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INFLUENCE OF COERCIVE FORCE AND EASY AXIS BIAS
ON DOMAIN WALL CREEP MOTION IN BLOCH WALL NiFeCo FILMS

by

Ling George Chow

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

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CHAPTER I
INTRODUCTION

The study of thin ferromagnetic films has attracted a great deal of attention from many researchers during the past decade. There are at least two reasons for this interest. First, the two dimension geometry of thin films provides a unique opportunity to study some of the basic problems of magnetism. Secondly, the two basic stable states and the high speed flux reversal at low drive field have been considered as attractive features of ferromagnetic thin films for potential computer memory application. However, the development in commercial computer memory systems has been somewhat delayed by problems such as manufacturing reproducibility, insufficient knowledge of flux reversal process, and probably most important at all, the destruction of information by domain wall creep motion. Many workers have engaged in this creep research in the past decade. However, the nature of domain wall creep motion is still not clearly understood.

I-1. High and low frequency creep

Middelhoek observed in 1962 that domain wall motion occurs when a thin permalloy film with uniaxial anisotropy is subjected to an ac field in the hard axis direction and simultaneously to a dc field less than the coercive force in the easy axis direction even though the vector sum of the fields lies well below the critical curve for static wall motion threshold field. This phenomenon is called low frequency creep.

In 1967, Stein and Feldtkeller observed that the hard axis pulse field with rise time less than 20 nsec can cause the Bloch wall to move without the presence of an easy axis bias field. This phenomenon has also
been discovered independently by Kusuda et al.9 This phenomenon is generally called "wall streaming" or "worm motion". With the presence of an easy axis bias field of magnitude less than the coercive force, the domain wall motion excited by fast rise time hard axis pulse fields is known as high frequency creep in order to distinguish it from similar low frequency creep motion.

During the past decade, a great deal of research activities has been done on domain wall creep motion. Various experimental techniques including Kerr apparatus, Bitter method, Lorentz microscope and electron pickup system have been used for this investigation.10-17 From the experimental data, several models have been proposed to explain both low and high frequency creep. These models including Bloch line motion theory, wall structure change theory, lever theory and gyromagnetic induced motion theory will be discussed in next section.

I-2. Origin of domain wall creep motion

a. Bloch line motion theory18

This theory is developed by Middelhoek and it can be generally formulated to state that the motion of Bloch lines or other lines taking place during wall transitions of some kind under the influence of a hard axis field will cause wall creeping, if simultaneously an easy axis field is applied. For film thickness less than 200 \(\AA\), the Neel walls of opposite polarity are separated from each other by Bloch lines, in which the magnetization is normal to the plane of the film. If the hard axis field is applied, the Neel wall segments in which the magnetization is parallel to the applied field start to enlarge at the expense of the
other segments. These enlargements occur by the motion of Bloch lines along the walls. This Bloch line movement causes transient displacement of domain wall. In the crosstie wall region, crosstie-Neel transition occurs in the presence of a hard axis field. Movement and nucleation of Bloch lines is still the basic reason for creeping. For Bloch wall films, creep is attributed to the Bloch-Neel transition. Creep occurs for hard axis fields with magnitude equal to or greater than those at which Bloch-Neel transition occurs.

It can be stated that the Bloch line motion theory offers a reasonable though complicated explanation of the creep phenomenon occurring in films of different thicknesses. However, the exact mechanism by which the Bloch line is able to reduce locally the wall motion coercive force is still not understood.

b. Wall structure change theory

This theory as suggested by Beeforth and Hulyer is based on the change of the structure of Neel wall in films of thickness less than 400 Å when hard axis fields are applied. Suppose the sense of rotation of magnetization in the Neel wall differs in alternate sections of the wall. Thus, the hard axis field creates greater or less divergence of the magnetization vector in alternate sections of the wall depending on whether the magnetization along the center of the wall reinforces or opposes the applied field. The less divergent parts of the wall are comparatively less restrained and can advance across the film under the influence of the easy axis field; nevertheless, any motion of the wall as a whole is prevented because the more divergent parts are unable to pass faults and inclusions. However, if the hard axis field is reversed
then the more divergent parts of the wall become less divergent and can now move past obstructions. Therefore, every time the hard axis field is reversed so alternate parts of the domain wall advance; the overall effect is that the entire wall creeps.

This theory is concerned primarily with Neel wall films. However, it fails to explain the creep motion due to unipolar hard axis field and the creep behavior for thicker films.

20-22

c. Lever theory

This theory is proposed by Olson and Torok. The magnetization within two domains is antiparallel if no hard axis field is applied and the magnetic charge on the wall is zero. If a hard axis field is applied together with an easy axis dc field, the domain with magnetization originally antiparallel to the applied easy axis field will rotate more than the domain with magnetization parallel to the easy axis field. Therefore, a net magnetic charge will exist on the wall. The magnetic charge on the wall causes a magnetic field which in some parts of the wall is parallel and in other parts antiparallel to the applied easy axis field. The part where the extra field is parallel will advanced slightly when the total field exceeds the wall motion coercive force. If the hard axis field direction is reversed, the additional stray field also changes its polarity, so that now the other parts of the wall can move. Therefore, creep will occur, according to this theory, when a bipolar hard axis field is applied in the presence of an easy axis field.

This theory can apply to all films and does not depend on wall structure. Yet this theory fails to explain the creep motion due to unipolar hard
axis field. Furthermore, it can not explain why creep occurs with very small easy axis field or with no easy axis field presence.

d. Gyromagnetic induced motion theory

This theory is proposed by Stein and Feldtkeller, and by Kusuda et al. The theory has been generally accepted as a reasonable explanation for high frequency creep and wall streaming. If a fast rise time hard axis pulse field is applied, the magnetization of the domains initially precesses around the field axis, thereby leaving the film plane; then it precesses around the demagnetizing field and finally reaches a stable direction within the film plane with the help of the intrinsic damping of the precession. This is practically a coherent rotation that the magnetization can closely follow the applied field and reaches its stable position very fast.

Within a wall the magnetization also precesses around the field axis. However, no additional demagnetizing field perpendicular to the film plane is thereby established, because there are locations where the magnetization component normal to the film plane is increased, and others where it is decreased. Therefore, with no help from the demagnetizing field, the magnetization undergoes a slow motion to its final position.

This difference in response time causes the magnetization within the wall to delay that of the domains and results in the discontinuity of magnetization component normal to the wall plane. A very large demagnetizing field normal to the wall plane is thereby established within the wall by these volume charges. Magnetization in the Bloch wall will precess and results the movement of the Bloch wall. When the hard axis pulse field rise time is increased, the magnetization within the wall begins to be able to catch up with that of domains. The high frequency creep becomes
weaker and finally stops, if the pulse rise time is so long that the equi-
librium is almost always assumed.

Bourne et al. 24 proposed that low frequency creep could also be
attributed to gyromagnetic induced motion. The demagnetizing field which
causes the low frequency creep motion may be produced by an instability
in the relation between the hard axis field and the magnetization in the
domains on sides of the wall.

e. Conclusions

Both high and low frequency creep processes are very complicated
and not yet clearly understood. A complete solution based on a satisfac-
tory mathematical model that predicts and explains all aspects of the
domain wall creep motion is not yet available. This seems to be mainly
due to a lack of systematic and complete experiments.

