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The influence of internal stress and grain size on the behaviour of domain wall interaction in pure nickel and Ni–Cu alloys

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The magnetic anisotropy, K, and the initial magnetic susceptibility, χ_a, were used to study the effect of internal stress and grain size on the interaction of lattice defects with magnetic domain walls under moderately strong magnetic fields in pure nickel and Ni–Cu alloys. The observed dependence of K and χ_a on the internal stress was attributed to the existence of structural defects producing a configuration of potential energy controlling the location of magnetic domains and the strength of magnetic pressure in the nickel matrix. The effect of grain size on K and χ_a was investigated, and the domain wall thickness was calculated. The existence of copper solute atoms in the nickel matrix was found to have an effect on both the magnetic anisotropy and initial magnetic susceptibility. This is assumed to be due to the induced magnetic free poles resulting from the magnetization variations produced by solute atoms in the matrix.

1. Introduction

One of the basic problems of ferromagnetic materials is the interpretation of the behaviour of magnetic domain wall displacements under the influence of the magnetic field. Many experiments were performed to determine the effect of lattice disorders on the reversible and irreversible displacement of domain walls in pure nickel and Ni–Cu alloys [1–3]. It has been found that when very low magnetic pressure predominates, lattice imperfections can have a strong influence on the structure-sensitive magnetic properties such as initial magnetic susceptibility χ_a, coercive field H_c, energy loss E, and remanent magnetization M_r [4, 5]. On the other hand, in the case of a moderately strong magnetic field, ferromagnetic materials are generally magnetized to their saturated state, where all domain wall displacements have been finished and the magnetization is almost parallel to the magnetic field [6]. In this range, the displacement of domain walls has already been completed and the magnetization takes place by rotation magnetization. Therefore, according to the theoretical prediction made by Soshin Chikazumi [7], in connection with the magnetization (B) in ferromagnetic material under a moderately strong magnetic field (H), the magnetic anisotropy (K) could be determined using the equation

$$\frac{\mathrm{d}B}{\mathrm{d}H} = M_s\left(\frac{a}{H^2} + \frac{2b}{H^3} + \ldots\right) + \chi_a \qquad (1)$$

where χ_a is the initial magnetic susceptibility M_s the saturation magnetization and a is a constant depending on the internal stress and non-magnetic inclusions in the matrix. This constant is valid only within a finite range of strength of the magnetic field [8], and b is a constant which can be determined using the equation

$$b = 0.0762(K^2/M_s^2) \qquad (2)$$

where K is the magnetic anisotropy.

On these grounds, under a moderately strong magnetic field where the constant $a = 0$ [8], the values of $(\mathrm{d}B/\mathrm{d}H)$ should give a straight line when plotted against $(1/H^3)$. From the gradient of this line we could determine the value of the constant b (see Equation 1). Therefore, the value of the magnetic anisotropy K could be obtained (see Equation 2). The actual value of the initial magnetic susceptibility χ_a can also be obtained from the extrapolated points of this straight line to the ordinate.

The magnetic anisotropy K and initial magnetic susceptibility χ_a have been investigated extensively by many researchers, chiefly because of technological interest in the study of the magnetization process and domain wall dynamics. Thus it was the purpose of this investigation to study in detail the influence of internal stress and grain size on the magnetic anisotropy and initial susceptibility of pure nickel and Ni–Cu alloys. The study is also extended to examine the effect of systematically varied copper contents in a nickel matrix on both K and χ_a. It was expected that from such measurements more information could be obtained on both the nature of magnetic domain wall motion and also on the behaviour of domain wall interaction with lattice imperfections in a nickel matrix.

2. Experimental procedures

Samples of Ni–Cu alloys were prepared from high-purity nickel and copper by induction melting and

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suitable homogenization at 1200°C for 24 h. The material was then shaped by extrusion into rods of 3 mm diameter. The rods were then subjected to a reduction in cross-sectional area by swaging at room temperature to wires of 1 mm diameter. The atomic absorption method was used in order to determine the composition of the alloys. Samples of different grain size were prepared by annealing for 5 h at different high temperatures. The mean grain size of the samples was measured using an ordinary microscope. The wire sample was introduced as the core of a magnetization coil and the ballistic galvanometer method was used to plot the room temperature ($\mathrm{d}B/\mathrm{d}H - 1/H^3$) curve at a moderately strong magnetic field [9]. In order to test the effect of torsional deformation on magnetic anisotropy and initial susceptibility, samples of pure nickel and Ni–Cu alloy were torsionally deformed by a locally conventional torsional machine. The different degrees of deformation were measured by the dimensionless quantity $ND/L = \Theta$, where N is the number of twist turns, D and L are the diameter and length of the sample, respectively. The demagnetization process was followed in order to standardize the initial demagnetizing state, where $H = B = 0$.

