MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963A
ANNEALING EFFECTS IN FERROMAGNETIC AMORPHOUS ALLOYS

C. D. Graham, Jr.
T. Egami

Department of Materials Science and Engineering
University of Pennsylvania
3231 Walnut Street
Philadelphia PA 19104

15 December 1983

Report for Period 1 August 1982 - 30 October 1983

Approved for public release; distribution unlimited
Reproduction in whole or in part is permitted
for any purpose of the United States government
ANNEALING EFFECTS IN FERROMAGNETIC AMORPHOUS ALLOYS

C. D. Graham, Jr.
T. Egami

Department of Materials Science and Engineering
University of Pennsylvania
3231 Walnut St.
Philadelphia PA 19104

INTRODUCTION

Ferromagnetic amorphous alloys, or glassy metals, have been under development as engineering materials for about ten years. They are now used commercially in various high-permeability applications such as recording heads and phonograph pickups. Large-scale application in power transformers, power switching devices, and similar equipment appears to be imminent.

In all these applications, heat treatment or annealing of the as-quenched alloys is normal practice. The properties of amorphous alloys, like those of crystalline alloys, are altered by annealing; this is true even when the annealing treatment is too short or at too low a temperature to cause crystallization. As might be expected, the structure-sensitive properties such as coercivity and permeability are strongly affected by annealing; sometimes they are greatly improved, but sometimes they are degraded. It is therefore important to understand the mechanisms of annealing so that heat treatments can be specified to give optimum properties with high reliability and reproducibility at the lowest possible cost.

RESEARCH RESULTS FOR THIS REPORTING PERIOD

Field-Induced Anisotropy and Curie Temperature

The kinetics of the formation and reorientation of the field-induced anisotropy $K$ have been carefully studied in as-received samples and samples pre-annealed in various ways. We have established clearly that the kinetics can be described by a distribution of activation energies that depend weakly on the pre-annealing treatment. Changes in
Curie temperature caused by annealing show similar kinetics, and in one particular alloy \((\text{Fe}_{40}\text{Ni}_{40}\text{P}_{14}\text{B})\) we have determined that the kinetics of these two phenomena are identical. This implies that they result from the same microscopic mechanism. We have also made careful measurements of internal friction in amorphous alloys, and in another composition \((\text{Fe}_{32}\text{Ni}_{36}\text{Cr}_{14}\text{P}_{12}\text{B})\), we have established that the change in Curie temperature is proportional to the change in internal friction \(1/Q\), as measured by the torsion pendulum method. Thus we conclude that changes in both \(K\) and \(T\) are caused by atomic level local shear transformations that change the local compositional short range order. The internal friction has been studied in considerable depth, and we now understand its behavior quite well even at a microscopic level.

**Magnetic permeability after-effect**

A time-decay of ac permeability after demagnetization, even at room temperature, is observed in some crystalline alloys. It is sometimes known as disaccommodation (DA), and is known to occur also in amorphous alloys. We have established that DA in zero-magnetostriction amorphous alloys is caused by induced anisotropy in the domain walls, and have found that cooling an amorphous alloy through the Curie temperature in a field applied perpendicular to the ribbon axis reduces the DA and at the same time increases the permeability. The field annealing induces a weak anisotropy perpendicular to the ribbon axis, causing magnetization to occur by spin rotation rather than domain wall motion.

In magnetostrictive alloys, we have confirmed the theory of Allia and Vinai (P. Allia and F. Vinai, Phys. Rev. B26 (1982) 6141) that DA is due to internal friction coupled to domain wall motion via the magnetostriction.

