UDR-TR-90-57

# METALLURGICAL PROCESSES IN MULTI-COMPONENT RARE EARTH-TRANSITION METAL PERMANENT MAGNET ALLOYS

FINAL REPORT

ALDEN E. RAY, PH.D.

MAY 30, 1990

U.S. ARMY RESEARCH OFFICE
CONTRACT DAAL03-87-K-0082
ARO PROPOSAL NUMBER 24674-MS



UNIVERSITY OF DAYTON
RESEARCH INSTITUTE
DAYTON, OH 45469-0170

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

# REPORT DOCUMENTATION PAGE

| | |
|---|---|
| 1a. REPORT SECURITY CLASSIFICATION<br>Unclassified | 1b. RESTRICTIVE MARKINGS |
| 2a. SECURITY CLASSIFICATION AUTHORITY | 3. DISTRIBUTION/AVAILABILITY OF REPORT<br>Approved for public release; distribution unlimited. |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE | |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S) | 5. MONITORING ORGANIZATION REPORT NUMBER(S) |
| 6a. NAME OF PERFORMING ORGANIZATION<br>University of Dayton Research Institute<br>6b. OFFICE SYMBOL (If applicable) | 7a. NAME OF MONITORING ORGANIZATION<br>U. S. Army Research Office |
| 6c. ADDRESS (City, State, and ZIP Code)<br>300 College Park Avenue<br>Dayton, OH 45469-0170 | 7b. ADDRESS (City, State, and ZIP Code)<br>P. O. Box 12211<br>Research Triangle Park, NC 27709-2211 |
| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION<br>U. S. Army Research Office<br>8b. OFFICE SYMBOL (If applicable) | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER |
| 8c. ADDRESS (City, State, and ZIP Code)<br>P. O. Box 12211<br>Research Triangle Park, NC 27709-2211 | 10. SOURCE OF FUNDING NUMBERS<br>PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO |

11. TITLE (Include Security Classification)
Metallurgical Processes in Multi-Component Rare Earth-Transition Metal Permanent Magnet Alloys

12. PERSONAL AUTHOR(S)
A.E. Ray

| 13a. TYPE OF REPORT | 13b. TIME COVERED | 14. DATE OF REPORT (Year, Month, Day) | 15. PAGE COUNT |
|---|---|---|---|
| Final | FROM 5-15-87 TO 5-14-90 | 1990 May 31 | 6 |

16. SUPPLEMENTARY NOTATION
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

| 17. COSATI CODES | | |
|---|---|---|
| FIELD | GROUP | SUB-GROUP |
| | | |
| | | |

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Permanent Magnets, Rare Earth-Transition Metal Permanent Magnets, R2:TM17 Type Rare Earth Magnets, Sm(Gd),Co,Fe,Cu, Zr Alloys, Model for Metallurgical Behavior.

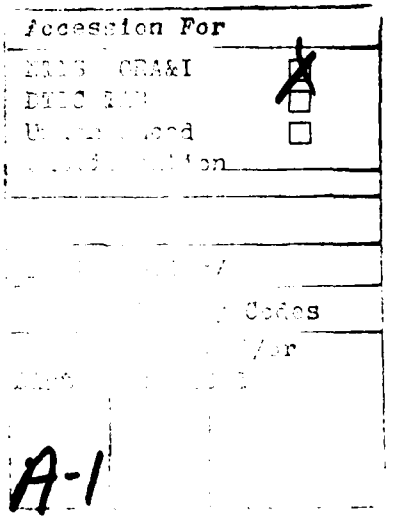
19. ABSTRACT (Continue on reverse if necessary and identify by block number)
A metallurgical model has been employed to achieve record values of energy product $Sm_2(Co,Fe)_{17}$ type permanent magnets modified by Cu and Zr, $(BH)_{max}$=33-34 MGOe. Record values were also obtained in fully temperature compensated versions modified by Gd, with $(BH)_{max}$=18-19 MGOe. Fourteen references. Eight publications appended to report.

| | |
|---|---|
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT<br>☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS | 21. ABSTRACT SECURITY CLASSIFICATION<br>Unclassified |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL | 22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL |

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

18. Permanent Magnet Properties, Temperature Dependence of Magnetic Properties, Temperature Compensated Permanent Magnets



# METALLURGICAL PROCESSES IN MULTI-COMPONENT RARE EARTH-TRANSITION METAL PERMANENT MAGNET ALLOYS

## FINAL REPORT

The primary objective of this research has been to improve and extend the technology of 2:17 type permanent magnets. The research has proceeded by employing a model for the complex metallurgical behavior of these alloys. This model was conceived by the principal investigator during ARO Proposal No. 17973[1-2]. It was defined and reported during 21026-MS[3-5] and has been continually refined during the present contract 24674-MS[6-8]. A description of the most recent version of the model is given in reference 9.