3. Results

3.1. Effect of torsional deformation on K and χ_a

The effect of pre-cold work by torsional deformation of two pre-annealed samples on the corresponding room temperature ($\mathrm{d}B/\mathrm{d}H - 1/H^3$) curves is shown in Fig. 1 for pure nickel and Ni-4.5 at % Cu alloy. In the present work, the saturation magnetization M_s of the different samples was determined and found to be 0.0485, 0.0468, 0.0460 and 0.0454T for pure nickel, Ni-1.5 at % Cu, Ni-4.5 at % Cu and Ni-6.5 at % Cu, respectively. The values of the magnetic anisotropy were calculated from the slope of the linear part of the curves, which characterized the magnetization by rotation domain wall motion for the different samples (Fig. 2a). The initial magnetic susceptibility was evaluated from the extrapolated point on the curve to the ordinate, which characterizes the magnetization by reversible domain wall motion and is given in Fig. 2b for pure nickel and Ni-4.5 at % Cu. From these results, the general trend is apparent that both the magnetic anisotropy and the initial susceptibility decrease with increasing torsional deformation in a nickel matrix.

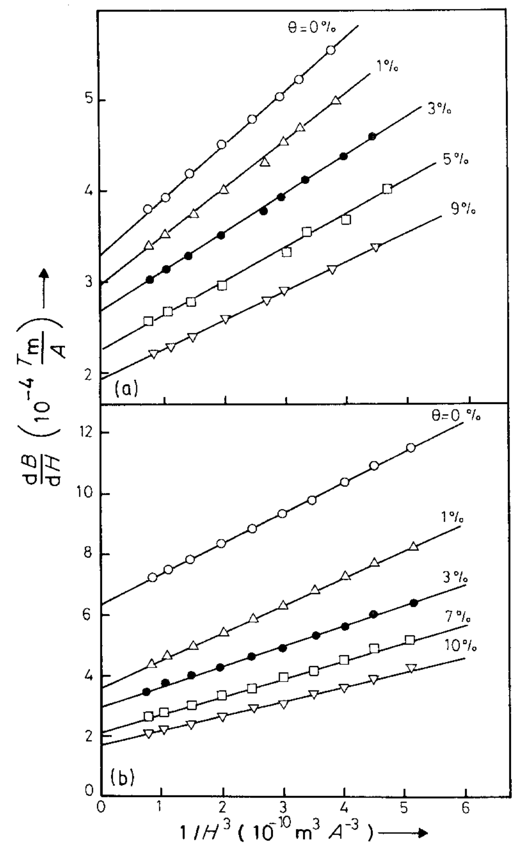

Figure 1 Effect of torsional deformation θ on the room temperature ($\mathrm{d}B/\mathrm{d}H - 1/H^3$) curves of (a) pure nickel and (b) Ni-4.5 at % Cu.

