RTO-TR-031
AC/323(AVT-060)TP/36

RTO-TR-031

NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION

BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

© RTO/NATO 2001

Single copies of this publication or of a part of it may be made for individual use only. The approval of the RTA Information Policy Executive is required for more than one copy to be made or an extract included in another publication. Requests to do so should be sent to the address above.

RTO TECHNICAL REPORT 31

NATO East-West Workshop on Magnetic Materials for Power Applications

(Atelier OTAN Est-Ouest sur les matériaux magnétiques pour applications propulsives)

Papers presented at the Workshop with Partnership for Peace Countries, sponsored by the RTO Applied Vehicle Technology Panel (AVT), organised by the US Air Force Office of Scientific Research, Arlington, VA, USA and held in Marathon, Greece, 25-30 June 2000.

Published August 2001

Distribution and Availability on Back Cover

This page has been deliberately left blank

Page intentionnellement blanche

RTO-TR-031
AC/323(AVT-060)TP/36

NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION

BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

RTO TECHNICAL REPORT 31

NATO East-West Workshop on Magnetic Materials for Power Applications

(Atelier OTAN Est-Ouest sur les matériaux magnétiques pour applications propulsives)

Papers presented at the Workshop with Partnership for Peace Countries, sponsored by the RTO Applied Vehicle Technology Panel (AVT), organised by the US Air Force Office of Scientific Research, Arlington, VA, USA and held in Marathon, Greece, 25-30 June 2000.

The Research and Technology Organization (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS Studies, Analysis and Simulation Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

The content of this publication has been reproduced directly from material supplied by RTO or the authors.

Published August 2001

Copyright © RTO/NATO 2001
All Rights Reserved

ISBN 92-837-1060-6

Printed by St. Joseph Ottawa/Hull
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada J8X 1C6

NATO East-West Workshop on Magnetic Materials for Power Applications

(RTO TR-031 / AVT-060)

Executive Summary

The Partners for Peace (PfP) NATO Workshop on Advanced Magnetic Materials for More Electric Vehicles and Electric Pulse Power Weapons (AVT-060) was organized with the aim of assessing the need for improved magnetic materials primarily in future generations of more electric vehicles and (to a lesser extent) in electric pulse power weapons. Knowledgeable scientists from 8 NATO countries were represented (Canada, France, Germany, Greece, Hungary, Poland, UK and USA), as were 3 non-NATO Eastern European countries (Bulgaria, Romania and Russia), plus Austria and Cyprus. The participants discussed recent advancements in relevant magnetic materials and how further improvements can be made to achieve the goals stated for military applications.

The first full day of this Workshop was devoted to an exposition of the needs of the user communities, with the focus on applications for military vehicles, primarily tanks and aircraft. Researchers presented electric vehicle and weapon concepts and configurations along with potentially enhanced features such as electric drives, power supplies for external consumers, electric braking and auxiliary subsystems. These advanced concepts are based on utilizing electric power to drive subsystems that are currently driven by a complex combination of hydraulic, pneumatic, electric and mechanical power transfer systems. The lack of hydraulics, homogeneous power supplies, automation and remote control options, and high reliability are system level benefits that arise from electric air and ground vehicle configurations. The first day of the workshop ended with a group discussion on the needs of military vehicle and electric weapon system applications. Table I (page 3) is a compilation of that open discussion.

The succeeding three and a half days were devoted primarily to reports on a number of recent materials development programs that have resulted in some significant advances in both hard (permanent) and soft magnetic materials that function reasonably well at somewhat elevated temperatures. Nevertheless, there is a continuing need to improve upon the recent successes to produce even higher temperature materials with higher energy products or higher saturation magnetization, and high mechanical strength. Additionally, some Workshop participants stressed the need for more advanced measurement techniques as a key to understanding what really needs to be done. It was generally concluded that while there has been substantial progress made in magnetics over the last four years, as reflected in the remainder of this report, there is still a need for higher temperature materials capable of higher energy products or saturation levels. Corrosion resistance and the need for higher strength were also emphasized along with the need for improved fabrication and processing techniques.