**Flash annealing**

A new technique of heat treatment of amorphous alloys, called flash annealing, has been developed and investigated. The sample ribbon is immersed in liquid nitrogen, and a dc pulse current up to several amperes is passed through the ribbon for a controlled time period of 80 msec to 1 sec. The sample temperature can be indirectly monitored by observing the change of magnetization when the sample passes through the Curie temperature. Because of the high heating and cooling rates, it is possible to heat samples to 1200 K without causing crystallization. Even when crystallization does occur, the sample surface remains shiny (unoxidized), and the sample remains ductile, presumably because the crystalline grain size is very small. This technique permits annealing treatments which have not previously been possi-
ble. One effect that we have observed is that flash annealing "rejuvenates" a sample previously relaxed by annealing treatments below $T_c$; that is, the slow annealing kinetics become fast again, as in an as-quenched sample. We are continuing to investigate this annealing technique.

Theory of magnetostriction

Magnetostriction is clearly an important phenomenon controlling the low-field properties of amorphous alloys. However, the origin of magnetostriction in amorphous alloys is not well understood at the microscopic level. We have developed a microscopic theory of magnetostriction within the screened point charge model. We find that if the point charges are not screened, the linear magnetostriction is always zero, and that the screening condition determines the sign of the magnetostriction. We have also made an atomistic computer simulation of magnetostriction during deformation.

PUBLICATIONS

Details of the results summarized above are contained in the publications that have appeared in the technical literature. A list of these publications is given at the end of this report. The identification numbers are the same as those used in our previous reports. Papers with numbers 10 and above were prepared during this reporting period.
Publications Resulting from
Contract N00014-80-C-0896; NR 039-204

1. Structure and Magnetism of Amorphous Alloys
   T. Egami
   (Invited paper at INTERMAG, Grenoble, France)

2. Kinetics of Formation of Induced Magnetic Anisotropy in
   a Zero-Magnetostrictive Amorphous Alloy
   Kai-Yuan Ho, P. J. Flanders, and C. D. Graham, Jr.

3. Physical Origin of Losses in Conducting Ferromagnetic
   Materials
   C. D. Graham, Jr.
   (Invited paper at Conf. on Magnetism and Magnetic
    Materials, Montreal)

4. Isotropic Behavior of the Kinetics of Reorientation of
   Induced Anisotropy in Amorphous and Crystalline Alloys
   Kai-Yuan Ho

5. Kinetics of Reorientation of Induced Anisotropy in
   Amorphous and Crystalline Alloys
   Kai-Yuan Ho

6. Kinetics of Changes in Initial Permeability Produced by
   Magnetic Annealing in a Zero-Magnetostrictive FeCoSiB
   Amorphous Alloy
   T. Jagielinski

7. Elimination of Disaccommodation in a Zero-
   Magnetostrictive FeCoSiB Amorphous Alloy
   T. Jagielinski

8. Structural Relaxation and Magnetism in Amorphous Alloys
   T. Egami
   (Invited paper, International Conf. Magnetism, Kyoto)
9. Single-Ion Anisotropy and Magnetostriction of Amorphous Alloys  
Y. Suzuki and T. Egami  

10. Internal Friction of a Glassy Metal Fe$_{32}$Ni$_{36}$Cr$_{14}$P$_{12}$B$_{6}$ During the Cross-Over Behavior of the Curie Temperature  
N. Morito and T. Egami  

11. Correlation Between the Changes Due to Heat Treatment in the Curie Temperature and Internal Friction of a Glassy Metal Fe$_{32}$Ni$_{36}$Cr$_{14}$P$_{12}$B$_{6}$  
N. Morito and T. Egami  

12. Field Induced Anisotropy in Zero Magnetostriction Amorphous Alloys Measured with a Rotating Sample Magnetometer  
P. J. Flanders, T. Egami, and C. D. Graham, Jr.  

