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Similarity rules of magnetic minor hysteresis loops in Fe and Ni metals

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Abstract

We have studied similarity rules of quasistatic minor hysteresis loops for Fe and Ni single crystals in the wide temperature range from 10 to 600 K. Two similarity rules of $M_R*/M_a*\sim 3/4$ and $W_R*/W_F*\sim 1/6$, were found in a medium field range where irreversible movement of Bloch walls plays a crucial role for magnetization; M_a*, M_R*, W_F*, and W_R* are magnetization, remanence, hysteresis loss, and remanence work of a minor hysteresis loop. The similarity rules hold true, being almost independent of kinds of ferromagnets, applied stress, and temperature. The origin was discussed from the viewpoint of pinning effects due to dislocations as well as eddy current effects which become predominant at low temperatures for samples with low dislocation density.

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Keywords: Minor hysteresis loop; Scaling rules; Iron; Nickel; Dislocation

1. Introduction

Magnetic hysteresis loops of ferromagnetic materials have been studied from the viewpoint of magnetic domain wall motion and the rotation of magnetic moments for a long time [1–3]. It is well-known that the magnetic properties of the major hysteresis loop such as initial susceptibility, coercive force, remanence, and pre-saturated susceptibility are sensitive to crystal structure as well as lattice defects. Many investigators have tried to quantitatively relate these structure-sensitive properties with density and distribution of dislocations both experimentally and theoretically [1]. On the other hand, minor hysteresis loops, which are obtained with lower magnetic field, have several advantages compared with the major loop. By measuring a set of minor loops with various magnetic field amplitudes, it would be possible to obtain much information on lattice defects in ferromagnetic materials with high sensitivity [4–7]. However, minor hysteresis loops have not been studied systematically compared with the major hysteresis loop, because magnetic properties of minor loops depend on field amplitude of a cyclic field and it is difficult to extract universal physical properties from them.

Recently, we measured a set of quasistatic minor hysteresis loops with various field amplitudes and analyzed them in relation to dislocations introduced by plastic deformation for Fe polycrystals [8], Fe single crystals [9], low carbon steels [10], and Ni single crystals [11]. Fig. 1(a) shows an example of a set of minor hysteresis loops which we measured. A cyclic magnetic field with field amplitude H_a was applied in a demagnetized state and a minor loop, which is symmetric about the origin was measured. By increasing H_a step-by-step, a set of minor loops was obtained. It was revealed that minor hysteresis loops exhibit several scaling power-law relations between the field-dependent parameters, such as

$$W_F^* = W_F^0 \left(\frac{M_a^*}{M_S}\right)^{n_F}, \quad (1)$$

$$W_R^* = W_R^0 \left(\frac{M_R^*}{M_R}\right)^{n_R} \quad (2)$$

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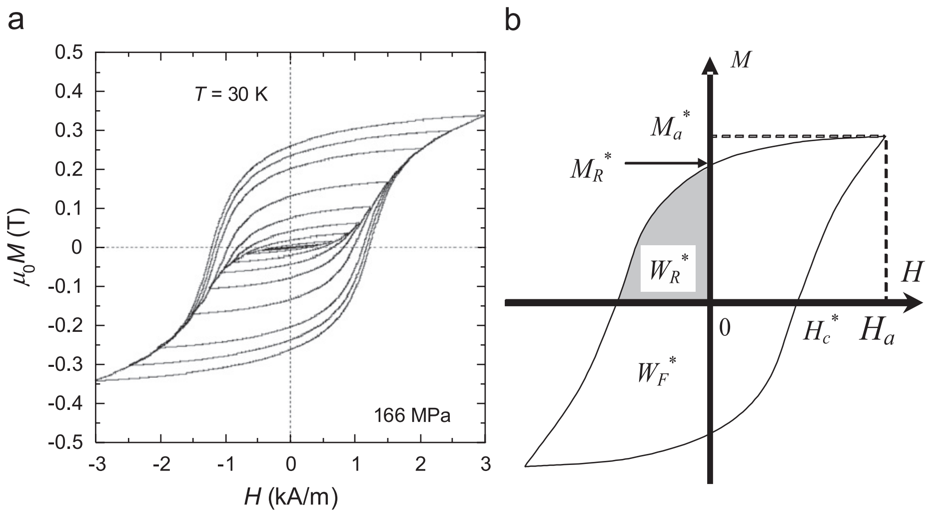

