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The effect of lattice disorders on the behavior of domain wall interaction in $fe_{50}ni_{50}$ ferromagnetic alloy

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ABSTRACT

The behavior of domain wall-dislocation interaction in $Fe_{50}Ni_{50}$ alloy has been investigated in pre-annealed and quenched samples using some magnetic structure-sensitive properties. In the two samples it was found that the maximum magnetic permeability (μ_{max}), the high field magnetic permeability (μ_a) and the magnetic anisotropy (K) were increased with the degree of plastic strain during the early stage of deformation, and attributed to the precipitation of $FeNi_3$ phase during pre-annealing or after quenching from high temperature. Further increase in dislocation density in the matrix during the later stage of deformation, affects the average value of the strength of interaction between the domain wall and dislocation, thus contributes to the decrease in μ_a and μ_{max}. The observed change in the magnetic anisotropy, K, with plastic strain deformation is explained in terms of the magnetic hardening of the material by dislocations. The domain wall surface energy, γ, the thickness of the magnetic domain, δ, and the exchange energy, A, of the present alloy were determined from a simple measurement of the magnetic permeability and magnetic anisotropy.

KEYWORDS

$Fe_{50}Ni_{50}$;
Ferromagnetic alloy;
Magnetic properties;
Plastic deformation;
Plastic strain.

INTRODUCTION

It is now almost universally accepted that in ferromagnetic material the displacement of magnetic domain walls under the influence of a magnetic field is hindered by lattice imperfections[1-8]. Several theories have been proposed in order to study the effect of domain wall-defect interaction on the behavior of domain-wall motion in the ferromagnetic material. The potential theory[9-12] assumes the domain wall to be finite and rigid, whereas the domain-wall bowing theory[5-8,13] considers the domain wall to be flexible in one dimension only. However, it was reported by others[14,15] that the behavior of pure materials and ferromagnetic alloys can be excellently described by the rigid domain-wall pinning model. Hilzinger and Kronmüller[16] came to the conclusion that domain-wall bowing out under the action of a magnetic field is expected to be predominant in materials in which strong defect interaction or more extended domain walls exist. Moreover, in the case of a large number of defects, randomly distributed on both sides of the domain wall, the average force acting on the sides of the domain wall cancels out.

TABLE 1 : Chemical composition of $Fe_{50}Ni_{50}$ alloy

Fe	Ni	Mn	Zn	Mg	Sn	Al	Cu
Major	Major	-	0.001	-	0.001	0.001	0.001

Only spatial fluctuations of the defect concentration act as effective pinning centers for domain-wall displacement[16].

Several theories has been proposed in order to study the effect of order-disorder transition on domain wall-defect interactions in ferromagnetic alloys containing some degree of chemical order. Chin[17] proposed a slip-induced directional order theory, states that in a ferromagnetic alloy containing some degree of chemical order (long or short range), there are more unlike nearest-neighbor atom pairs than in a random solid solution. During plastic deformation, like-atom pairs are created at the expense of unlike pairs[11]. Due to the crystallographic nature of slip, these induced like-atom pairs are distributed asymmetrically. Such asymmetrical distribution increases the microstress in the alloy matrix leading to a change in the structural sensitive magnetic properties of the ferromagnetic alloys. Based on this model, important specific parameters characterizing a domain wall, such as domain wall surface energy (γ), the magnetic anisotropy (K), and the exchange energy (A) are determined in series of ferromagnetic polycrystalline materials[18,19]. These parameters which control the field dependence of the domain hindrance by lattice imperfections are good enough to establish proportion laws as far as the effect of structural changes by order-disorder transformation on the magnetization processes of $Fe_{50}Ni_{50}$ alloy. From these considerations, the present work reports some experimental results on the effect of plastic deformation on the behavior of domain wall motion in $Fe_{50}Ni_{50}$ alloy under the action of impressing magnetic field. The maximum magnetic permeability (μ_{max}) and the critical magnetic field (H_{Cr}) were taken in the present work as a tool of study the effect of structural changes induced by plastic deformation on the behavior of interaction of domain wall in $Fe_{50}Ni_{50}$ alloy. Also, it is shown in principle how to evaluate the domain wall surface energy (γ), the magnetic anisotropy (K) and the exchange energy (A) from a simple measurement of magnetic permeability which in addition would lead to the confirmation of domain wall theory in ferromagnetic alloys.

