A low-field scaling rule of minor hysteresis loops in plastically deformed steels

Satoru Kobayashi[a], Seiki Takahashi[a], Yasuhiro Kamada[a], Hiroaki Kikuchi[a]

[a] NDE&Science Research Center, Iwate University, Morioka, Japan

The Steinmetz law [1], which describes the relation between maximum magnetization M_{max} and hysteresis loss W_{hys}, i.e. $W_{hys} \propto M_{max}^{1.6}$, is now widely used for various purposes such as design of transformers. The exponent value is almost independent of temperature, stress and types of ferromagnets, and the coefficient reflects the material's properties including defect density, magnetocrystalline anisotropy, internal stress [2,3]. This law generally holds true at the medium range of magnetization, where irreversible movement of Bloch walls dominates the magnetization process; $\mu_0 M$ = 0.2-1.0 T and 0.2-0.4 T for Fe and Ni single crystals, respectively.

Quite recently, another scaling power-law rule between remanence and hysteresis loss of minor loops was proposed for characterization of ferromagnetic phases in a paramagnetic matrix [4]. The rule is independent of volume fraction of the ferromagnetic phases and offers useful information on the morphology. On the other hand, our analysis based on the Rayleigh law suggests that this scaling rule is also useful for evaluation of magnetic quality of polycrystals with sample imhomogeneities where the Steinmetz law no longer holds true. This is attributed to the fact that this scaling rule between remanence and hysteresis loss selectively reflects the magnetization process due to irreversible motion of Bloch wall even if there remains significant contribution of the reversible process. This seems to indicate that this rule is valid even at the very low range of magnetization and could be applied to evaluate the magnetic quality of ferromagnets as far as the Rayleigh law applies.

In this study, we have examined a scaling power-law rule between remanence and hysteresis loss of minor loops in low carbon steels and Ni polycrystals, in which dislocation density was systematically changed by cold rolling and tensile deformation, respectively. A set of symmetrical minor hysteresis loops with various field amplitudes up to 8 kA/m was measured for magnetically closed (frame or toroid) and open (Charpy impact test pieces) samples. We found that the power-law rule with an exponent of 1.4 holds true for both materials over the wide range of magnetization from the very low range, for which the Steinmetz law is not valid. This magnetization range was hardly affected by defect density and temperature unlike the Steinmetz law. A coefficient of the scaling rule shows a linear relation with coercivity of the major hysteresis loop. This behavior of the coefficient is qualitatively explained on the basis of the Rayleigh law and Néel theory.

[1] C. P. Steinmetz, Trans. Am. Inst. Electr. Eng. **9** (1892) 3.
[2] S. Takahashi, S. Kobayashi, H. Kikuchi, Y. Kamada, J. Appl. Phys. **100** (2006) 113908.
[3] S. Kobayashi, S. Takahashi, T. Fujiwara, H. Kikuchi, Y. Kamada, K. Ara, T. Shishido, Philos. Mag. **89** (2009) 651.
[4] S. Kobayashi, A. Saito, S. Takahashi, Y. Kamada, H. Kikuchi, Appl. Phys. Lett. **92** (2008) 182508.

Corresponding author e-mail: koba@iwate-u.ac.jp