It is the purpose of this thesis to present the results of a quan-
titative evaluation of the influence of coercive force and easy axis
bias field upon domain wall creep motion in Bloch wall films. Such eva-
ulation may provide a better understanding of the basic mechanism involved
in domain wall creep motion as well as an appropriate procedures to sup-
press creep motion.
CHAPTER II
SAMPLE PREPARATION

II.1. Fabrication Technique

Thin ferromagnetic NiFeCo films are chosen for this investigation. The magnetic properties of NiFeCo films are extensively reported in the literature.25-28 Nonmagnetostriuctive, low dispersion, uniaxial anisotropy NiFeCo films together with a wide range of coercive force and anisotropy field can be obtained by controlling the cobalt content and the substrate temperature. The films used in this study are fabricated in this laboratory according to the following procedures.

1. Cleaning The corning 0211 glass substrate (1.6 x 1.6 x 0.07 cm) are cleaned in an ultrasonic cleaner for ten minutes in acetone, alcohol and distilled water and then a vapor degreaser is used. After the cleaning processes, the substrates are dried with warm air.

2. Evaporation Varian vacuum system (VE30M) has been used for the evaporation. All evaporation are made at a pressure less than 10 TO RR. It is relatively difficult to evaporate thick NiFeCo films from resistance heated tungsten boats or resistance heated alumina crucibles because the boats are dissolved by the melt and the crucibles are easily fractured for temperature necessary for reasonable evaporation rates. To solve this difficulty, an electron gun has been used to heat the source material. Normally the cobalt, available in powder form, is premelted under vacuum to reduce subsequent sputtering before adding suitable quantities of nickel and iron to form the desired nonmagnetostriiction composition.

The glass substrate is placed in an aluminum holder and clamped on a copper block. The temperature of this copper block can be controlled by
a quartz lamp for annealing. A shutter in the vacuum system controls
the evaporation times, which in fact, controls the evaporated film thick-
ness. A Sloan crystal monitor is used to measure the film thickness. All
the films have been made with the thickness greater than 1000Å to assure
the Bloch wall structure exists. The normal evaporation rate is 15 Å/sec.

3. Annealing In order to obtain good adhesion of films deposited
at a typical substrate temperature of 100°C, it is still necessary to
heat the substrate at 300°C for several hours for outgasing purpose. A
30 oe magnetic field supplied by a pair of Helmholtz coil outside the
bell jar is present during the evaporation which induces the uniaxial
anisotropy. It has been found that in order to obtain consistent quality
in the film properties, it is necessary to anneal the films with 30 oe
field at the deposition temperature for 12 hours. After this long period
of annealing, the films then permit to cool to room temperature but still
with the field presents. Fig. 2.1. illustrates in details the evaporation
systems.

II.2. Magnetic Properties of NiFeCo Films

The uniaxial anisotropy field $H_k$, angular dispersion $\alpha_{90}$, coercivity
$H_c$, thickness T, magnetization M and composition of vapor evaporated
NiFeCo films have been carefully measured. $H_c$, $H_k$, $\alpha_{90}$ and M are measured
using a 400 Hz B-H loop tracer. Thickness is determined by Talysurf
machine and composition is determined by X-ray diffraction technique.
Details of these measurement techniques can be found in general thin film
text books which are listed in the reference section.

With the melt composition and substrate temperatures corresponding to
the recipes in ref.25, the film properties are remarkably predictable. The
results are tabulated in Table I.
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Table I. Magnetic Properties of NiFeCo Films
CHAPTER III

INFLUENCE OF COERCIVE FORCE ON LOW FREQUENCY CREEP

III.1. Introduction

In a previous report dealing with low frequency creep in low coercive force NiFe films of Bloch wall thickness, it is shown that, for a given hard axis field magnitude (0.6 $H_k$), the creep displacement increases linearly in the amount of easy axis bias in excess of the value necessary to cause net motion. As the amount of easy axis bias field approaches the conventional wall motion threshold, the creep displacement increases at a much faster rate. Eventually this threshold is exceeded and continuous wall motion takes place. This initial rate of increase with easy axis bias is observed to depend on reciprocal wall coercive force ($0.6 \leq H_C \leq 4$ oe). It is also found that for hard axis field in the range $0.4 \leq H_h/H_k \leq 0.8$, the conventional wall motion threshold and the creep motion threshold are well separated. The creep motion is very consistent, net random, and the amount of easy axis bias necessary for the onset of creep motion $(H_e)_{crit}$ is very nearly independent of the hard axis field amplitude.

III.2. Experimental Technique

On account of their smooth surface, thin films are very suitable for the application of the Bitter technique. The experimental results in this chapter are obtained by using this technique. This technique is first invented by Bitter and independently by Hamos and Thiessen. A drop of a suspension which contains fine ferromagnetic colloidal particles, is applied to the thin film surface and is squeezed to a thin layer by a microscope coverglass. The particles in the
suspension are so small that they perform Brownian motion. When the particles come close to the domain wall, they are attracted by the stray field which is associated with the walls and then the pattern of magnetic structure is observed. The elegance of this technique is that it can indicate the domain wall structure changes which is fundamentally related to low frequency creep.

The colloidal solution used in this laboratory is prepared according to the recipe by Chikazumi\(^{30}\). A Nikon optical microscope is used in this study. At the highest magnification (x3000) using a wide aperture oil-immersion lens (numerical aperture = 1.25), a Bloch wall may be clearly seen even in thick films (2400 A). Crosstie and Neel wall are also easily observed.

A disadvantage of the usual Bitter technique is the comparatively short observation time due to the rapid evaporation of the colloid, especially when the objective of the microscope presses too strongly on the coverglass. If a silicone grease is applied to the substrate to form a reservoir around the film, a drop of colloid placed on the center of the film surface and sandwich completed with a microscope coverglass, the colloid is completely isolated from the air and the oil immersion lens. In this way the observation time can be extended to more than two days. Fig. 3.1 shows the configuration of experimental set up. The stripe line system may be used to apply superimposed fast pulses when appropriate.

All observations are made on an isolated bridge domain walls parallel to the easy axis and near the center of the films. Two pairs of Helmholtz coil are used to supply easy and hard axis fields.
The hard axis bipolar field is obtained by means of a toggle switch. The ambient stray field are carefully reduced by a compensating field to less than 0.01 oe.

III.3. Experimental Results

III.3.a. Threshold field of creep

Fig. 3.2 indicates a typical creep threshold curve for a Bloch wall NiFeCo film together with the normal states wall motion threshold. The rise time of hard axis field is greater than 100 microseconds. This result suggests that creep is critically associated with the magnitude of the hard axis field while normal wall motion is associated more closely with the easy axis field.

The general features of the creep threshold curves for NiFe and NiFeCo films are identical with the threshold curve in Fig. 3.2 except for the value of \((H_e)_{\text{crit}}\). As long as the creep threshold is sufficiently separated from the rotational threshold curve.

However, for very high coercive force films, there is a tendency for the creep threshold to merge into the Stoner-Wohlfarth rotational threshold (see Fig. 3.3) and \((H_e)_{\text{crit}}\) is not well defined. This can be understood that if the creep threshold curve inferred from the low coercive force, low dispersion sample lies outside of the rotational threshold curve of the sample being considered, then the observed creep threshold will coincide with rotational threshold because the rotational process, now able to occur at fields below the inferred creep threshold, act to assist or even trigger the creep transition. Hence, the observed creep threshold curve never exceeds
Fig. 3.2 Creep and wall motion thresholds for a typical NiFeCo sample.
Fig. 3.3 Creep threshold for very high coercive force NiFeCo sample showing relationship to the rotational threshold.
the rotational threshold.

