enhancing the incentive magnetic field $H$, the Barkhausen jump within the specimen will generate pulse current $i$ in the induction coil. The exciting circuit generates a sine wave incentive signal and its amplitude is ± 10 V. By changing the number of magnetizing coils $m$, the intensity of incentive magnetic field $H$ is changed. In order to study the effect of stress $\sigma$ on the AVMBJ $\bar{v}$, the tensile and compressive stress are applied to the ends of the specimen.

The total volume of specimens in the induction coil is $V$ and cross-sectional area is $s$. The magnetic reversal volume generated by one Barkhausen jump is $v$, the corresponding change of irreversible magnetic flux is $\Delta\Phi$, and the number of Barkhausen jump in unit time is $n$. Thus, the current $i$ in the induction coil is written as follows:

$$i = As\Delta B f(t) = 8\pi I_s s A v f(t)/V \tag{3}$$

where $f(t)$ is the function which reflects the current $i$ change with time. According to the eddy-current change of cylinder, the following relation can be obtained:

$$\begin{cases} \int_{-\infty}^{+\infty} f(t)\mathrm{d}t = 1 \\ \int_{-\infty}^{+\infty} f^2(t)\mathrm{d}t = 2\rho/s\mu_r \end{cases} \tag{4}$$

The average current $\bar{i}$ and average square current $\overline{i^2}$ are respectively written as,

$$\bar{i} = n\int_{-\infty}^{+\infty} i\mathrm{d}t = nAs\bar{\Delta B}\int_{-\infty}^{+\infty} f(t)\mathrm{d}t = 8\pi I_s sA\bar{v}n/V \tag{5}$$

$$\begin{aligned} \bar{i^2} &= n\int_{-\infty}^{+\infty} i^2\mathrm{d}t \\ &= nA^2s^2(\bar{\Delta B})^2\int_{-\infty}^{+\infty} f^2(t)\mathrm{d}t \\ &= 2n(8\pi I_s A\bar{v}/V)^2(\rho s/\mu_r) \end{aligned} \tag{6}$$

$\overline{i^2}$ includes $(\bar{\Delta B})^2$. When substituting formula (6) into (1), it can be found that a direct proportion relationship exists between the AVMBJ $\bar{v}$ and $(\bar{\Delta B})^2$.

In order to investigate the theoretical relationship between stress $\sigma$ and the AVMBJ $\bar{v}$, the relationship of magnetic induction intensity and magnetic field intensity is applied and the irreversible permeability of domain wall displacement process is given as follows:

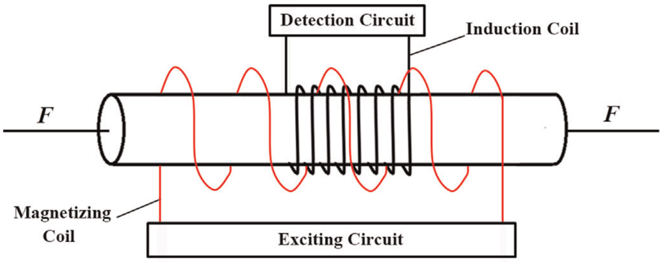

**Fig. 1.** The schematic diagram of experimental apparatus.

$$\mu_{irr} = 1 + \chi_{irr} = 1 + \frac{2M_s}{H_0} = 1 + \frac{4\mu_0 M_s^2 l'}{3\pi\lambda_s(\sigma_{in} + \sigma_{out})\delta} \tag{7}$$

Here,

$$\delta = \sqrt{A_1/K_1} \tag{8}$$

and $M_S$ is saturation magnetization; $H_0$ is critical magnetic field for the irreversible displacement of domain wall; $\mu_0$ denotes the permeability of vacuum; $\lambda_S$ represents the saturation magnetostriction constant in isotropic material; $\sigma_{in}$ is the maximum stress (amplitude) within materials and the $\sigma_{out}$ represents the maximum external stress (amplitude) applied to materials; $l'$ is the displacement distance of domain wall; $A_1$ and $K_1$ respectively denotes the exchanged integral constant and magnetocrystalline anisotropy constant.

Substituting formula (7) into (1), the following can be obtained,

$$\bar{v} = \frac{0.2 l \mu_r \bar{i^2}}{A^2 \rho B_S\left\{1 + \left[4\mu_0 M_s^2 l'/3\pi\lambda_s(\sigma_{in} + \sigma_{out})\delta\right]\right\}\mathrm{d}H/\mathrm{d}t} \tag{9}$$

Formula (9) gives out the theoretical relationship among AVMBJ $\bar{v}$, stress $\sigma$ ($\sigma = \sigma_{in} + \sigma_{out}$) and the incentive magnetic field $H$ where $\sigma_{in}$ represents structural or residual stress of material. When the external stress $\sigma_{out}$ is not applied to the materials, the theoretical relationship between AVMBJ $\bar{v}$ and incentive magnetic field $H$ is given as follows:

$$\bar{v} = \frac{0.2 l \mu_r \bar{i^2}}{A^2 \rho B_S\left[1 + \left(4\mu_0 M_s^2 l'/3\pi\lambda_s\sigma_{in}\delta\right)\right]\mathrm{d}H/\mathrm{d}t} \tag{10}$$

Formula (10) indicates that the Barkhausen jump signal could be received by pick-up coil, regardless of whether the external stress exists. That is to say that the generation of Barkhausen jump signal is not related to the external stress and the incentive magnetic field $H$ is the fountainhead for the generation of Barkhausen jump.

Formula (9) is the theoretical relationship proposed in this paper, which reflects the map relation among stress $\sigma$, incentive magnetic field $H$ and AVMBJ $\bar{v}$. When incentive magnetic field $H$ and AVMBJ $\bar{v}$ are given, the external stress $\sigma_{out}$ can be solved according to this theoretical relationship. If the incentive magnetic field $H$ is constant, the Barkhausen jump characteristic value depends on how much stress is applied to ferromagnetic materials.

Thus this theoretical relationship in the paper provides a new method for detecting the external stress $\sigma_{out}$. Besides, in the engineering application of Barkhausen method, this theoretical relationship also provides reference for the calibration of Barkhausen jump signal ($AVMBJ-\sigma$).

## 3. Analysis of the displacement process of domain wall

Formula (9) is adopted to analyze the displacement process of domain wall for single crystal that is under the effect of stress and