EXPERIMENTAL WORK

The test material, $Fe_{50}Ni_{50}$alloy, was prepared from high purity Fe and Ni by induction melting followed by a suitable homogenization at 1200 ^{o}C under a helium atmosphere for 24 hours, then slowly cooled to room temperature. The material shaped by extrusion into rods of 3 mm diameter followed 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 alloy, (see TABLE 1). The wire sample was introduced as the core of a magnetization coil and the cathode ray technique was employed to obtain room-temperature B-H curves at different magnetizing fields. The maximum magnetic permeability was obtained from the relation $\mu_{max} = (B/H)_{max}$, which characterizes the magnetization of both reversible and irreversible domain-wall motion. Plastic strain deformation was induced on the samples by a locally conventional strain machine. The pre-annealed sample was quenched from 900 ^{o}C in cold water at a quenching rate of 10^3 ^{o}C.s^{-1}. The different degrees of plastic strain deformation were measured by the dimensionless quantity $\eta\% = (\Delta L/L)$ % where ΔL and L are the change in length and the initial length of the sample respectively[20].

RESULTS

Effect of plastic strain on μ_{max} and H_{cr}

The magnetic permeability (μ) measured at room temperature as a function of the magnetic field (H) for pre-annealed and quenched samples of different degrees of plastic strain is presented in Figure 1a,b. The curves are characterized by a pronounced peak value in magnetic permeability (μ_{max}) which is found

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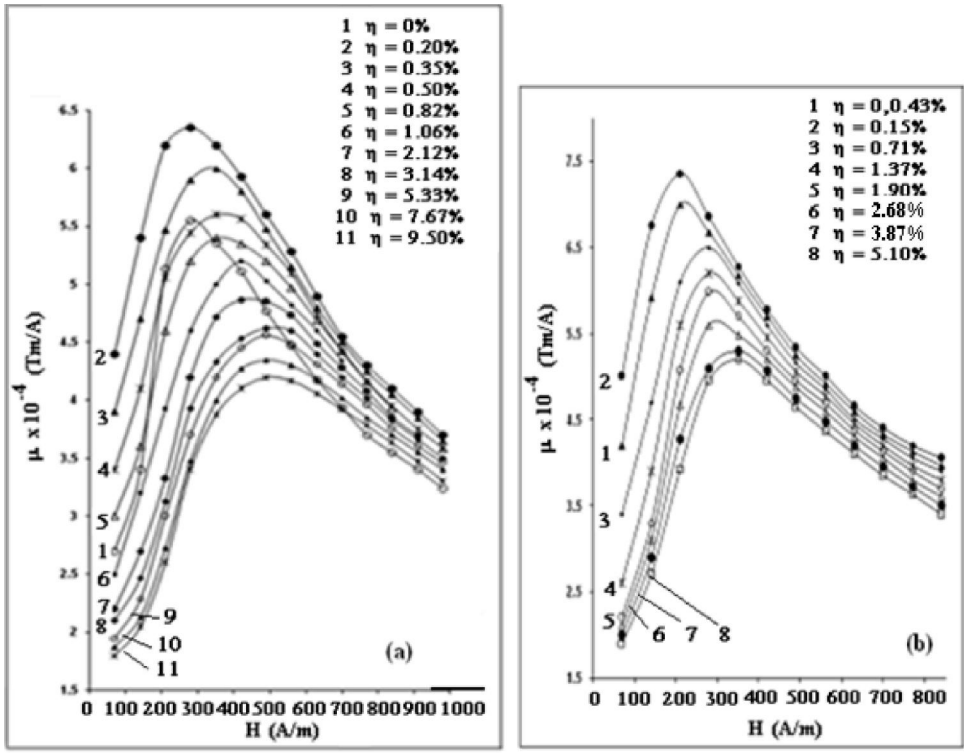