III.3.b. **Critical easy axis field**

It has been found that for low coercive force NiFe film, if the hard axis field is greater than the wall transition field, net creep displacement begins with a very small easy axis bias. This indicates that the intrinsic driving mechanism is able to overcome the low coercive force constraint. However, for NiFeCo films, a finite easy axis bias is necessary in order to overcome the high coercive force, although the wall structure change still occur, no jump is induced by these transitions and consequently, no net creep motion occurs without exceeding a critical value \( H_e \text{ crit.} \) of the easy axis bias field. In Fig. 3.4, this critical easy axis field is shown as a function of wall coercive force. The critical easy axis field seems linearly related to the coercive force for low coercive force films. However, it tends to saturate with continued increase in coercive force beyond 4 oe until rotational processes dominate the creep threshold and a unique definition of \( (H_e) \text{crit.} \) is not possible.

III.3.c. **Average creep displacement**

The creep displacement curves for several NiFe and NiFeCo Films are shown in Fig. 3.5. The individual displacement curves correspond to bipolar creep with the amplitude of the hard axis field in the vicinity of 0.6 \( H_k \) to ensure that the fundamental creep transition has a high probability of occurrence without other processes interfering. If the initial slope of net creep displacement versus easy axis bias curves, corresponding to the same degree of hard axis
Fig. 3.4 Critical value of easy axis field for net creep motion as a function of coercivity. Superscripts in legend indicate data source.
Fig. 3.5 Net creep displacement versus normalized easy axis bias for several NiFe and NiFeCo films.
excitation, are plotted against reciprocal wall coercive force. (see Fig. 3.6) A linear relationship results for most films of this and other reports regardless of composition. The data from Middelhoek and three assitional NiFe samples, however, are charaterized by anomalously high creep rates. This anomaly does not appear to be correlated directly to the magnetic properties, such as mobility, or to the thickness of the samples. A low coercive force NiFe film $H_c = 0.6 \text{ oe}$ although off the scale falls exactly on the curve. The sample from Telesnin et al. is shown with horizontal error bars because the exact wall coercive force is not known. The source of the NiFe film data is indicated by appropriate superscripts in the legend of Fig. 3.6. Most of the films represented have nominal wall mobilities $2 \times 10^3 \text{ cm/oe-sec}$.

An additional and unexpected feature of Fig. 3.6 is that the extrapolated creep rate approaches zero for a large but apparently finite value of coercivity. Creep is effectively eliminated, however, on a practical level when the creep thresholds are forced to approach the rotational threshold curve.

Nevertheless, the experimental results indicate that the initial slope of the creep displacement curve for Bloch wall NiFeCo films is fundamentally related to the reciprocal wall coercivity and otherwise independent of a wide range of composition and film thickness. Previous theories of low frequency creep described in Chapter one do not appear to explain the strong and simple coercive force dependence on low frequency creep motion.
Fig. 3.6 Initial slope of creep displacement curves against reciprocal wall coercivity. Superscripts in legend indicate data source.
CHAPTER IV
INFLUENCE OF COERCIVE FORCE ON HIGH FREQUENCY CREEP

The study of domain wall high frequency creep motion is less intensive compared to low frequency creep studies. This may be due to the fact that high frequency creep is only discovered in late 1967. Previous studies high frequency creep are mainly focused on the pulse rise time dependence $^{31}$ and the film thickness dependence $^{32}$. In this chapter, the domain wall high frequency creep motion is examined with regard to coercive force and compared to the low frequency creep results in chapter III. The study has been focused on Bloch wall films, since high frequency creep is somewhat more easily modeled by gyromagnetic induced motion for films of this thickness as discussed in chapter I.

IV.1. Experimental Technique

IV.1.a. Kerr magneto-optic effect

The Kerr magneto-optic effect has been used by many people for observation of domains in thin films. When linearly polarized light is reflected by a ferromagnetic sample, the plane of polarization is rotated through an angle which depends on the magnetization direction in the sample. Very often a thin film consists of domains with antiparallel magnetization. An analyzer can be adjusted in such a way that the light reflected from one kind of domain is extinguished.

Depending on the direction of the magnetization with respect to the plane of the film and the plane of incidence, three Kerr magneto-optic effects are known (1) Kerr longitudinal effect where the magnetization is in the plane of the film and parallel to the plane of incidence. (2) Kerr transverse effect where the magnetization is in
the plane of the film but perpendicular to the plane of incidence. 

(3) Kerr polar effect where the magnetization is perpendicular to 
the plane of the film.

IV.1.b. **Experimental set up**

In this experiment the longitudinal Kerr magneto-optic effect has 
been utilized to observe the domains and the movement of thin 
boundaries. A mercury-vapor lamp with collimating lenses and a 
mercury green-line filter is used as light source. To utilize 
the small Kerr rotation, the high Quality glan laser prisms are used 
as the polarizer and the analyzer. Magnetic domain patterns are 
observed directly through a low power telescope.

A shorted, biplate, 50 ohm stripline with an optical window 
close to the short-circuited end is used to supply the hard axis 
pulse field. The sample is placed in a plastic plate and then the 
plastic plate is mounted inside the stripline by silicone grease. 
In this way, the sample position and orientation can be easily adju- 
sted. A pair of Helmholtz coils is used to generate easy axis bias 
field. The influence of the earth has been reduced to less than one 
millioersted by a compensating field supplied by three pairs of 
Helmholtz coils arranged perpendicularly to each other. Two high 
voltage mercury pulse generators made by E-H laboratory (model 126) 
and S-K laboratory (model 503) are used to generate nanosecond pulses. 
The fastest rise time of both pulse generators is 0.5 nsec. The rise 
and fall time of a pulse can be adjusted independently. The rise time 
can be changed by using a rise time integrator at the output of the
pulse generator. The fall time can be adjusted by placing a RC network at the end of the charging cable. Fig. 4.1 shows the schematic diagram of this experimental set up.

In many of the previous reports, the reported measurements were usually made by sensing an entire thin film using either inductive pickup loop or Kerr optic utilizing photo multipliers. These are measurements of the entire film; edge effects, domain tip motion, domain wall coupling, demagnetized field etc, are averaged into the results. Hence, extrapolation to specific mechanisms causing creep is practically impossible. To avoid such difficulties, the measurements present here are made on an isolated, single, straight, smooth, planar domain walls which are parallel to easy axis and near the center of the film. To reduce the effects of film inhomogenities, the wall is made to travel in a given direction over a specified distance (137 \( \mu \text{m} \)) and the number of applied pulses counted. After the displacement is completed, the wall is reset to its initial position by applying an sinusoid field in the easy axis direction. During the experiment, care is exercised to prevent domain tip motion and other nucleation processes that interfere with planar wall motion.

IV.2. Experimental Results

IV.2.a. Threshold field of creep

The threshold field of domain wall high frequency creep for NiFe and NiFeCo films is shown in Fig. 4.2. The threshold field is determined for a dc easy axis bias field set at a desired level, the hard axis pulse field amplitude was then slowly increased until the onset of creep was detected. The unidirectional hard axis pulse field
Fig. 4.1. Schematic diagram of Kerr magneto-optic apparatus
Fig. 4.2 Domain wall motion thresholds in terms of normalized hard axis pulse and easy axis bias field.
with rise time 0.5 nsec and fall time 200 nsec was used to determine the threshold curve. It is found that the magnitude of hard axis field necessary to cause creep decreases as the easy axis bias field increases and the relation is reasonably linear. Both NiFe and NiFeCo films have the same threshold characteristics despite large differences in their composition and thickness. This feature is shown in Fig. 4.2 for the $H_c = 1.68$ oe NiFe film and the $H_c = 4.8$ oe, 7 oe NiFeCo films. This can be explained due to the fact that, the threshold hard axis pulse field amplitude is below the normal Bloch-Neel transition field which is $\geq 1/3 H_K$. Therefore, the gyromagnetic process is responsible for the high frequency creep and this creep process is somewhat independent of composition and thickness.

