# Calculation of Basic Domain Width Considering Lancet Domains in (110)[001]Fe3%Si

Kejii Iwata[1,2], Satoshi Arai[1] and Kazushi Ishiyama[2]
[1]Nippon Steel & Sumitomo Metal Corporation,Futtsu,Chiba 293-8511,Japan
[2]Research Institute of Electrical Communication,Tohoku University,Aoba Sendai 980-8577,Japan
E-mail: iwata.24h.keiji@jp.nssmc.com

***Abstract*—This paper presents the calculation method of basic domain width in demagnetized states of (110)[001]Fe3%Si under tensile stress in the range of the occurrence of lancet domains. Previously, stripe domain models, under enough strong tensile stress to annihilate lancet domains, were used so that the discrepancy between the calculated width and the observed width under tensile stress in which lancet domains occur became large. Applying the decrease of the surface magnetic charge by lancet domains to calculations of the stray field energy of basic domains enables us to accurately evaluate not only the 180° basic domain width under tensile stress but also the eddy current losses.**

***Index Terms*—Magnetic domains, steel, stress**

## I. Introduction

Fe3%Si is an industrially important soft magnetic material used in the cores of transformers and motors. Recently, the further reduction of iron loss has been required to save energy. It is well known that iron loss and the magnetostriction of Fe3%Si are caused by the behavior of magnetic domain structures that depend on various material conditions, for example, the orientation of crystals, stress, and surface conditions, etc. (110)[001]Fe3%Si has relatively simple magnetic domain structures that mainly consist of 180° basic domains and lancet domains. Therefore, numerous calculation models based on magnetic domains have been investigated to predict the magnetic properties of (110)[001]Fe3%Si in the past [1]-[7]. Furthermore, the accurate estimation of 180° basic domain width in demagnetized states would enable us to predict anomalous eddy current losses [2],[7]-[8].

This paper presents the calculation method of basic domain width in demagnetized states of (110)[001]Fe3%Si under tensile stress in the range of the occurrence of lancet domains. Previously, the analytical calculation of 180° basic domain width in (110)[001] Fe3%Si with a tilt angle of [001] out of the sheet surface β has been performed, for example, in [1]-[2]. The stripe domain model was used in this example, under enough strong tensile stress to annihilate lancet domains. The calculations show the tendency that the basic domain width decreases inversely with increasing β, similar to the well-known experimental phenomenon. However, the quantitative discrepancy between the calculated basic domain width and the one observed under practical tensile strength in which lancet domains occur became large. This is because the existence of lancet domains, which is affected by not only β but also stress, is not considered in the previous models at all. Calculation models for lancet domains have been investigated, for example, in [3]-[6]. The model of [3] is mathematically simplified and is independent of stress. In [4], details for single lancets are discussed. This model is also independent of stress and needs domain observation data. On the other hand, the lancet structure in [5]-[6] is theoretically optimized by energy minimization without using domain observation data and also depends on stress. However, the models are such that lancet domains exist in the single basic domain with infinity width.

In the present method, we adopt a calculation model that combined the lancet domains model in [5] and the stripe domains model with finite width. The surface magnetic charge of Fe3%Si would decrease if lancet domains occur. The stray field energy is calculated considering the decrease of the surface magnetic charge by lancet domains. Then, the 180° basic domain width and the configuration of magnetizations are optimized so as to minimize the magnetic Gibbs free energy. Our present method can be applied to not only plane sheets but also any shaped sheets because of using the finite element method.

## II. Computation method

The calculation model of lancet domains proposed in [5] is shown in Fig. 1. This model contains the lancet width $W$, the lancet length $L$, and the lancet period $P$ as three unknown parameters. The total energy of lancet domains per unit surface $E_{\mathrm{Lancet}}$, which consists of the surface stray field energy of the lancet domain $E_{stL}$, the 180° domain wall energy $E_{180L}$, the 90° domain wall energy $E_{90L}$, and the magnetoelastic energy $E_{\mathrm{elL}}$, is represented as follows.

$$E_{Lancet} = E_{stL} + E_{180L} + E_{90L} + E_{elL} \qquad (1)$$

$$E_{stL} = \frac{{M_s}^2}{2\mu_0}\frac{\beta^2(1-V)^2}{\mu^*} + \frac{{M_s}^2\beta^2 L}{\mu_0\,(1+\mu^*)d}\,q(V,e),$$

$$E_{180L} = 2\sqrt{2A_sK_c}\,\frac{V}{d}\,f(e)g(e)\,,\ E_{90\mathrm{L}} = \frac{1.42}{L}\,2\sqrt{2A_sK_c}\,,$$

$$E_{\mathrm{elL}} = \frac{3}{2}\lambda_{100}\sigma_{\mathrm{u}}\sqrt{2}\,\beta\,V,$$

$$V = \frac{W}{P},\ \ \mu^* = 1 + \frac{{M_s}^2}{2\mu_0 K_c}\,,\ e = \frac{W}{2L\beta} - 1$$

Where $\mu_0$ is the vacuum permeability, $M_s$ is the saturation magnetization, $A_s$ is the stiffness constant, $K_c$ is the cubic anisotropic constant, $d$ is the thickness of the specimen, $\lambda_{100}$ is the magnetostriction constant of Fe3%Si, and $\sigma_{\mathrm{u}}$ is the tensile stress. The details for $q(V,e)$, $f(e)$ and $g(e)$ are described in [5]. In our present method, three unknown parameters, $W$, $L$, $P$, are decided so as to minimize $E_{\mathrm{Lancet}}$ using Powell's method. It can be considered that when lancet domains occur, the surface magnetic charge decreases from $M_s\sin\beta$ to $(1\text{-}V)M_s\sin\beta$. Therefore, unless this decrease of surface magnetic charge is considered, the calculated values of the 180° basic domain width in Fe3%Si would result in smaller values than the experiments because the stray field energy of the basic domain is overestimated.