Figure 1 : The dependence of the magnetic permeability, (μ) on the magnetic field, H for: (a) pre-annealed $Fe_{50}Ni_{50}$ alloy (Ta = 800 °C, ta = 2 h) and (b) quenched $Fe_{50}Ni_{50}$ alloy (Tq = 900 °C), with the degree of plastic deformation (η%)

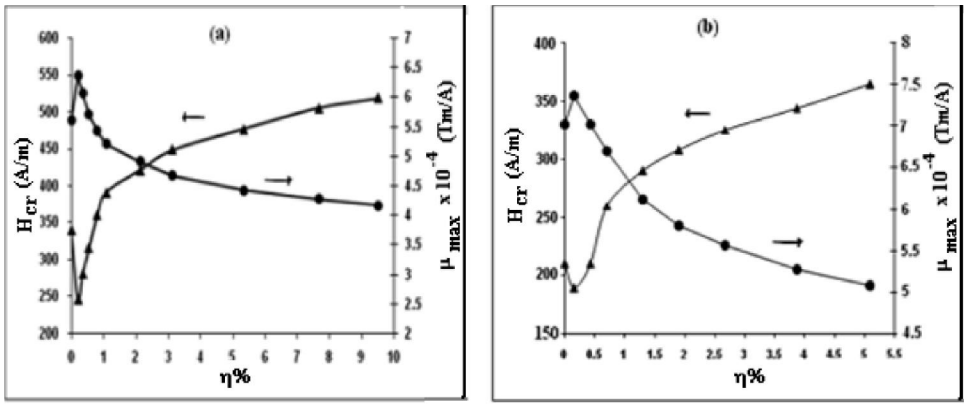

Figure 2a,b : The dependence of both the maximum magnetic permeability (μ_{max}) and the critical magnetic field (H_{cr}) on the degree of plastic strain for: (a) pre-annealed (Ta = 800 °C, ta = 2 h) and (b) quenched (T_q = 900 °C) samples

to shift position with magnetic field (H) when increasing the degree of plastic deformation. The dependence of both the maximum magnetic permeability (μ_{max}) and the critical magnetic field (H_{cr}) on the degree of plastic strain is illustrated in Figure 2a,b. It is clear that for pre-annealed (Ta = 800 °C, t_a = 2 h) and quenched (T_q = 900 °C) samples, the maximum magnetic permeability (μ_{max}) initially increased followed by a pronounced decrease with the degree of plastic strain (η%). Mean while,the critical magnetic field (H_{cr}) initially decreased followed by pronounced increase with the degree of plastic strain (η%). The dependence of the product of the maximum magnetic permeability (μ_{max}) and critical magnetic field (H_{cr}) on the degree of plastic deformation (η%) of $Fe_{50}Ni_{50}$ alloy is shown in Figure 2c,d.

Correlation between magnetic anisotropy (K) and high-field magnetic permeability (μ_a)