13. The Relationship Between Changes in Field-Induced Anisotropy and Curie Temperature for Fe$_{40}$Ni$_{40}$B$_{14}$P$_{6}$  
P. J. Flanders, N. Morito, and T. Egami  

14. Annealing Kinetics for Curie Temperature Changes in the Amorphous Alloy Fe$_{32}$Ni$_{36}$Cr$_{14}$P$_{12}$B$_{6}$  
P. J. Flanders, N. Morito, and T. Egami  

15. Effects of Anisotropy on Domain Structure in Amorphous Alloys  
J. D. Livingston, W. G. Morris, and T. Jagiekiinski  

16. Flash Annealing of Amorphous Alloys  
T. Jagiekiinski  

17. Disaccomodation of Magnetic Permeability in Amorphous Iron-Nickel-Boron Alloys  
T. Jagiekiinski  

18. Elastic Stress-Induced Coercive Field Changes in NiCo Films Used in a Rotating Disk  
P. J. Flanders  
Closely-related work not paid for by the ONR Contract appears in:

A. Magnetic After Effect in a Zero-Magnetostriction Amorphous Alloy
   T. Jagielinski

**REPORT DISTRIBUTION LIST**

<table>
<thead>
<tr>
<th>copies</th>
<th>recipient</th>
</tr>
</thead>
</table>
| 1      | Dr. Donald Polk  
Office of Naval Research  
800 N. Quincy St.  
Arlington VA 22217 |
| 1      | Office of Naval Research  
Eastern/Central Regional Office  
Bldg. 114, Section D  
666 Summer St.  
Boston MA 02210 |
| 1      | Office of Naval Research  
3E1 David Rittenhouse Laboratory  
University of Pennsylvania |
| 6      | Naval Research Laboratory  
NLR Code 2627  
Washington DC 20375 |
| 12     | Defense Technical Information Center  
Bldg. 5, Cameron Station  
Alexandria VA 22314 |
| 1      | Dr. A. E. Clark  
Naval Surface Weapons Center  
White Oak  
Silver Spring MD 20910 |
Publications Resulting from
Contract N00014-80-C-0896; NR 039-204

1. Structure and Magnetism of Amorphous Alloys
   T. Egami
   (Invited paper at INTERMAG, Grenoble, France)

2. Kinetics of Formation of Induced Magnetic Anisotropy in
   a Zero-Magnetostriction Amorphous Alloy
   Kai-Yuan Ho, P. J. Flanders, and C. D. Graham, Jr.

3. Physical Origin of Losses in Conducting Ferromagnetic
   Materials
   C. D. Graham, Jr.
   (Invited paper at Conf. on Magnetism and Magnetic
   Materials, Montreal)

4. Isotropic Behavior of the Kinetics of Reorientation of
   Induced Anisotropy in Amorphous and Crystalline Alloys
   Kai-Yuan Ho

5. Kinetics of Reorientation of Induced Anisotropy in
   Amorphous and Crystalline Alloys
   Kai-Yuan Ho

6. Kinetics of Changes in Initial Permeability Produced by
   Magnetic Annealing in a Zero-Magnetostrictive FeCoSiB
   Amorphous Alloy
   T. Jagielinski

7. Elimination of Disaccomodation in a Zero-
   Magnetostrictive FeCoSiB Amorphous Alloy
   T. Jagielinski

8. Structural Relaxation and Magnetism in Amorphous Alloys
   T. Egami
   (Invited paper, International Conf. Magnetism, Kyoto)

9. Single-Ion Anisotropy and Magnetostriction of Amorphous
   Alloys
   Y. Suzuki and T. Egami
10. Internal Friction of a Glassy Metal Fe$_{32}$Ni$_{36}$Cr$_{14}$P$_{12}$B$_6$
During the Cross-Over Behavior of the Curie Temperature
N. Morito and T. Egami

11. Correlation Between the Changes Due to Heat Treatment
in the Curie Temperature and Internal Friction of a
Glassy Metal Fe$_{32}$Ni$_{36}$Cr$_{14}$P$_{12}$B$_6$
N. Morito and T. Egami

12. Field Induced Anisotropy in Zero Magnetostriction
Amorphous Alloys Measured with a Rotating Sample
Magnetometer
P. J. Flanders, T. Egami, and C. D. Graham, Jr.