During the three year period of this research, we have succeeded in establishing a record value $(BH)_{max}$=34 MGOe for energy product in uncompensated $Sm(Co_uFe_vCu_xZr_y)_z$ magnets[10,11]. This was achieved by increasing the Fe content to v=0.31-0.33 (28-30 at.%) while developing heat treatments to maintain the coercivity at high levels. While 34 MGOe represents about a 6% increase over the previously announced laboratory record, we believe that the technology we have developed should routinely yield 31-32 MGOe magnets in commercial production - a 15% increase over the best 2:17 magnets presently produced. Utilizing similar compositions, slightly modified heat treatments, and Gd substitution for slightly less than half of the Sm, we achieved $(BH)_{max}$=18-19 MGOe in fully temperature compensated magnets. This also represents a 15% increase over the best commercially available magnets of this type[10,12]. Finally, we have been able to raise the remanence, $B_r$, of uncompensated 2:17 magnets by the partial substitution of Sm by light rare earths (Ce, Pr, and Nd singly and in combination)[13,14]. We also obtained excellent loop shapes from the latter substitutions, apparently by the development of more uniform, but high energy pinning sites.

From our present understanding of the metallurgy of 2:17 alloys, it appears we have about reached the practical limit for increasing the Fe content as a means for raising $B_r$ and $(BH)_{max}$. Further improvement is possible, however, by optimizing the solutionizing and aging heat treatments to obtain better second quadrant loop shapes. We can prepare magnets with $B_r$=12.2 Kg and ${}_MH_c$>18 kOe, but due to the poor loop shape, $H_k$ and ${}_BH_c$ are

low. With proper heat treatment, such magnets should be capable of 36-37 MGOe energy products.

ARO has supported our work on 2:17-type permanent magnets for nine years. During that period, we have developed a fundamental understanding of the metallurgical behavior of the magnet alloys. We have utilized that knowledge to achieve world record energy products for magnets of this type in both uncompensated and fully temperature compensated modifications. We believe we now possess a unique and valuable body of knowledge concerning these high performance magnet materials. We believe the magnet compositions and processing procedures we have developed could be utilized in commercial production to yield 2:17 type permanent magnets substantially better than those presently available.

Scientific personnel supported by this project include Alden E. Ray, Karl J. Strnat, Herbert F. Mildrum, Shiqiang Liu, J. Douglas Wolf, Meng Li, and Christopher Ivary. Shiqiang Liu was awarded the Ph.D. degree in Materials Engineering in December 1989. Meng Li was awarded the M.S. degree in Materials Engineering in April 1990 and Christopher Ivary will be awarded the M.S. degree in Materials Engineering in July 1990.

## REFERENCES


1. A.E. Ray, "A Model for the Metallurgical Behavior of $Sm(Co,Fe,Cu,Zr)_z$ Alloys in the Development of Hard Magnetic Properties," **7th International Workshop on Rare Earth-Cobalt Permanent Magnets**, Beijing, China, September, 1983, pp. 261-268.

2. A.E. Ray, "A Study of the Magnetic and Metallurgical Properties of $Sm(Co,Fe,Cu,Zr)_z$ Alloys Near z=8.5," Final Report **UDR-TR-84-08**, Contract No. DAAG-81-K-0120, Grant No. P-17973-MS (February 1984).

3. A. E. Ray, "The Metallurgical Behavior of $Sm(Co,Fe,Cu,Zr)_z$ Alloys," J. **Appl. Phys. 55**, 2094-2096, (1984).

4. A.E. Ray, "The Development of High Energy Product Permanent Magnets from 2:17 RE-TM Alloy," **IEEE Transactions on Magnetics, MAG-20**, No. 5, September 1984.

5. A.E. Ray, "The Development of High Coercivity in 2:17 Type Rare Earth-Transition Metal Permanent Magnets," pp. 105-118 in **Soft and Hard Magnetic Materials with Applications**, Book edited by J.A. Salsgiver, et al. Published by the American Society for Metals, Metals Park, Ohio October 1986. Presented at ASM's Materials Week '86, Lake Buena Vista, FL, October, 1986.