The magnetic anisotropy (K) and the high-field

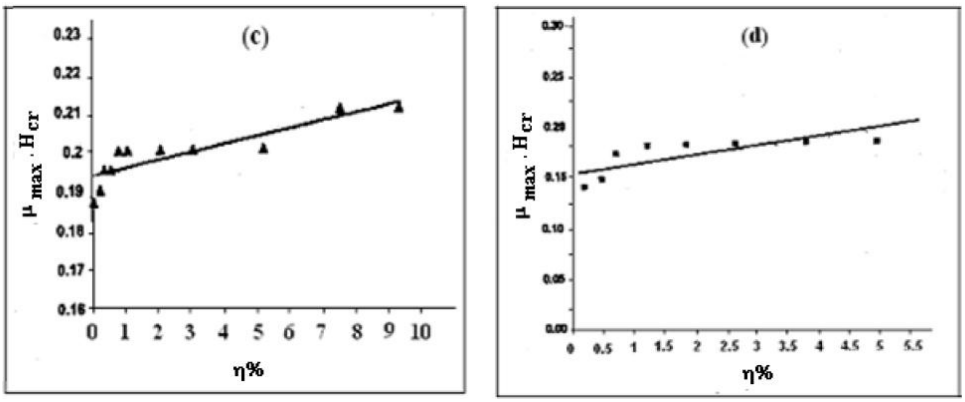

Figure 2c,d : The dependence of the product of maximum magnetic permeability (μ_{max}) and critical magnetic field (H_{cr}) on the degree of plastic strain for: (c) pre-annealed (Ta = 800 °C, ta = 2 h) and (d) quenched (Tq = 900 °C) samples

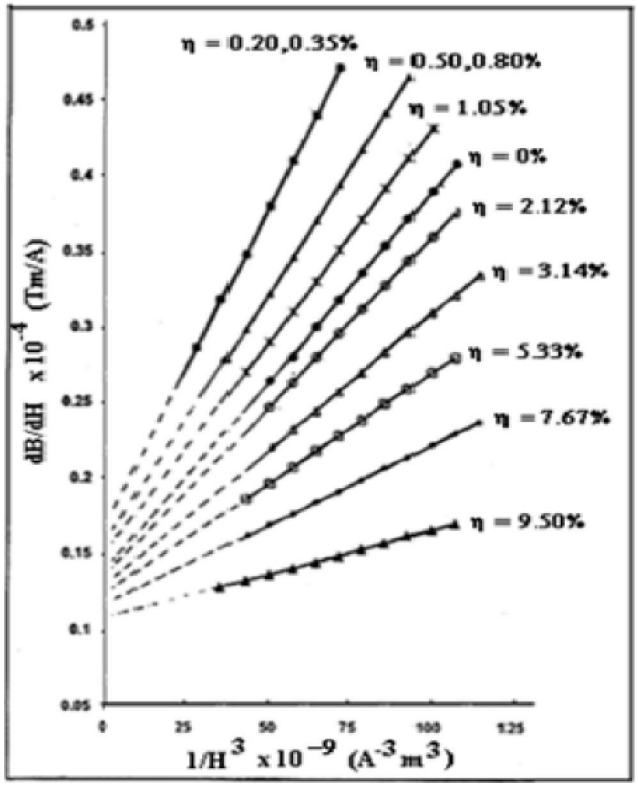

Figure 3 : The effect of plastic deformation (η%) on (dB/dH,1/H³) curves for pre-annealed $Fe_{50}Ni_{50}$ alloy

