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Effects of laser irradiation on iron loss reduction for Fe–3%Si grain-oriented silicon steel

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Abstract

The effects of laser irradiation on iron loss reduction for Fe–3%Si grain-oriented silicon steel sheet were investigated. The local tensile residual stress states near the laser irradiated cavity lines were observed by using the new X-ray stress measurement method for a single crystal. Although the higher laser power induced the larger tensile residual stresses, the minimum iron loss was obtained at the medium tensile residual stress conditions of about 100–200 MPa. The increase of Vickers hardness was observed with increasing laser power, which was the mark of the plastic deformations induced by the laser irradiation. The tensile residual stress reduces eddy current loss and the plastic deformation increases hysteresis loss of the material. The total iron loss is determined by the balance of these two effects of laser irradiation.

Keywords: Grain-oriented silicon steel; Laser treatment; Residual stresses; Magnetic domain; Hardness

1. Introduction

Fe–3%Si grain-oriented silicon steel, consisting of $\{110\}\langle 001\rangle$ oriented large grains, has been widely used for transformer cores. The reduction of iron loss is one of the most important industrial issues and lower iron loss materials have been developed by improving $\{110\}\langle 001\rangle$ alignment, making thinner-gauge sheet and refining magnetic domain wall spacing [1]. In particular, the magnetic domain-refining techniques, such as laser-irradiation [2], groove-forming [3] and etching [4] techniques have been developed over the past 20 years and are known to be very effective for refining magnetic domain wall spacing and hence reducing iron loss. It has been speculated that the induced tensile stresses [5] or recrystallized micro grains [6] might be the origin of the magnetic domain refining. Very recently, the present authors have developed a new X-ray measurement method of a plane stress state for a single crystal [7,8] and showed for the first time that local residual tensile stresses are induced in laser-irradiated Fe–3%Si grain-oriented silicon steels [9]. It was supposed that the local residual tensile stresses change the magnetic anisotropy of the material and destabilize the magnetic domains along the rolling direction so as to refine the domains. However, a precise study of the effects of laser irradiation on the reduction of iron loss has not been carried out hitherto.

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In this paper, the residual stress distributions of a plane stress state in laser-irradiated Fe–3%Si grain-oriented silicon steel sheet were measured with various laser irradiation conditions by the newly developed X-ray stress measurement method for a single crystal. We investigated the relationship between the iron core loss and the residual stress distributions and the deformations in order to clarify the mechanism of iron loss reduction by laser irradiation on this material.

2. Experimental

2.1. Sample preparation

A single crystal grain of 30×15 mm^2 was prepared by cutting from a Fe–3%Si grain oriented silicon steel sheet of 0.23 mm thick for the X-ray stress measurements. The oxide coating films on the sheet were removed beforehand. The length direction of the specimen (30 mm) was set to be parallel with the rolling direction (RD) of the sheet. Then, the specimen was annealed at 1027 K for 2 h in pure hydrogen in order to remove the effect of cutting. Four dotted cavity lines were formed in air along the transverse direction (TD) by using Nd:YAG laser with the energy levels of 1.6, 3.3, 4.9 and 6.6 mJ/pulse. The pitch of the lines was 6.0 mm. Fig. 1 shows the schematic illustration of the specimen used in this study. Although the grain-oriented silicon steel is manufactured to be highly aligned in $\{110\}\langle 001\rangle$ direction, each grain has its individual orientation. The orientation of the specimen determined by Laue method was $\{50\,66\,3\}\langle -10\,12\,7\rangle$, which is very close to the ideal orientation, $\{110\}\langle 001\rangle$ in this study.

Fe–3%Si grain oriented silicon steel sheets of $60 \times 300 \times 0.23$ mm^3 were used for the specimens of magnetic measurements. These sheets were also annealed at 1027 K for 2 h in pure hydrogen before the laser-irradiation. Nd:YAG pulsed laser was irradiated on the surface of each sheet with the energy levels of 0.3–9.0 mJ/pulse in 6.0 mm pitch along TD.