However, for a high coercive force film as indicated in Fig. 4.2 for the film with $H_c = 12.8$ oe, the amplitude of hard axis threshold field is above the Bloch-Neel transition field. The creep motion involves two mechanism: gyromagnetic effects of the Bloch wall and transition effects as the wall structure changes. The threshold field becomes steeper and can not be interpreted by the gyromagnetic process alone. In general, the threshold field seems directly related to coercive force. As the coercive force increases, eventually the threshold curve emerges into the static wall motion threshold.

IV.2.b. Average creep displacement per pulse
b.1. fast rise and slow fall time hard axis pulse

The creep displacement are obtained by applying fast rise time 0.5 nsec and slow fall time 200 nsec pulse fields in the hard axis
direction and a dc field in the easy axis direction. It has been observed that when the pulse are initially applied, with the easy axis bias presence, the wall remains approximately stationary while bulging and becoming wavy. After this process the wall then moves uniformly, straightening itself out due to wall stiffness. As described in chapter 1, the magnetization in the Bloch wall reverses its direction out of the plane of the film from segment to segment in order to reduce the stray fields. According to the gyromagnetic procession motion, at least a majority of the wall must be magnetized in one direction for creep to take place. The bulging and waving of the wall is attributed to the remagnetization of the Bloch wall segment. Fig. 4.3 shows the average creep displacement per pulse, for a given hard axis pulse field, versus the easy axis field normalized by the wall coercive force for several samples. The magnitude of the hard axis pulse field has been kept below the B-N transition field to assure that no wall structure change occurs so that the gyromagnetic process is solely responsible for the wall displacement. As shown in Fig. 4.3, the creep step size is increased linearly with respect to easy axis bias once the bias exceeds a certain critical value. As the easy bias field approaches the conventional wall motion threshold, the creep step size increases to a much faster rate. This result is similar to previous low frequency creep results, although the creep displacement curves in Fig. 4.3 look somewhat more parabolic and the creep step size is an order of magnitude larger. The interesting result is the average creep displacement curves result in almost identical curves for both NiFe and NiFeCo films except for a shift
Fig. 4.3 Average creep displacement versus normalized easy axis bias with fast rise and slow fall time hard axis pulse field.
associated with the threshold field. The result is consistent with low frequency creep results despite the different excitation field in this case. The resemblance suggests that the basic mechanism for both high and low frequency creep may be closely related.

b.2. **equal vise and fall time hard axis pulse**

To examine the correlation between high and low frequency creep move closely, equal rise and fall time (2 nsec) hard axis pulse fields are used. This pulse field is similar to unidirectional hard axis ac field except for the rise and fall times. The average creep displacement, for a given hard axis pulse field, is plotted against normalized easy axis field in Fig. 4.4 for NiFeCo films. Again the magnitude of hard axis field is kept below the B-N transition field to assure that gyromagnetic induced motion is responsible for the creep process. The average creep displacement per pulse is considerably reduced when compared to Fig. 4.3 and is on the same order of magnitude as the low frequency creep step size. According to gyromagnetic induced motion mechanism, the creep displacement due to the leading and trailing edges of the hard axis pulse has the same magnitude but in the opposite direction. With an easy axis bias present, the bias field can aid the motion in the direction favored by the field and oppose the motion in other direction. Therefore, the net wall displacement is the difference between these two opposite wall displacements. The creep displacement curves indicate the same feature as Fig. 4.3 and as low frequency creep results of Fig. 3.5.

It has also found that the high frequency creep displacement curve can be reproduced by using a bipolar hard axis low frequency ac field with the appropriate magnitude. The measurements were made
Fig. 4.4 Average creep displacement versus normalized easy axis bias for NiFeCo films with equal rise and fall time hard axis pulse field.
on a domain wall at the same position of the film for both high and low frequency creep to avoid the errors due to film inhomogenity. This and above results may imply that the gyromagnetic nature of the low frequency creep process in these experiments.

IV.3. Discussion

The experimental results in this chapter strongly indicate that the high frequency creep displacement curves for Bloch wall NiFeCo films are reciprocally related to the wall coercivity and otherwise independent of composition and film thickness. These results are to be expected because the high frequency creep is agyromagnetic process. Further, the consistency of high and low frequency creep results indicates the gyromagnetic process is fundamental for low frequency creep. However, Previous published theories as described in chapter one do not appear to explain the simple reciprocal coercive force dependence on domain wall creep motion.

From the experimental results, it is concluded that the influence of the domain wall coercive force predominates in the behavior of the domain wall creep motion once the motion is triggered by a hard axis pulse or a low frequency ac field. Previous theories probably can account for the initiation of the creep motion. However a complicated coercive force model must be invoked in order to explain all aspects of the creep motion.

With the gyromagnetic process as a trigger together with a non-conservative spring coercive force model, the high frequency creep is analyzed quantitatively in chapter VI.
CHAPTER V
INFLUENCE OF EASY AXIS BIAS ON HIGH FREQUENCY CREEP
AND ON CONVENTIONAL WALL MOTION

V.1. Gyromagnetically induced kinds of wall motion

The domain wall motion in Bloch wall films occurs when the film is subjected to a hard axis pulse field or an easy axis field. Both are gyromagnetically induced kinds of wall motion.

If a magnetic field is applied parallel to a Bloch wall, one of the adjacent domains which should therefore grow at the expense of the other domain. At the moment of application, the spins in a Bloch wall process around the applied field, hence there is a rotation of the spins out of the plane of the wall and this results in a large demagnetizing field perpendicular to the wall. The subsequent motion of the spins is to precess around this demagnetizing field, which causes the wall to move in a transverse direction. The direction of the motion is independent of the direction of spins in the wall as indicated in Fig. 5.1-a.

When a fast rise time pulse is applied perpendicular to a Bloch wall and as long as the wall structure is not in a equilibrium with the applied field and the anisotropy, the spins in the wall center processes around the field and the wall is thereby displaced. However, the direction of motion in this case is dependent on the spin polarity in the wall. As indicated in Fig. 5.1-b, the direction of basic wall motion under this excitation depends upon the two possible spin polarities in the wall.
Fig. 5.1. The dependence of the direction of motion on the rotation of wall spin by the application of (a) a field along the Bloch wall and (b) a fast rise time pulse field perpendicular to the wall.
V.2. A new type of wall motion

For high frequency creep, the presence of an easy axis bias field can either aid or oppose the basic motion, a new type of wall motion is discovered. As the bias field opposing the basic motion is increased from zero, the net wall displacement gradually decreases and it is somewhat surprising to find out that the wall eventually moves in the direction favored by the easy axis field even with the bias field considerably less than the wall coercive force. Fig. 5.2 shows the effect of easy axis bias aiding and opposing the basic wall motion for NiFe and NiFeCo films. The easy axis field necessary to cause the negative wall motion is directly dependent on the wall coercive force. For NiFe film with lower coercive force value, the critical easy axis field is about 0.5 $H_c$. Fig. 5.3 shows the effect of easy axis bias for NiFe film with a hard axis pulse field as parameter. Note that the critical easy axis bias field for causing the negative wall motion directly depends on the magnitude of hard axis pulse field.