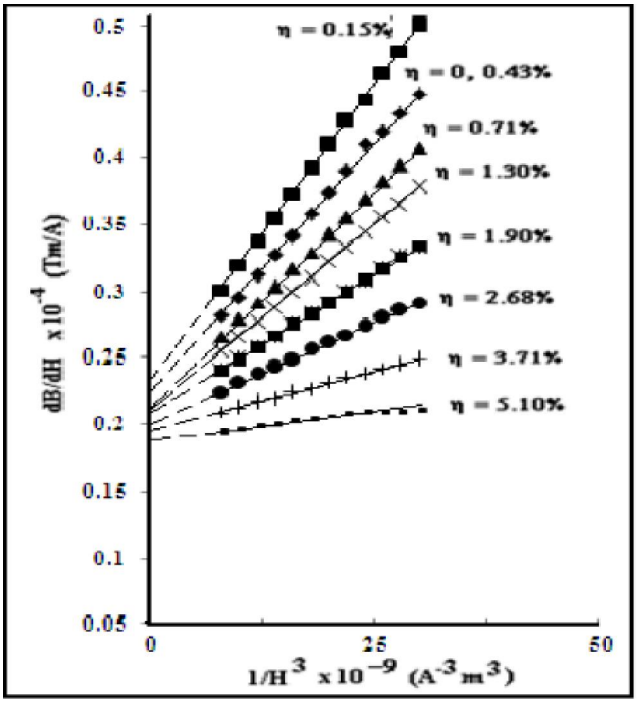

Figure 4 : The effect of plastic deformation (η%) on (dB/dH,1/H³) curves for pre-quenched $Fe_{50}Ni_{50}$ alloy

magnetic permeability (μ-$_a$) were determined in connection with the magnetization M, in ferromagnetic material under a moderately strong magnetic field (H) using the equation[10,11,21-24]:

$$\mu = M_s\left(\frac{a}{H^2} + \frac{2b}{H^3} + \ldots\ldots\ldots\ldots\right) + \mu_a, \qquad (1)$$

Where M_s is the saturation magnetization, and a is a constant depending on the internal stress and non-magnetic inclusions in the matrix. This constant is val.id only within a finite range strength of the magnetic field[10,11], and b is a constant which can be determined using the equation[10,11,21-23]

$$b = \frac{8}{105}\left(\frac{K^2}{M_s^2}\right), \qquad (2)$$

Where K is the magnetic anisotropy and M_s is the saturation magnetization. On these grounds, under a moderately strong magnetic field where the constant a = 0,[10,11,19,23], the values of the magnetic permeability (μ) should give a straight line when plotted against ($1/H^3$). From the gradient of this line we could

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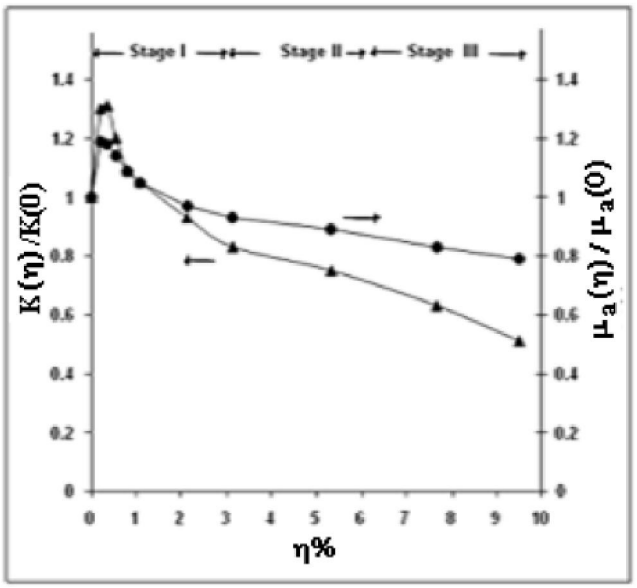

Figure 5 : The relative changes of the magnetic anisotropy and the high field magnetic permeability on the degree of plastic deformation (η%) for pre-annealed $Fe_{50}Ni_{50}$ alloy (Ta = 800 °C, ta = 2 h)