Atelier OTAN Est-Ouest sur les matériaux magnétiques pour applications propulsives

(RTO TR-031 / AVT-060)

Synthèse

L'atelier AVT 060 de l'OTAN ouvert aux partenaires pour la paix (PpP) sur « Les matériaux magnétiques avancés pour le développement de véhicules militaires exploitant davantage l'énergie électrique des génératrices à impulsions électriques », a été organisé dans le but d'évaluer les besoins en matériaux magnétiques améliorés, principalement pour de futures générations de véhicules à plus fort composant électrique et (dans une moindre mesure) pour génératrices à impulsions électriques. Etaient présents : des scientifiques éminents de 8 pays de l'OTAN (le Canada, la France, l'Allemagne, la Grèce, la Hongrie, la Pologne, le Royaume-Uni et les Etats-Unis), ainsi que des représentants de 3 pays non-NATO de l'Europe de l'Est (la Bulgarie, la Romanie et la Russie) et de l'Autriche et de Chypre. Les participants ont discuté des derniers progrès réalisés dans le domaine des matériaux magnétiques et de l'approche à adopter pour atteindre les objectifs annoncés pour les applications militaires.

La première journée de l'atelier a été consacrée à un exposé des besoins des différents utilisateurs, l'accent étant mis sur les applications pour les véhicules militaires, et principalement les chars et les aéronefs. Les chercheurs ont présenté des concepts et configurations de véhicules électriques et de systèmes d'armes incorporant des éléments améliorés tels que les commandes électriques, les alimentations électriques pour consommateurs externes, les systèmes de freinage électriques et leurs sous-systèmes auxiliaires. Ces concepts avancés sont basés sur l'utilisation de l'électricité pour alimenter des sous-systèmes actuellement mus par une combinaison complexe de systèmes de transfert d'énergie hydrauliques, pneumatiques, électriques et mécaniques. L'absence d'hydraulique, d'alimentations homogènes, d'automatisation et de télécommandes et une grande fiabilité sont autant d'avantages offerts au niveau systèmes par des configurations électriques de véhicules aériens et terrestres. La première journée de l'atelier s'est terminée par une discussion de groupe sur les besoins en matière d'applications pour les véhicules militaires et les systèmes d'armes.

Les trois jours et demi qui ont suivi ont été principalement consacrés à l'examen d'un certain nombre de rapports sur des programmes récents de développement de matériaux qui ont permis de réaliser des progrès importants dans le domaine des matériaux magnétiques rigides (permanents) et souples se comportant de façon satisfaisante à des températures relativement élevées. Cependant, il faudra encore améliorer les réalisations récentes pour obtenir des matériaux résistant à des températures plus élevées avec des produits à plus haute énergie, une magnétisation à plus grande saturation et une résistance mécanique plus élevée. Aussi, certains participants ont souligné le besoin de disposer de techniques de mesure plus avancées afin de mieux cerner le problème. Les participants étaient unanimes à reconnaître que malgré les progrès considérables réalisés dans le domaine du magnétisme au cours des quatre dernières années, comme en témoigne ce rapport, le besoin existe toujours de disposer de matériaux résistant à des températures plus élevées et capables de fournir des produits à plus haute énergie ou des niveaux de saturation plus élevés. Une plus grande résistance à la corrosion, une plus grande résistance mécanique, ainsi que des techniques améliorées de fabrication et de traitement ont également été soulignées comme nécessaires.

Click inside the blue boxes to view the corresponding section

Contents

Foreword

The Partners for Peace (PfP) NATO Workshop on Advanced Magnetic Materials for More Electric Vehicles and Electric Pulse Power Weapons (AVT-060) was held at Marathon, Greece, 25-30 June 2000. It was organized with the aim of assessing the need for improved magnetic materials primarily in future generations of more electric vehicles and (to a lesser extent) in electric pulse power weapons. Moreover, after assessing that need, the Workshop was designed to both review the status of recent advances in relevant magnetic materials and to discuss how further improvements can be made, e.g., via compositional and/or processing changes, to achieve the desired magnetic and mechanical properties required at elevated temperatures. Finally, by bringing together knowledgeable scientists from numerous NATO countries and Eastern Europe, it was hoped that collaborations would be formed that could hasten the development of the new magnetic materials that are required to optimize future military and commercial systems. The stated goals for temperatures at which these materials would operate successfully are 600°C for soft materials and 450°C for hard materials.