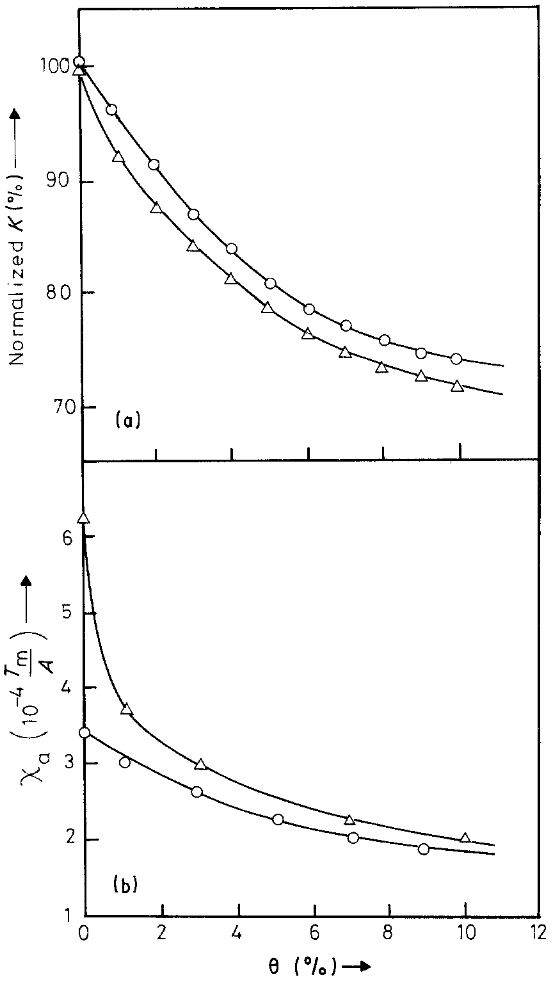

Figure 2 The dependence of the magnetic anisotropy, K, and the initial magnetic susceptibility, χ_a, on the torsional deformation θ in ○, pure nickel and △ Ni-4.5 at % Cu.

3.2. Effect of grain size on K and χ_a

The effect of grain size on the corresponding room temperature ($\mathrm{d}B/\mathrm{d}H - 1/H^3$) curves is shown in Fig. 3 for pure nickel, Ni-1.5 at % Cu, and Ni-4.5 at % Cu. From the gradient of these lines, the value of the constant (b) was determined and the magnetic anisotropy (K) was obtained for the different samples. The change in magnetic anisotropy, K and the initial susceptibility, χ_a, with the mean grain size is demonstrated in Figs 4a and b for pure nickel Ni-1.5 at % Cu, and Ni-4.5 at % Cu. It is evident that the initial magnetic susceptibility is proportional to the grain

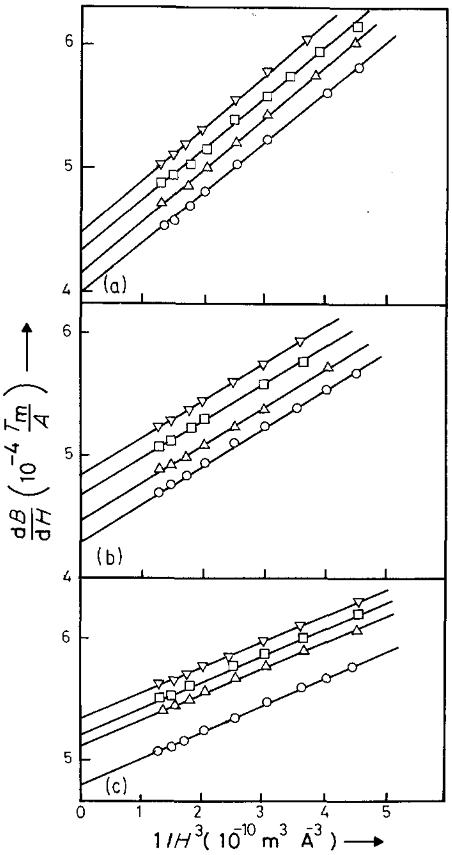

Figure 3 Effect of mean grain size D on the room-temperature $(\mathrm{d}B/\mathrm{d}H - 1/H^3)$ curves of (a) pure nickel, (b) Ni-1.5 at % Cu, and (c) Ni-4.5 at % Cu. (a, b) D = (▽) 40, (□) 33, (△) 27, (○) 20 μm; (c) (▽) = 42, (□) 32, (△) 26, (○) 20 μm.

size (see Fig. 4a), while the magnetic anisotropy is obviously independent of the grain size for pure nickel and Ni–Cu alloys (see Fig. 4b).

3.3. Effect of copper-solute atoms on K and χ_a

Fig. 5 shows the effect of copper-solute atoms in a nickel matrix on the room temperature $(\mathrm{d}B/\mathrm{d}H - 1/H^3)$ curves for pure nickel, Ni-1.5 at % Cu, Ni-4.5 at % Cu and Ni-6.5 at % Cu. The introduction of copper-solute atoms into the nickel matrix markedly increased the initial magnetic susceptibility, χ_a, while the magnetic anisotropy K decreased (see Fig. 6).