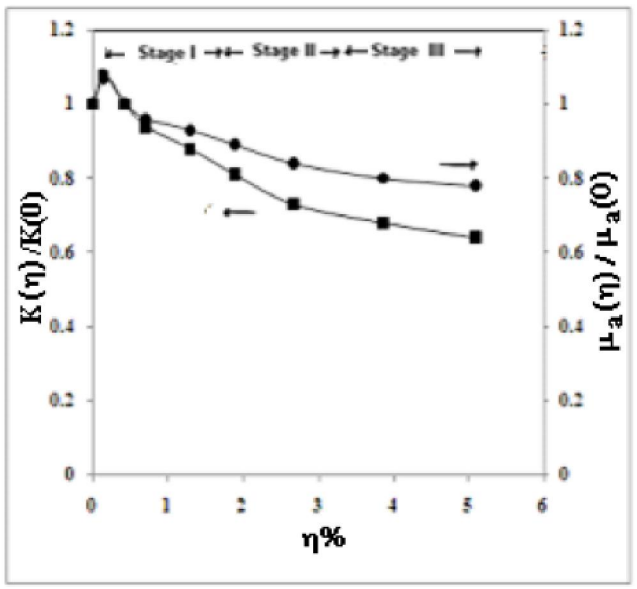

Figure 6 : The relative changes of the magnetic anisotropy and the high field magnetic permeability on the degree of plastic deformation (η%) for quenched $Fe_{50}Ni_{50}$ alloy (T_q=900 °C, quenching rate = 10^3 °C.s^{-1})

TABLE 2 : Represents the general numerical constants obtained in the present work for $Fe_{50}Ni_{50}$ alloy

Sample	Magnetic anisotropy, K (J/m^3) x 10^4	Width of magnetic domain, δ (m) x 10^{-8}	No. of spins involved in one Domain, N	Surface energy of magnetic domain, γ (J/m^2) x 10^{-3}
Annealed T_a = 800 °C	4.73	8.51	343	4.02
Quenched T_q = 900 °C	4.39	8.84	356	3.88

determine the value of the constant b (see Equation 1). Therefore, the value of the magnetic anisotropy, K, could be determined (see Equation 2). The actual value of high-field permeability, μ_a can also be determined from the extrapolated points of this straight line to the ordinate.

In the present work, the effect of pre- cold work by plastic strain of pre-annealed and quenched $Fe_{50}Ni_{50}$ alloy on the corresponding room temperature curves are shown in Figure 3 and Figure 4, respectively. The values of the magnetic anisotropy (K) were calculated from the slope of the linear part of the curves which characterized the magnetization by rotation domain-wall motion for $Fe_{50}Ni_{50}$ alloy. The high field magnetic permeability (μ_a) was evaluated from the extrapolated point on the curve to the ordinate using equation 2, where M_s = 432 Am^{-1}[10]. The dependence of relative changes of both μ_a and K on the degree of plastic deformation for pre-annealed and quenched $Fe_{50}Ni_{50}$ alloy are illustrated in Figures 5 and 6, respectively, from these results, the general trend is apparent that factors which contribute to the change of dislocation density are also factors which effect the motion of magnetic domain walls.

DISCUSSION AND CONCLUSION

The effect of plastic strain deformation on the structure-sensitive magnetic properties of ferromagnetic material might be interpreted in terms of an exiting network of structure defects particularly dislocations[25-30]. This seems to affect the magnetic properties by controlling the location of magnetic domain[29-33]. Near the core of dislocation, the regular arrangement of atoms becomes highly distorted.

Therefore, a weak interaction between the atomic magnets is thus expected and the magnetic domain might wrap around any obstacle or dislocation that cross its path.

The formation of wall-wrapping dislocation is presumably a compromise between the tendency of the dislocation to impose a certain orientation on the wall in its vicinity, and the tendency of the wall to adopt a different orientation related to the crystal structure[34]. The formation of such pinched-of loops of boundaries was previously found in different ferromagnetic materials[34,35].