This reverse wall motion does not appear to be due to a change of spin polarity inside the wall. During this experiment, the possibility of spin polarity change inside the wall has been carefully examined. As soon as the reversed wall motion is observed, the easy axis bias field is immediately removed and the same hard axis pulse field is applied on the wall. The direction of wall motion indicates that the spin polarity does not change.

The influence of easy axis bias on domain wall motion excited
Fig. 5.2 Average creep displacement versus normalized easy axis bias with fast rise and slow fall time hard axis pulse field showing effect of negative bias field.
Fig. 5.3 Average creep displacement versus normalized easy axis bias with fast rise and slow fall time hard axis pulse field showing effect of negative bias field.
by an easy axis pulse field has also been studied. Very short duration pulses with amplitudes much larger than the wall coercive force are used to excite the domain wall. Fig. 5.4 shows the wall displacement curves versus easy axis bias for two different pulse durations. The result is remarkably similar to the high frequency creep data. The easy axis bias field necessary to cause negative wall motion is larger than the high frequency creep case. This fact indicates that hard axis pulse field may be more effective in exciting this reverse motion. It is also found from the displacement curves that there is an equivalence in high frequency creep and conventional wall motion by very short duration pulse fields. This relation is shown explicitly in the quantitative analyses of creep in next chapter.

This new and significant results can not be explained by a simple gyromagnetic process and the normal models of wall coercive force. When the hard axis pulse field is applied, the presence of easy axis bias will cause unequal rotation of magnetization in the adjacent domains. This creates a net change on the wall and induces a stray field along the wall. The easy axis bias together with this induced stray field could overcome the film coercive force. However, these pulses are unipolar so that this induced field should not contribute to sustained motion along a large section of the wall. The hard axis pulse lowers the wall energy and reduces the coercive force, However, static wall motion threshold curve indicates that this effect should be negligible for hard axis bias fields of this magnitude.

This new type of wall motion may be attributed to the nature of
Fig. 5.4 Domain wall displacement versus easy axis bias with very short duration easy axis pulse field showing the effect of negative bias field.
the interaction of magnetic domain walls with imperfections. A non-conservation spring coercive force model which will be discussed in next section could be used to explain this wall motion qualitatively.

V.3. Nonconservative spring coercive force model

It is well known that the motion of domain walls is affected by crystalline imperfections such as localized stresses, inclusions, grain boundaries, etc. In order to understand the domain wall motion phenomenon, it is important to know the nature of the interaction between a wall and a defect.

The interaction of a domain wall with crystalline imperfection is frequently represented by means of a conservative potential function which gives the energy of the wall as a function of position. In 1956 Rodbell and Bean criticized this conservative point of view and showed that it could not be brought into agreement with the experimentally determined dependence of wall velocity on applied magnetic field. They showed that the interaction as more closely approximated by a constant frictional drag, which is purely nonconservative and suggested that the origin of this interaction might be found in the breaking away of Neel spikes from a moving wall.

Baldwin proposed a nonconservative spring coercive force model which is based on Rodbell and Bean's nonconservative model but with some modifications. This model will be discussed here and used to solve creep motion analytically in next chapter.

In making calculations concerning the motion of magnetic domain wall, it is usual to ignore the flexibility of a wall, i.e. its ability
to deform in the vicinity of an irregularity in the material. According to this nonconservative spring coercive force model, the real flexible wall is replaced by an equivalent rigid plane wall which is parallel to the x-z plane and whose position is y. The static and dynamic motion of the equivalent wall are approximately the same as those of the average position of a real wall. The interaction of the equivalent wall, which position is y, with a localized defect at y=0 is represented by a massless spring connecting the rigid wall to the defect. The spring constant is k. As the wall moves through y=0 the spring is connected to the wall. As the wall moves on the spring exerts a force f on the wall according to the relation \( f = -ky \). When the extension of the spring reaches a value \( y_o \) (called defect range) characteristic of the defect, the spring breaks and the stored energy is lost. The defect then no longer exerts a force on the wall. The uniform motion of the wall is accompanied by a continuous attachment and breakage of springs. The result is a frictional energy loss.

Consider a wall moving through a random distribution of identical defects, i.e., they all have the same defect range \( y_o \). It will be connected by a spring to all defects in its wake within a distance \( y_o \) and will not be connected to any defects ahead of it. If there are N defects per unit volume, therefore, the pressure \( P_s \) on the wall due to defects is given by \( P_s = -Nk y_o^2/2 \), where the minus sign indicates that the pressure is in the minus y direction and the subscript s indicates that the pressure is saturated (independent of y). It is assumed that the total number of attached defect is large so that we may deal with average values and not be concerned with fluctuation from the average. The wall is now stopped and allowed to move backward a distance less than \( y_o \). This situation is
shown in Fig. 5.5.a. The pressure $P_u$ is now unsaturated and depends on $y$. It is given by

$$ P_u = Nk \int_{-\frac{y_o}{2}}^{\frac{y_o}{2}} \left( y' - y \right) dy' = -Nky_o y. $$

The pressure exerted by the defects on the wall is then as shown by the full line in Fig. 5.5.b. Wall motion within the region $-y_o/2 \leq y \leq +y_o/2$ is reversible. Outside this region wall motion is irreversible. If the wall is moved past $y_o/2$, say to point A and then allowed to move backward, it will proceed along the dashed line rather than the full line.

The behavior of negative wall motion described in the last section can be qualitatively explained by utilizing this nonconservative spring coercive force model. Since the wall has an effective mass and is bound by a breakable spring. With no easy axis bias field, the hard axis pulse excitation does not break springs attached on the wall, then the wall may perform an damped oscillation until reaching its equilibrium position. With an easy axis bias field presents, however, the equilibrium position of the wall is shifted, and the oscillatory excursions of the wall about the shifted equilibrium may be such that springs are broken and net displacement occurs in the direction favored by the easy axis bias even though the pulse excitation favors the motion in the opposite direction.
Fig. 5.5.a. Equivalent plane rigid wall according to the spring model. The wall, previously moving to the right, has been stopped and allowed to move a short distance to the left. Defects are represented by circles. The springs are all identical and have a maximum extension $y_0$.

Fig. 5.5.b. Pressure exerted on the equivalent rigid wall by a random distribution of identical defects. Motion within the limits $-y_0/2 \leq y \leq y_0/2$ is reversible while motion outside these limits shows frictional hysteresis.
CHAPTER VI
MATHEMATICAL FORMULATION
OF DOMAIN WALL CREEP MOTION

VI.1. The equations of dynamic wall motion

When the magnetization is excited by an externally applied field, the following motion of the magnetization can be described by the Landau-Lifshitz equation \(^{38}\) which was proposed by Landau and Lifshitz in 1935, in terms of the torque \(\vec{T}\) acting on the magnetization \(\vec{M}\), this equation is

\[
\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{T} - \frac{\lambda}{|\vec{M}|^3} \vec{M} \times \vec{T}
\]  

(1)

where \(\gamma\) is the gyromagnetic ratio and \(\lambda\) is the damping constant.