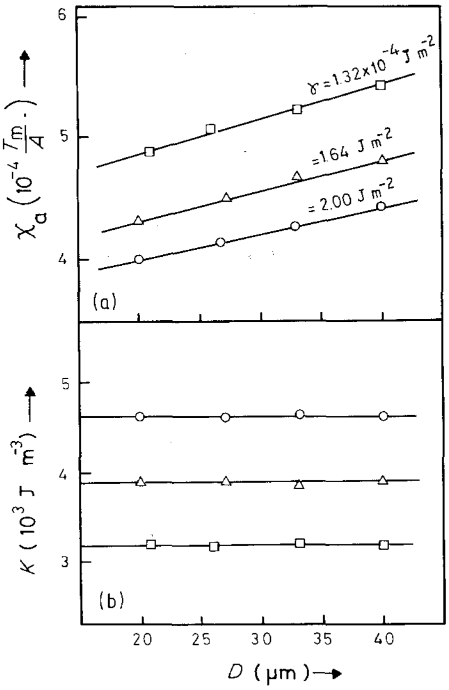

Figure 4 The dependence of the initial magnetic susceptibility χ_a and the magnetic anisotropy K on the mean grain size D. For ○, pure nickel; (△), Ni–1.5 at % Cu; and □, Ni-4.5 at % Cu.

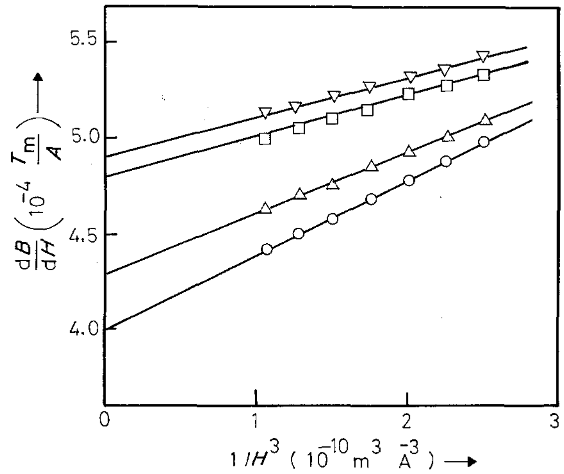

Figure 5 Effect of content solute copper atoms on the room temperature $(\mathrm{d}B/\mathrm{d}H - 1/H^3)$ curves for ○, pure nickel; △, Ni–1.5 at % Cu; □, Ni-4.5 at % Cu; and ▽, Ni-6.5 at % Cu (for mean grain size D = 20 μm).

4. Discussion

The interaction behaviour of different lattice imperfections with magnetic domain walls in pure nickel and Ni–Cu alloys could be interpreted in terms of an existing network of structural defects producing a configuration of potential energy in the matrix. This seems to control the location of the magnetic domain walls and the strength of the magnetic pressure in the matrix [10]. In the present work, the torsional deformation is made to produce different types of defects in the tested samples. The domain wall motion, under the action of magnetic pressure, is thought to interact with the different types of lattice defects in the matrix [2]. For thoroughly annealed, undeformed samples where the matrix is relatively free from dislocations, domain walls are likely to extend over large areas between dislocation pinning points [9], so that the initial magnetic susceptibility is large. The large

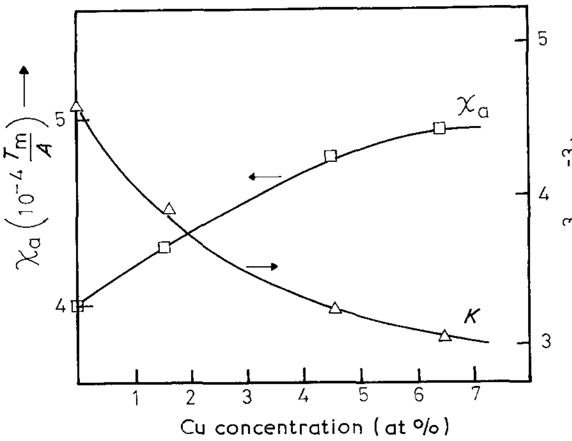

Figure 6 The dependence of initial magnetic susceptibility χ_a and magnetic anisotropy K on the concentration of copper atoms in a nickel matrix, for mean grain size D = 20 μm.

change in the concentration of defects, particularly in dislocation density produced by torsional deformation, should impose a pinning effect on the magnetic domain walls, preventing them from normal detachment from any fixation points. This effect tends to decrease the initial magnetic susceptibility with torsional deformation which is actually observed in this work (see Fig. 2b). On the other hand, in the range of a moderately strong magnetic field, the pinning action of magnetic domain walls by dislocations was inferred to leak out the magnetic pressure exerted by the magnetic field on domain walls [5], and as expected the torque exerted by the magnetic pressure on the domain walls decreased with increasing torsional deformation in the matrix. Therefore, the observed decrease in the magnetic anisotropy K with torsional deformation might be related to the leak out of the torque exerted by the magnetic field on domain walls which originated during torsional deformation in the matrix. This result reflects the dependence of the reversible and rotational motion of magnetic domain walls on the internal stress of the material.