In the present work, pre-annealed and quenched samples showed a reduction in the critical magnetic field and an increase in the maximum magnetic permeability during the early stage of plastic deformation (see Figure 2a,b). This is most probably related to the precipitation of $FeNi_3$ phase during pre-annealing or rapid quenching from Tq e" 900 °C to room temperature. The precipitation of this phase causes a marked expansion of the material, leading to an increase in dislocation density in the precipitated alloy matrix[32,33]. As pre-annealed or quenched samples are plastically deformed, the rebounding dislocation induced by precipitated phase ($FeNi_3$), and their possible annihilation with the dislocations produced during the early stage of plastic deformation[1], thereby reducing their density in some volume of the material causing reversible changes in the dislocation structure. This process represents some sort of recovery showing itself as an increase of μ_{max} and decrease of H_{cr} to some extent during the early stage of plastic deformation (see Figure 2a,b). Further increase in dislocation density produced by plastic strain, presumably affects the average value of the strength of interaction between the domain wall and dislocation and thus contributes to the decrease in the value of μ_{max} and increase in H_{cr}. However, in the present work no observable change in the product ($\mu_{max}H_{cr}$) is noticed at higher degree of plastic strain deformation (see Figure 2c,d). This indicates the independence of this product on both the strength and density of lattice defects, particularly the density of dislocation produced by plastic strain deformation in $Fe_{50}Ni_{50}$ alloy. This would be due to the expected rise in the lattice defects in rather equal proportions on both sides of a domain wall[10]. Therefore, the average forces acting on the sides of a domain wall cancels each other.

The situation is different for the effect of plastic strain deformation on the magnetic anisotropy (K), which reflects the strength of the torque exerted by magnetic pressure on the rotational motion of domain walls. Therefore, in the range of a moderately strong magnetic field, the pinning action of magnetic domain walls by dislocations was inferred to leak out of the magnetic pressure exerted by the magnetic field on domain walls[10,11,39] and, as expected, the torque exerted by the magnetic pressure on the domain walls decreased with increasing internal stress in the matrix. Hence it is reasonable to assume that the observed decrease in the magnetic anisotropy with plastic strain might be related to the leak out of the torque exerted by the magnetic field on domain walls which originated during plastic- strain deformation in the matrix. On the other hand, the observed change in the magnetic anisotropy, K and the high field permeability, $\mu_{a,}$ with plastic-strain deformation in three stages (see Figures 5 and 6) could correspond, respectively, to the following phenomena[2]: creation of an isolated dislocation (stage I), clustering of dislocation into tangles (stage II) and onset of the cellular structures composed of dislocation walls (stage III). The relative small changes observed in the magnetic anisotropy and the high field permeability during stages I and II (see Figure 4) leads to the conclusion that the rotation magnetization of domain walls depends only on the magnitude of magnetic anisotropy, which is fairly insensitive to weak internal stress in the matrix[10,11], whereas the maximum magnetic permeability due to the reversible and irreversible displacement of domain walls is very sensitive to the irregularity of the substance[10,11,25,26]. Moreover, it is generally admitted that in polycrystal.ine ferromagnetic materials the domain wall surface energy, γ, (the total. energy per unit area of the domain wall), the width of the magnetic domain, δ, (the volume of wall per unit area), and the number of spins involved in a domain wall, N, are related to the magnetic anisotropy (K) by the relations[10,36-38,40]:

$$\gamma = \pi\sqrt{AK},\quad \delta = \pi\sqrt{A/K},\quad N = \delta/a = \frac{\pi}{a}\sqrt{\frac{A}{K}} \qquad (3)$$

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Where, 'a' is the lattice parameter ($a = 2.48 \times 10^{-10}$ m for $Fe_{50}Ni_{50}$)[41] and A is the exchange stiffness constant represents the average exchange energy,and it is measure the stiffness of the magnetization vector against twisting, and it is related to the exchange integral constant, Jex by the relation[10]: $A = nJ_{ex}S^2/a$. For $Fe_{50}Ni_{50}$, $J_{ex} = 2.16 \times 10^{-21}$ J, S = 1, $a = 2.48 \times 10^{-10}$ m and n = 4, so that $A = 3.48 \times 10^{-11}$ $J.m^{-1}$[10].

Using the values of the magnetic anisotropy (K) and the exchange energy (A) in the present work for $Fe_{50}Ni_{50}$ alloy we can determine the numerical values of these quantities see TABLE 2. All these values are in good agreement with the previously reported values in ferromagnetic materials[10,18].

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