13. The Relationship Between Changes in Field-Induced
Anisotropy and Curie Temperature for Fe$_{40}$Ni$_{40}$B$_{14}$P$_6$
P. J. Flanders, N. Morito, and T. Egami

14. Annealing Kinetics for Curie Temperature Changes in the
Amorphous Alloy Fe$_{32}$Ni$_{36}$Cr$_{14}$P$_{12}$B$_6$
P. J. Flanders, N. Morito, and T. Egami

15. Effects of Anisotropy on Domain Structure in Amorphous
Alloys
J. D. Livingston, W. G. Morris, and T. Jagieinski

16. Flash Annealing of Amorphous Alloys
T. Jagieinski

17. Disaccommodation of Magnetic Permeability in Amorphous
Iron-Nickel-Boron Alloys
T. Jagieinski

18. Elastic Stress-Induced Coercive Field Changes in NiCo
Films Used in a Rotating Disk
P. J. Flanders
Closely-related work not paid for by the ONR Contract appears in:

A. Magnetic After Effect in a Zero-Magnetostriction Amorphous Alloy
   T. Jagielinski
### ANNEALING EFFECTS IN FERROMAGNETIC AMORPHOUS ALLOYS

#### 1. REPORT NUMBER
Annual Report No. 3

#### 2. GOVT ACCESSION NO.
AP-A13-843

#### 3. RECIPIENT'S CATALOG NUMBER

#### 4. TITLE (and Subtitle)
Annealing Effects in Ferromagnetic Amorphous Alloys

#### 5. TYPE OF REPORT & PERIOD COVERED
Annual Report
1 August 82-30 October 83

#### 6. PERFORMING ORG. REPORT NUMBER

#### 7. AUTHOR(s)
C. D. Graham, Jr.
T. Egami

#### 8. CONTRACT OR GRANT NUMBER(s)
N00014-80-C-0896
NR 039-204

#### 9. PERFORMING ORGANIZATION NAME AND ADDRESS
Dept. of Materials Science and Engineering
University of Pennsylvania
Philadelphia PA 19194

#### 10. PROGRAM ELEMENT, PROJECT, TASK, AREA & WORK UNIT NUMBERS

#### 11. CONTROLLING OFFICE NAME AND ADDRESS
Office of Naval Research
890 N. Quincy St.
Arlington VA 22217

#### 12. REPORT DATE
15 December 1983

#### 13. NUMBER OF PAGES
7

#### 14. MONITORING AGENCY NAME & ADDRESS (IF different from Controlling Office)

#### 15. SECURITY CLASS. (OF REPORT)
Unclassified

#### 16. DISTRIBUTION STATEMENT (OF REPORT)
distribution list shown on last page of report

#### 17. DISTRIBUTION STATEMENT (OF ABSTRACT ONLY, IF DIFFERENT FROM REPORT)

#### 18. SUPPLEMENTARY NOTES

#### 19. KEY WORDS (Continued on reverse side if necessary and identify by block number)
amorphous alloys; glassy metals; magnetic properties; disaccomodation; magnetostriction

#### 20. ABSTRACT (Continued on reverse side if necessary and identify by block number)
The kinetics, and therefore probably the atomic mechanism, of the annealing of field-induced anisotropy, Curie temperature, and internal friction have been shown to be the same in certain ferromagnetic amorphous alloys. Disaccomodation can be almost eliminated, and permeability increased, by annealing a zero-magnetostriction amorphous alloy in a perpendicular field. Flash annealing of amorphous alloys permits new annealing treatments.
that are not otherwise possible. A model of magnetostriction in amorphous alloys relates the magnitude and sign of the magnetostriction directly to the magnitude and sign of the screening in a screened point-charge model. In particular, the linear magnetostriction is zero if there is no screening.