The dependence of the initial magnetic susceptibility χ_a on the grain size observed here for pure nickel and Ni–Cu alloys (see Fig. 4a) is thought to be due to the bulging and subsequent displacement of magnetic domain walls bounded by the grain size [11]. This seems to affect the initial magnetic susceptibility by controlling the location of magnetic domains. The increase in grain size caused by thermal annealing decreases the residual stresses in the matrix and presumably affects the average value of the strength of interaction of the magnetic domain wall [10]. This process leads to an increase in the value of initial magnetic susceptibility χ_a with grain size for pure nickel and Ni–Cu alloys (see Fig. 4a). The situation is different for the effect of grain size on magnetic anisotropy, which reflects the strength of the torque exerted by magnetic pressure on the rotational motion of the domain wall. Hence it is reasonable to assume the observed constancy of the magnetic anisotropy to be due to the independence of the magnetic pressure in the matrix from the grain size. It is likely that the increase in grain size will not impose any loading effect on the rotational motion of the magnetic domain walls. Therefore the magnetic torque exerted on the domain walls would not leak out, and the constancy of the magnetic anisotropy with the grain size might thus be accounted for. The present investigation shows that the magnetic anisotropy is independent of grain size (see Fig. 4b), which is consistent with this interpretation.

On the other hand, it is generally admitted that in polycrystalline ferromagnetic materials the wall thickness (δ) is related to the magnetic anisotropy K by the relation $\delta \simeq \gamma/K$ [12], where γ is the surface domain wall energy [13]

$$\gamma = \frac{3}{16}(DM_s^2/\chi_a) \tag{3}$$

In the present work, the values for domain wall surface energy were calculated from the results of the initial magnetic susceptibility for the different samples and are given in Fig. 4a. Table I summarizes the present results on the domain wall surface energy and magnetic anisotropy for pure nickel and Ni–Cu alloys. The value of the domain wall surface energy found here agrees well with the value previously found for these materials [4].

From these results, the general trend is apparent that the numerical value of the domain wall thickness $\delta = 4.23 \times 10^{-8}$ m, corresponding to about 120 lattice constant. This result shows that the magnetic walls are very thin, which supports the idea that the strength of the magnetic torque exerted on rotational domains is independent of grain size.

On the other hand, the observed increase in initial magnetic susceptibility χ_a with increasing solute constant of copper atoms in a nickel matrix supports the idea that the induced magnetic free poles, resulting from magnetization variations produced by solute atoms, can also be affected by domain wall displacement [14]. Therefore the increase in solute content of copper atoms will increase the density of induced magnetic free poles in the matrix, which consequently increases the restoring force on the motion of magnetic domains. This process gives rise to a fluctuation in local magnetic fields in the matrix, which may cause more reversible displacement of unstable domains [14]. This would anticipate an increase in the reversible magnetic susceptibility χ_a with increasing solute content of copper atoms in the nickel matrix, which was actually observed (see Fig. 6). Moreover, the increase in restoring force on domain wall motion produced by the magnetic free poles should increase the value of the magnetostatic energy of the matrix [15]. This increase in magnetostatic energy is counterbalanced by a decrease in magnetic anisotropy caused by a rotation of domain magnetization [15]. Therefore, a decrease in the magnetic anisotropy K with increasing solute copper atoms would be expected, and was actually observed in the present work.

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TABLE I

Material	Domain wall energy $\gamma(10^{-4}\,\mathrm{J\,m^{-2}})$	Magnetic anisotropy $K(10^3\,\mathrm{J\,m^{-3}})$	Domain wall thickness $\delta(10^{-7}\,\mathrm{m})$
Pure Ni(99.999%)	2.00	4.6	0.43
Ni-1.5 at % Cu	1.64	3.9	0.42
Ni-4.5 at % Cu	1.32	3.2	0.41
Ni-6.5 at % Cu	1.30	3.0	0.43

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