Fig. 1. (a) A set of minor hysteresis loops; data at $T = 30$ K for Ni single crystal deformed by 166 MPa are given for an example. (b) Parameters of a minor hysteresis loop measured with a field amplitude H_a.

and

$$H_c^* = H_c^0\left(\frac{M_R^*}{M_R}\right)^{n_C}, \quad (3)$$

where W_F* is minor-loop hysteresis loss, M_a* is minor-loop magnetization, W_R* is minor-loop remanence work, M_R* is minor-loop remanence, and H_c* is minor-loop coercive force as denoted in Fig. 1(b). W_F^0, W_R^0, and H_c^0 are minor-loop coefficients sensitive to lattice defects and M_s and M_R are saturation magnetization and remanence, respectively. The power-law exponents n_F, n_R, and n_C are about 1.5, 1.5, and 0.45, respectively, being nearly independent of kinds of ferromagnets, applied stress and temperature. Note that the relation between W_F* and M_a* with $n_F = 1.6$ is well-known as the Steinmetz law [12]. These scaling rules were found to hold true in the wide H_a range where irreversible movement of Bloch wall mainly contributes to magnetization and magnetization steeply increases against applied fields; this field range is known as the second stage, whereas the first and third stages correspond to field ranges where reversible domain wall motion and magnetization rotation play a dominant role, respectively [3].

Our detailed analysis for Fe metals [8,9] also revealed that minor hysteresis loops obtained with different H_a have a similarity between their shapes in the second stage; M_R*/M_a*~3/4 and W_R*/W_F*~1/6. These similarity rules were found to be almost independent of the kind of ferromagnets and lattice defects such as dislocations, the grain size. Unlike traditional relations of major loop such as M_R/M_s [13], the similarity rules of minor hysteresis loops obtained with low applied fields are useful for practical application where hysteresis characterization at medium magnetization range is particularly important. Nevertheless, the physical origin and generality of similarity rules in various conditions were not studied in detail so far. In this paper, we present results of minor-loop measurements for Fe and Ni single crystals, where effects of stress and temperature on the similarity rules were examined in the wide temperature range from 10 to 600 K.

2. Experimental procedure

Sheets of Fe single crystals with 1 mm in thickness were prepared with strain-annealing method by courtesy of Dr. Tomoyuki Takeuchi [14]. The sheet samples have (1 0 0) plane on the sheet surface. Cylindrical Ni single crystals with 12 mm in diameter were prepared with electron-beam floating zone melting in vacuum. The growth rate was 1.0 mm/min and the growth direction determined by Laue X-ray diffraction was about [1 1 3]. To see effects of dislocations on magnetic properties, some sheet Fe samples were plastically deformed in tension at room temperature, whereas cylindrical Ni samples were compressively deformed. The critical shear stress was about 50 and 17 MPa for Fe and Ni single crystal samples, respectively.

For magnetic measurements, Fe single crystals were cut into picture frames with [1 0 0] and [0 1 0] frame axes, whereas Ni ones were cut into rings. Both exciting and pickup coils were wound around the samples. The samples were mounted in a He-gas closed cycle refrigerator with high-temperature stage where temperature was varied from 10 to 600 K. A set of minor hysteresis loops with various amplitudes of a cyclic field up to 4 kA/m and with a frequency of 0.05 Hz were measured. Before measuring each minor loop, the sample was demagnetized with decaying alternating magnetic field.

3. Experimental results

Fig. 2(a)–(f) show relations between M_R* and M_a*, and between W_R* and W_F*, taken at various temperatures from 10 to 500 K for Fe single crystals before and after plastic deformation. It can be clearly seen that both curves