Gilbert has pointed out that in the limit of very large \(\lambda\), the damping torque, \((\frac{\lambda}{|\vec{M}|}) \vec{M} \times \vec{T}\) becomes greater than the applied torque \(\vec{T}\) and \(\vec{M}\) does not move in the direction of \(\vec{T}\); an impossible result. Thus Gilbert proposes a modified equation \(^{39}\) in which the damping appears in the more familiar and logically consistent way as proportional to \(\frac{\partial \vec{M}}{\partial t}\); this equation is

\[
\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{T} + \alpha \left( \frac{\vec{M} \times \frac{\partial \vec{M}}{\partial t}}{|\vec{M}|} \right)
\]  

(2)

where \(\alpha\) is the Gilbert's damping constant.

The torque acting on the magnetization is derived from the total free energy \(E\) by the equations \(\vec{F} = -\nabla E\), \(\vec{T} = \vec{r} \times \vec{F} = -\vec{r} \times \nabla E\);

(3)

where \(\vec{F}\) is the generalized force and \(\vec{r}\) is the radius vector in the direction of \(\vec{M}\). In spherical coordinates we have:
\[ M = \vec{\lambda} \cdot \vec{M} \quad (4) \]

\[ \frac{\partial \vec{M}}{\partial t} = M \left( \vec{\lambda} \frac{\partial \varphi}{\partial t} + \vec{\lambda} \frac{\partial \theta}{\partial t} + \vec{\lambda} \sin \varphi \frac{\partial \varphi}{\partial t} \right) \quad (5) \]

\[ \vec{T} = -\vec{r} \times \left( \vec{\lambda} \frac{\partial \vec{E}}{\partial \theta} + \vec{\lambda} \frac{\partial \vec{E}}{\partial \phi} \cos \varphi + \vec{\lambda} \frac{1}{\sin \theta} \frac{\partial \vec{E}}{\partial \varphi} \right) \]

\[ = -\vec{r} \frac{\partial \vec{E}}{\partial \theta} + \vec{r} \frac{1}{\sin \theta} \frac{\partial \vec{E}}{\partial \varphi} \quad (6) \]

By using the variational derivative instead of the partial derivative of the free energy \( E(\theta, \phi, \theta', \phi') \), not only the magnetostatic and anisotropy contributions, but also exchange contributions to the local torque can be regarded. The variational derivatives are

\[ \frac{\delta E}{\delta \theta} = \frac{\partial E}{\partial \theta} - \frac{d}{d\chi} \left( \frac{\partial E}{\partial (\frac{\partial \theta}{\partial \chi})} \right) - \frac{d}{d\varphi} \left( \frac{\partial E}{\partial (\frac{\partial \theta}{\partial \varphi})} \right) \quad (7) \]

and

\[ \frac{\delta E}{\delta \phi} = \frac{\partial E}{\partial \phi} - \frac{d}{d\chi} \left( \frac{\partial E}{\partial (\frac{\partial \phi}{\partial \chi})} \right) - \frac{d}{d\varphi} \left( \frac{\partial E}{\partial (\frac{\partial \phi}{\partial \varphi})} \right) \quad (8) \]

A one dimensional Bloch wall is assumed to exist in a bulk specimen of ferromagnetic material described by a uniaxial anisotropy constant \( K \), an exchange constant \( A \) and a saturation magnetization \( M \), with the coordinate system shown in Fig. 6.1.
Fig. 6.1. Domain Wall Coordinate System
The total energy can be expressed as

\[ E = - H_y \sin \theta \sin \Phi - H_z \cos \theta + K \sin^2 \theta \left( (\nabla \theta)^2 + \sin^2 \theta (\nabla \Phi)^2 \right) \]  

(9)

the field \( H_y \) and \( H_z \) permit the introduction of stray and applied fields and the \( Z \) axis is the easy direction. Substituting (9) into (7) and (8), we get

\[ \frac{\delta E}{\delta \theta} = - H_y \cos \theta \sin \Phi + H_z \sin \theta + 2K \sin \theta \cos \theta (\nabla \Phi)^2 - 2A \nabla^2 \theta \]  

(10)

\[ \frac{\delta E}{\delta \Phi} = - H_y \sin \theta \cos \Phi - 2A \sin^2 \theta \nabla^2 \Phi - 4A \sin \theta \cos \theta (\nabla \theta \cdot \nabla \Phi) \]  

(11)

Now substituting (10), (11), (5) & (6) into Gilbert equation (2) and equating the \( \dot{i}_\theta \) and \( \dot{i}_\Phi \) components on both side, the following equations can be derived.

\[ \frac{M \sin \theta}{r} \frac{\Theta}{\dot{r}} + \frac{M M}{r} \sin^2 \theta \frac{\dot{\Phi}}{\dot{r}} = H_y \sin \theta \cos \Phi + 2A \sin^2 \theta \nabla^2 \Phi + 4A \sin \theta \cos \theta (\nabla \theta \cdot \nabla \Phi) \]  

(12)

\[ \frac{M \sin \theta}{r} \frac{\dot{\Phi}}{\dot{r}} - \frac{M M}{r} \frac{\Theta}{\dot{r}} = - H_y \cos \theta \sin \Phi + H_z \sin \theta + 2K \sin \theta \cos \theta + 2A \sin \theta \cos \theta (\nabla \Phi)^2 - 2A \nabla^2 \theta \]  

(13)

However, these two nonlinear partial differential equations are too complicated to solve analytically. Even a numerical solution is not likely because it requires enormous amount of computer time. Therefore, in order to simplify the problem, we shall only consider our calculation.
at the wall center.

With the presence of an applied field in the hard axis direction for high frequency creep, \[ H_y = H - \left( \frac{M}{\mu_0} \right) \sin \Theta \sin \varphi \] (14)
where \( H = H_h + \frac{M}{\mu_0} \left( \frac{H_h}{H_k} \right) \) and \( H_k = 2K/M \), \( H_h \) is the actual applied hard axis field and \( \frac{M}{\mu_0} \left( \frac{H_h}{H_k} \right) \) is the induced field by a sudden change in the magnetization in the neighboring domains.

By using the conditions \( \Theta = \pi/2 \) and \( \frac{\partial^2 \Theta}{\partial y^2} = 0 \) at the wall center together with the assumption that \( \nabla^2 \varphi \) is negligible at wall center, we can obtain the following two equations from (12), (13) & (14).

\[
\frac{\partial \Theta}{\partial t} + \alpha \frac{\partial \varphi}{\partial t} = \gamma \cos \varphi - \frac{\gamma M}{\mu_0} \cos \varphi \sin \varphi \quad (15)
\]
\[
\frac{\partial \varphi}{\partial t} - \alpha \frac{\partial \Theta}{\partial t} = \gamma H_z \quad (16)
\]

With \( \tau = \frac{\gamma M}{\mu_0} \), \( h = \frac{H}{M/\mu_0} \), \( h_z = \frac{H_z}{M/\mu_0} \); (15) & (16) can be rearranged to get

\[
(1 + \alpha^2) \frac{\partial \varphi}{\partial t} = \alpha \cos \varphi - \alpha \cos \varphi \sin \varphi + h_z \quad (17)
\]
\[
(1 + \alpha^2) \frac{\partial \Theta}{\partial t} = \cos \varphi - \sin \varphi \sin \varphi - \alpha h_z \quad (18)
\]

(17) & (18) are the equations of motion of high frequency creep motion with easy axis bias presence.