6. A.E. Ray, W.A. Soffa, J.R. Blachere, and B. Zhang, "Cellular Microstructure Development in $Sm(Co,Fe,Cu,Zr)_{8.35}$ Alloys," **IEEE Trans. Magn., MAG-23** (1987) 2711.

7. B. Zhang, J.R. Blachere, W.A. Soffa, and A.E. Ray, "AEM Studies of SmCo 2:17 Permanent Magnet Alloys," **J. Appl. Phys., 64** (1988) 5729.

8. A.E. Ray, S. Liu, and J.D. Wolf, "Magnetic Properties of the Platelet Phase in $Sm_2TM_{17}$ Magnets," **Proceedings of the 10th Int'l REPM Workshop**, Kyoto, Japan, May 1989, Vol II, pp. 255-264.

9. A.E. Ray, "A Revised Model for the Metallurgical Behavior of 2:17 Type Permanent Magnet Alloys," to be published in **J. Appl. Phys., 65** (1990).

10. S. Liu and A.E. Ray, "2:17 Type RE-TM Magnets with Improved Magnetic Properties," **Proceedings of the 10th Int'l REPM Workshop**, Kyoto, Japan, May 1989, Vol II, pp. 265-273.

11. S. Liu and A.E. Ray, "$Sm_2(Co,Fe,Cu,Zr)_{17}$ Magnets with Higher Fe Content," **IEEE Trans. Magn., MAG-25,** (1989) 3785.

12. S. Liu, A.E. Ray, and H.F. Mildrum, "Temperature-Compensated 2:17 Type Permanent Magnets with Improved Magnetic Properties," to be published in **J. Appl. Phys., 65** (1990).

13. S. Liu, A.E. Ray, and H.F. Mildrum, "Sintered $Sm_2(Co,Fe,Cu,Zr)_{17}$ Magnets with Light Rare Earth Substitutions," to be published in **IEEE Trans. Magn., MAG-26** (1990).

14. S. Liu, A.E. Ray, and H.F. Mildrum, "Magnetic Properties and Microstructure of Light Rare Earth Substituted 2:17 Magnets," to be presented at the 35th Annual Conference on Magnetism and Magnetic Materials, San Diego, California, October 29-November 1, 1990.

## LIST OF PUBLICATIONS DURING THIS CONTRACT

1. A.E. Ray, W.A. Soffa, J.R. Blachere, and B. Zhang, "Cellular Microstructure Development in $Sm(Co,Fe,Cu,Zr)_{8.35}$ Alloys," **IEEE Trans. Magn., MAG-23** (1987) 2711.

2. B. Zhang, J.R. Blachere, W.A. Soffa, and A.E. Ray, "AEM Studies of SmCo 2:17 Permanent Magnet Alloys," **J. Appl. Phys., 64** (1988) 5729.

3. A.E. Ray, S. Liu, and J.D. Wolf, "Magnetic Properties of the Platelet Phase in $Sm_2TM_{17}$ Magnets," **Proceedings of the 10th Int'l REPM Workshop**, Kyoto, Japan, May 1989, Vol. II, pp. 255-264.

4. S. Liu and A.E. Ray, "2:17 Type RE-TM Magnets with Improved Magnetic Properties," ibid, pp. 265-273.

5. S. Liu and A.E. Ray, "$Sm_2(Co,Fe,Cu,Zr)_{17}$ Magnets with Higher Fe Content," **IEEE Trans. Magn., MAG-25**, (1989) 3785.

6. A.E. Ray, "A Revised Model for the Metallurgical Behavior of 2:17 Type Permanent Magnet Alloys," to be published in **J. Appl. Phys., 65** (1990).

7. S. Liu, A.E. Ray, and H.F. Mildrum, "Temperature-Compensated 2:17 Type Permanent Magnets with Improved Magnetic Properties," to be published in **J. Appl. Phys., 65** (1990).

8. S. Liu, A.E. Ray, and H.F. Mildrum, "Sintered $Sm_2(Co,Fe,Cu,Zr)_{17}$ Magnets with Light Rare Earth Substitutions," to be published in **IEEE Trans. Magn., MAG-26** (1990).

9. S. Liu, A.E. Ray, and H.F. Mildrum, "Magnetic Properties and Microstructure of Light Rare Earth Substituted 2:17 Magnets," to be presented at the 35th Annual Conference on Magnetism and Magnetic Materials, San Diego, California, October 29-November 1, 1990.