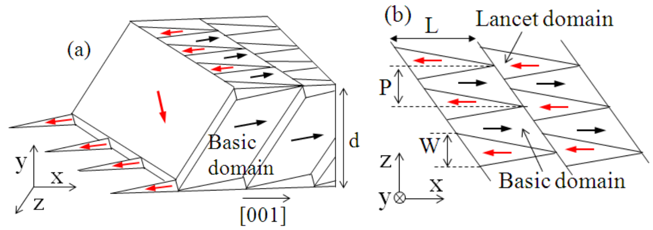


Fig. 1. (a) Calculation model of lancet domains, (b) surface of lancet domains

The 180° basic domain width and the equilibrium configuration of the magnetizations in the demagnetized state have the property to minimize the magnetic Gibbs free energy of the basic domains per unit volume.

$$E_{basic} = \frac{1}{2\mu_0}\int (\nabla \times \boldsymbol{A} - M_s \boldsymbol{m})^2 dV + K_c \sum_{i,j} \int \alpha_i^2 \alpha_j^2 \, dV + \frac{4\sqrt{A_s K_c}}{D_w \cos 32^\circ} - \frac{3}{2} \lambda_{100} \sum_i \sigma_{ii} \left( m_i^2 - \frac{1}{3} \right) \quad (2)$$

Where, $\boldsymbol{m}$ is the unit vector, $\alpha$ denotes the angle between $M_s \boldsymbol{m}$ and the easy axis, $\sigma_{ii}$ denotes the stress tensor, and $D_w$ is the 180° basic domain width in demagnetization state. The first part shows the stray field energy of the basic domains represented by the magnetic vector potential $\boldsymbol{A}$ [9]. The second, third, and fourth part respectively show the magnetic domain wall energy, magnetocrystalline anisotropic energy, and magneto-elastic energy. The bowling of the domain wall [10] is ignored. $\boldsymbol{m}$ is represented using polar coordinates. The system is discretized into hexahedral elements, and $\boldsymbol{A}$ is approximated by vector interpolation functions. $E_{basic}$ is minimized with respect to the configuration of $M_s\mathbf{m}$, $\boldsymbol{A}$, and $D_w$ by the conjugate gradient method. If the $M_s$ of Fe3%Si is inserted into (2) as usual, $D_w$ would become narrower than the observed values because the decrease of the surface magnetic charge by the occurrence of the lancet domain is not considered. The minimization of (2) makes $M_s\mathbf{m}$ relax due to the surface stray field and the influence of the easy axis. This corresponds to the μ*-correction. Therefore, in order to consider the decrease of the surface magnetic charge by the lancet domain, we substituted $(1\text{-}V)M_s$, where $V=W/P$ is obtained by the structure optimizations of the lancet domain, for $M_s$ in (2). This approach also makes it possible to deal with the effect of the stress because the $V=W/P$ of the lancet domain model depends on the stress imposed on Fe3%Si.

## III. Results and Discussion

Fig 2 shows the calculated surface area ratio of the lancet domains in Fe3%Si against β under the tensile stress of 4.9 MPa, 9.8 MPa, and 14.7 MPa, in which lancet domains occur when β is beyond about 1.1°, 1.3°, and 1.55°, respectively. Based on these results, $D_w$ was calculated according to our present method. Fig 3 shows that comparison of the calculated $D_w$ with experimental values under 14.7 MPa in [1]. This calculated $D_w$ is quantitatively in good agreement with the observed domain width compared with values by previous methods [1]-[2]. Especially, our calculations are improved in the range of β above about 3°. This indicates that our method can correctly take into account the decrease of the surface magnetic charge that occurred due to lancet domains and the influence of tensile stress. As the result, our present method makes it possible to accurately evaluate the stray field energy of Fe3%Si. Fig 3 also shows the dependence of $D_w$ on the tensile stress against β. It is indicated that when tensile stress becomes stronger, $D_w$ is refined with increasing β.

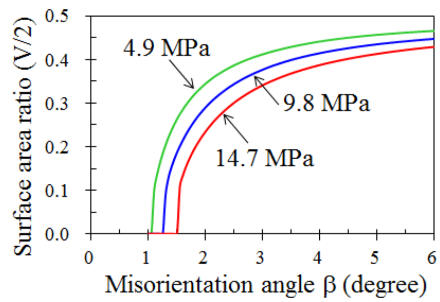


Fig. 2. Calculated surface area ratio of lancet domains; *d* is 200 μm.

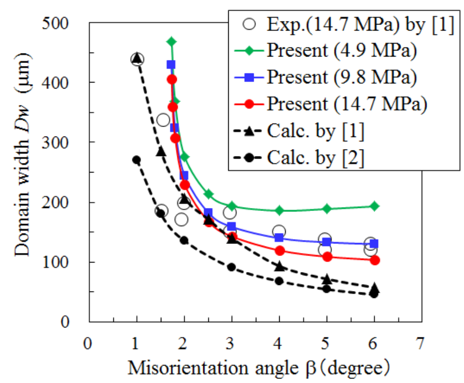


Fig. 3. Comparison between the calculated and experimental domain width

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