The nonconservative spring coercive force model as previous described in chapter V can be included in this stage, therefore, the equations of motion becomes
\[(1 + \alpha^2) \frac{\partial \varphi}{\partial \tau} = \lambda \cos \varphi - \lambda \cos \varphi \sin \varphi + \left[ h_z - \left( \frac{\tau}{\Delta} \right) h_c \right] \quad (19) \]

\[(1 + \alpha^2) \frac{\partial \theta}{\partial \tau} = h \cos \varphi - \cos \varphi \sin \varphi - \lambda \left( h_z - \left( \frac{\tau}{\Delta} \right) h_c \right) \quad (20) \]

for \( y \leq \Delta/2 \)

\[(1 + \alpha^2) \frac{\partial \varphi}{\partial \tau} = \lambda \cos \varphi - \lambda \cos \varphi \sin \varphi + \left( h_z - h_c \right) \quad (21) \]

\[(1 + \alpha^2) \frac{\partial \theta}{\partial \tau} = h \cos \varphi - \cos \varphi \sin \varphi - \lambda \left( h_z - h_c \right) \quad (22) \]

for \( y \geq \Delta/2 \)

where \( h_c = \frac{H_c}{M/\mu_0} \) and \( \Delta \) is the characteristic range of the defects.

With the assumed spin direction in the wall (see Fig. 6.1.), a negative hard axis drive field \( H \) corresponds to a gyromagnetic precession which moves the wall in the positive direction. The velocity of the wall center, which is equal to the velocity of the wall is

\[
\frac{d y}{d \tau} = - \frac{\partial \theta}{\partial \tau} \frac{\partial \varphi}{\partial y} \quad (23)
\]

Therefore, as the equations of the motion for the magnetization at the wall center is known, one should be able to understand the dynamic behavior of the Bloch wall in principle by solving above (19)-(23) equations. However, the analytical solution is difficult because of the nonlinear nature of these equations.

VI. 2. Computer solutions

To obtain interpretable results it is necessary to use a computer.
With the following typical data, $M = 1\ \text{Wb/m}^2$, $\kappa = 0.01$, $A = 10^{-11}\ \text{J/m}$, $\gamma = 1.76 \times 10^7/\text{oe-sec}$, the high frequency creep displacement has been solved numerically from (19)-(23) by using the Runge-Kutta numerical technique. The result is shown in Fig. 6.2.

The displacement is plotted against the easy axis bias field normalized by the wall coercive force with coercive force as parameter. There are at least three points of interest: (1) the creep displacement is linearly increased with respect to increasing easy axis bias field, (2) the fact that all the creep displacement curves results in almost identical curves except for a shift which is due to the threshold field, (3) the negative wall motion occurs for bias field opposing the basic wall motion. All these features have been remarkably predicted by previous experimental results.

VI. 3. An analytic solution

The analytic solution of the equations of motion for high frequency creep has obtained with some reasonable approximations.

The $\phi$ angle is usually small because of the small amplitude of the hard axis drive field. Therefore, with $\cos \phi \approx 1$, $\sin \phi \approx \phi$ and $\kappa^2 \ll 1$, the equations of motion (19)-(22) become

$$\frac{d\phi}{dt} + \kappa \phi = \alpha h + (h_z - \left(\frac{\gamma}{A}\right) h_c) \quad (24)$$

$$\frac{d\theta}{dt} = h - \phi - \kappa \left(h_z - \left(\frac{\gamma}{A}\right) h_c \right) \quad (25)$$

for $y \leq \Delta/2$
Fig. 6.2 Average creep displacement versus normalized easy axis bias field by computer solution of equation of motion with nonconservative spring coercive force model.
\[ \frac{\partial \varphi}{\partial t} + \lambda \varphi = \lambda h + h_z - h_c \quad (26) \]

\[ \frac{\partial \Theta}{\partial t} = h - \varphi - \lambda (h_z - h_c) \quad (27) \]

for \( y > \Delta/2 \)

The last term at the right hand side of (25) & (27) can be neglected, since it is relatively small compared to the rest of the terms. With (23); (25) and (27) become

\[ (-\frac{\partial \Theta}{\partial y}) \frac{dy}{dt} = \varphi - h \quad (28) \]

By combining (24), (28) and (26), (28); two linearized second order differential equations in \( y \) result

\[ (-\frac{\partial \Theta}{\partial y}) \frac{d^2 y}{dt^2} + \lambda (-\frac{\partial \Theta}{\partial y}) \frac{dy}{dt} + \left( \frac{h_c}{\Delta/2} \right) y = h_z - \frac{dh}{dt} \quad (29) \]

\[ y \leq \Delta/2 \]

\[ (-\frac{\partial \Theta}{\partial y}) \frac{d^2 y}{dt^2} + \lambda (-\frac{\partial \Theta}{\partial y}) \frac{dy}{dt} = h_z - h_c - \frac{dh}{dt} \quad (30) \]

\[ y \geq \Delta/2 \]

These simple equations show some very important features. (1) The second order derivative term indicates the effective mass behavior of the wall during dynamic wall motion. (2) These equations of motion describe not only creep wall motion but also conventional wall motion. With \( h = 0 \), these equations reduce to Doring's analysis\(^2\) of wall motion for reversible wall displacement and to Baldwin's analysis for a massless wall. (3) The difference between conventional wall motion and creep motion is shown at the right hand side of (29) and (30). With
a step function hard axis applied field, the domain wall creep motion is excited by an impulse function field. However, the conventional wall motion is excited by a step function field. Therefore, with very short easy axis pulse durations, the conventional wall motion is very similar to the high frequency creep motion. This feature agrees remarkably with experimental results of chapter V. (4) For low frequency creep motion, the precise form of the applied hard axis ac field seen by the wall is not known. But it is possible to represent this ac hard axis field as an appropriate hard axis pulse field and get the same wall displacement results. Thus, these equations can also be used to analyse the low frequency creep motion.

Assume $h$ is a step function field and with the wall has the initial position $y(0^-) = (\Delta/2) \frac{h_z}{h_c}$ and initial velocity $\dot{y}(0^-) = 0$, equation (29) can be easily solved as

$$y(\tau) = \left(\frac{\Delta}{2}\right) \frac{h_z}{h_c} - \frac{h}{\omega_d \left(\frac{3y}{2y}\right)} e^{-(\Delta/2)\tau} \sin \omega_d \tau \quad (31)$$

where

$$\omega_d = \sqrt{\frac{h_c}{\frac{2y}{2y} \left(\frac{\Delta}{2}\right)}} - \frac{\Delta^2}{4} \quad \text{for} \quad y \leq \Delta/2$$

According to the experimental results, the negative wall motion can occur for both high frequency creep motion and conventional wall motion. This is possible only if the wall performs a damped oscillatory motion under the excitation of an external field which is not enough to break the springs. Thus, $\omega_d$ in (31) must be real. $\Delta/2$ does not have an
unique experimentally defined value. Previous experimental results indicate \( \Delta / 2 \) could range from \( 500 \text{Å} - 4000 \text{Å} \). Nevertheless, with typical bulk permalloy value, \( \alpha = 0.01 \), \( \frac{\partial \theta}{\partial y} = (\text{K/Å})^{1/2} = 4.463 \mu \text{m} \), \( H_c = 1 \text{ oe} \), \( M_s = 1 \text{ Wb/m}^2 \), \( \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \); \( \omega_d \) calculated from above expression is real. \( \omega_d = 2.05 \times 10^{-2} \) (for \( \Delta / 2 = 500 \text{Å} \)) and \( 0.458 \times 10^{-2} \) (for \( \Delta / 2 = 4000 \text{Å} \)).