2.2. X-ray stress measurement

The $\sin^2\psi$ method [10] has been commonly used to investigate the stress states in various materials. This method cannot be applied, however, for the stress measurements in coarse grains or single crystals because this method is based on the assumption of randomly oriented elastic polycrystalline material. In principle, we can obtain the stress state in a single crystal, when the absolute lattice displacements of the several directions can be measured precisely. It is difficult, however, to determine the reliable lattice spacing in the stress-free condition. Several methods, such as the pseudo-Kössel pattern [11] or Debye ring measurements [12], have been examined for this purpose, but have not come into wide use. Recently, Yoshioka et al. [13] proposed a unique and practical X-ray stress measurement method for a single crystal. Very recently, Suzuki et al. [7–9,14–16] have refined this method so as to improve the accuracy of the measurement and data analysis and succeeded in determining the stress states in single crystal Si and Fe–3%Si grain-oriented silicon steel.

The following is the essential points of the stress measurement method for a cubic single crystal applied in this study. Fig. 2 shows a crystal coordinate system X_i, a laboratory coordinate system L_i and a specimen coordinate system P_i. ϕ and ψ are the rotation angle between P_1 and L_1 and P_3 and L_3, respectively. A lattice strain of nth plane, $\varepsilon^L_{33(n)}$ in the L_3 direction on the laboratory coordinate system in the plane stress condition is expressed with the stress components σ^S_{11}, σ^S_{12} and σ^S_{22} on the specimen coordinate system by the following equation [14]:

$$\begin{aligned}\varepsilon^L_{33(n)} &= -(\theta_n - \theta_0)\cot\theta_0 \\ &= \left(S_{11} - S_{12} - \tfrac{1}{2}S_{44}\right)\left[(\gamma^2_{31}\pi^2_{11} + \gamma^2_{32}\pi^2_{12} + \gamma^2_{33}\pi^2_{13})\sigma^S_{11}\right. \\ &\quad + 2(\gamma^2_{31}\pi_{11}\pi_{12} + \gamma^2_{32}\pi_{12}\pi_{22} + \gamma^2_{33}\pi_{13}\pi_{23})\sigma^S_{12} \\ &\quad \left.+ (\gamma^2_{31}\pi^2_{21} + \gamma^2_{32}\pi^2_{22} + \gamma^2_{33}\pi^2_{23})\sigma^S_{22}\right] + S_{12}(\sigma^S_{11} + \sigma^S_{22}) \\ &\quad + \tfrac{1}{2}S_{44}(\sigma^S_{11}\sin^2\phi - \sigma^S_{12}\sin 2\phi + \sigma^S_{22}\cos^2\phi)\sin^2\psi \\ &= A_n\sigma^S_{11} + B_n\sigma^S_{12} + C_n\sigma^S_{22}, \qquad (1)\end{aligned}$$

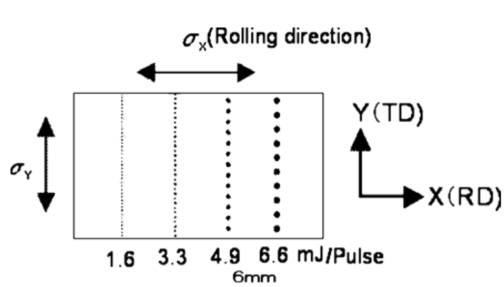

Fig. 1. Schematic illustration of laser-irradiated grain-oriented silicon steel used in this study.

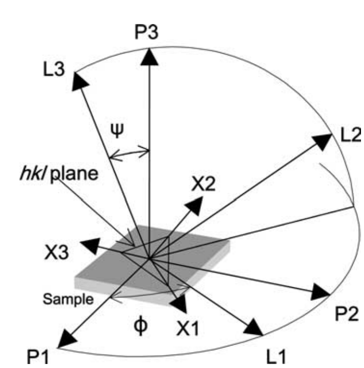

Fig. 2. Relationship between a crystal coordinate system X_i, a laboratory coordinate system L_i and a specimen coordinate system P_i.