After the wall motion starts, it takes certain amount of time for the wall to break the attached springs. This time, denoted as \( T_o \), can be calculated from (31) with \( y(T_o) = \Delta / 2 \).

Using small argument approximation about exponential and sinusoidal terms, \( T_o \) is obtained as

\[
T_o = \frac{\Delta}{(\frac{\partial \theta}{\partial y})} \left( \frac{h_y}{h_c} - 1 \right)
\]  

(32)

Note that \( h < 0 \), \( h_y < h_c \).

(32) indicates that the time required for the wall to break the attached springs is dependent on wall coercive force. Previous theoretical analysis have assumed a nonconservative wall coercive force model corresponding to the limit of \( \Delta / 2 \to 0 \). Therefore, \( T_o \) is equal to zero. As a result, the influence of coercive force on creep motion has not been fully appreciated.

For \( y \geq \Delta / 2 \), (30) becomes

\[
(\frac{\partial \theta}{\partial y}) \frac{d^2 y}{dT^2} + d(\frac{\partial \theta}{\partial y}) \frac{dy}{dT} = h_y - h_c
\]  

(33)
With the initial condition \( y(\tau_0) = \Delta/2 \), equation (33) can be easily solved. The solution is found as

\[
y'(\tau) = \left\{ \frac{y'(\tau) - \frac{1}{k\left(\frac{\partial h}{\partial \theta}\right)}(\dot{h}_z - h_c)}{\lambda} \right\} \left[ 1 - e^{-\lambda(\tau - \tau_0)} \right] + \frac{[h_z - h_c]}{\lambda \left(\frac{\partial^2 h}{\partial \theta^2}\right)}(\tau - \tau_0)
\]

\[
+ \frac{\Delta}{2}
\]

(34)

The domain wall motion will stop when the wall velocity reaches zero. The wall will then be pulled back by the attached springs and perform an oscillatory motion until the wall reaches its final equilibrium position.

Let \( \tau_1 \) be the time when wall velocity reaches zero and it can be calculated from (34) by \( \dot{y}(\tau_1) = 0 \). \( \tau_1 \) is found as

\[
\tau_1 = \frac{1}{\lambda} \ln \left\{ 1 - \frac{\lambda \left(\frac{\partial h}{\partial \theta}\right) y(\tau_1)}{h_z - h_c} \right\} + \tau_0
\]

(35)

The net displacement of the wall can be calculated from (34) & (35).

\[
y_{\text{net}} = y(\tau_1) - \Delta/2
\]

Hence,

\[
y_{\text{net}} = \frac{1}{\lambda} \dot{y}(\tau_0) + \frac{1}{\lambda^2 \left(\frac{\partial^2 h}{\partial \theta^2}\right)} (h_z - h_c) \ln \left\{ 1 - \frac{\lambda \left(\frac{\partial h}{\partial \theta}\right) y(\tau_1)}{h_z - h_c} \right\}
\]

(36)

From (31),

\[
y(\tau) = \left(\frac{\Delta}{2}\right) \left(\frac{h_z}{h_c}\right) - \frac{h}{\omega_d \left(\frac{\partial h}{\partial \theta}\right)} e^{-\left(\frac{d}{2}\right)\tau} \sin \omega_d \tau
\]
Thus

\[ \dot{y}(\tau) = \frac{h}{w_d \left( \frac{\partial \phi}{\partial y} \right)} e^{-\frac{\alpha}{2} \tau} \left( \frac{\partial}{\partial x} \sin \omega_d \tau - \omega_d \cos \omega_d \tau \right) \]

\[ \approx \frac{h}{w_d \left( \frac{\partial \phi}{\partial y} \right)} \left( 1 - \frac{\alpha}{2} \tau \right) \left( \frac{\partial}{\partial x} \omega_d \tau - \omega_d \right) \]

\[ \approx -\frac{h}{\left( \frac{\partial \phi}{\partial y} \right)} \left( 1 - \alpha \tau \right) \quad (37) \]

From (37) & (32)

\[ \dot{y}(\tau_o) = -\frac{h}{\left( \frac{\partial \phi}{\partial y} \right)} + A (\Delta / 2) \left( \frac{h_z}{h_c} - 1 \right) \quad (38) \]

Thus, the net displacement becomes

\[ y_{net} = \frac{G}{y} \dot{y} + \left( \frac{h_z}{h_c} - 1 \right) + \left( \frac{h_z - h_c}{\alpha^2 \left( \frac{\partial \phi}{\partial y} \right)} \right) \ln \left\{ 1 - \frac{1}{h_z - h_c} \right\} \]

\[ \left( 39 \right) \]

where \( G = \frac{\alpha}{A \left( \frac{\partial \phi}{\partial y} \right)} \) is the wall mobility.

The slope of the displacement versus \( h_z \) can be derived from (39).

\[ \frac{\partial y}{\partial h_z} = \left( \frac{\alpha}{2} \right) \frac{\dot{y}(\tau_o) + \frac{\Delta}{2} \left( \frac{h_z}{h_c} - 1 \right)}{h_c} \left[ \frac{h_z - h_c}{\alpha \left( \frac{\partial \phi}{\partial y} \right)} \right] + \ln \left\{ 1 - \frac{1}{h_z - h_c} \right\} \]

\[ \left( 40 \right) \]

Equation (39) shows that the creep displacement is linearly proportional to hard axis drive field as well as easy axis bias field and reciprocally proportional to wall coercive force. Furthermore, in the extent the slope of the creep displacement versus easy axis field normalized by coercive force is the same for different coercive force values. All these features agree very well with observed experimental results.
CHAPTER VII

CONCLUSIONS AND FUTURE RESEARCH SUGGESTIONS

Domain wall creep motion in Bloch wall NiFeCo films has been extensively studied in the past few chapters. The normal wall coercive has been found as an exceedingly important parameter in both high and low frequency creep processes.

The creep displacement for both high and low frequency creep is reciprocally related to the wall coercive force and otherwise independent of composition and film thickness. The consistency between high and low frequency creep results indicates that the basic mechanism of high and low frequency creep may be closely related.

It is found that gyromagnetically induced motion is fundamental in both high and low frequency as a trigger to initiate the creep motion. However, the behavior of the domain wall creep motion is dominated by the wall coercivity once the wall motion is started.

The easy axis bias field has also been found as an important parameter in creep process. A new type of domain wall motion is discovered in high frequency creep motion. With the easy axis bias field opposing the basic wall motion, the wall eventually move into the direction favored by the easy axis field even with the bias field considerably less than coercive force and the spin polarity inside the wall does not change. This negative wall motion has also been found for conventional wall motion excited by very short duration easy axis pulse field. A nonconservative spring coercive force model has been invoked to explain this new type of wall motion.

A theory based on the dynamic torque equation and nonconservative
spring coercive force model has been developed to explain the creep phenomenon. This theory predicts the observed creep dependence on coercive force and easy axis bias field.

One obvious extension of the present work would be to develop a satisfactory theoretical model for thin films which have more complicated wall structure. Experimentally, this work also suggests that the future investigations should include (1) the control of wall mobility in ferromagnetic thin films in terms of deposition parameters, (2) the influence of wall mobility on creep motion, (3) the influence of coercive force on creep motion in crosstie wall and Neel wall films, (4) creep motion in other materials, and (5) investigation of defect range of materials.
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