The first full day of this Workshop was devoted to an exposition of the needs of the user communities, with the focus on applications for military vehicles, primarily tanks and aircraft. The succeeding three and a half days were devoted primarily to reports on a number of recent materials development programs that have resulted in some significant advances in both hard (permanent) and soft magnetic materials that function reasonably well at somewhat elevated temperatures. Nevertheless, there is a continuing need to improve upon the recent successes to produce even higher temperature materials with higher energy products or higher saturation magnetization, and high mechanical strength. Additionally, some Workshop participants stressed the need for more advanced measurement techniques as a key to understanding what really needs to be done, and it was stated that the interaction of microstructure and domain structure would go a long way to determining the ultimate limits that can be attained.

Among the 27 participants in the Workshop, 8 NATO countries were represented (Canada, France, Germany, Greece, Hungary, Poland, UK and USA), as were 3 non-NATO Eastern European countries (Bulgaria, Romania and Russia), plus Austria and Cyprus. The discussions could be considered primarily in the realm of basic research in the physics, chemistry and materials engineering of magnetic materials. Participants were mostly from academia and national or defense laboratories, although 2 were from industrial organizations. Over the 5-day period there was ample opportunity for both formal and informal discussion, and it is anticipated that a few strong bi-national research collaborations will result.

The program was formulated through a joint effort of Professor George Hadjipanayis of the University of Delaware and myself, with most of the effort falling on his shoulders. Dr. Dimitris Niarchos of "Demokritos," the Greek National Center for Scientific Research, ably handled local arrangements. Funds for the 5 Eastern European scientists were made available through the NATO PfP Workshop program under the direction of Mr. Dimitris Stamatopoulos. The bulk of the funding for this Workshop results from grant support from 3 US Department of Defense organizations located in London: the European Research Office of the Army, the Office of Naval Research European Office, and the European Office of Aerospace Research and Development. Additional funding was provided by the Greek Ministry of Defense. We are indebted to all these individuals and organizations for making this Workshop possible. Finally, it is a pleasure to acknowledge the tremendous effort made by Dr. Richard (Rick) Fingers in distilling the information presented at the Workshop and preparing the report you are about to read.

Dr. Harold Weinstock
US Air Force Office of Scientific Research
Physics and Electronics
801 N. Randolph St., Room 732
Arlington, VA 22203-1977
Tel: 1-703-696-8572
Fax: 1-703-696-8481
harold.weinstock@afosr.af.mil

Publications of the RTO Applied Vehicle Technology Panel

MEETING PROCEEDINGS (MP)

Design for Low Cost Operation and Support
MP-37, September 2000

Gas Turbine Operation and Technology for Land, Sea and Air Propulsion and Power Systems (Unclassified)
MP-34, September 2000

Aerodynamic Design and Optimization of Flight Vehicles in a Concurrent Multi-Disciplinary Environment
MP-35, June 2000

Structural Aspects of Flexible Aircraft Control
MP-36, May 2000

New Metallic Materials for the Structure of Aging Aircraft
MP-25, April 2000

Small Rocket Motors and Gas Generators for Land, Sea and Air Launched Weapons Systems
MP-23, April 2000

Application of Damage Tolerance Principles for Improved Airworthiness of Rotorcraft
MP-24, January 2000

Gas Turbine Engine Combustion, Emissions and Alternative Fuels
MP-14, June 1999

Fatigue in the Presence of Corrosion
MP-18, March 1999

Qualification of Life Extension Schemes for Engine Components
MP-17, March 1999

Fluid Dynamics Problems of Vehicles Operation Near or in the Air-Sea Interface
MP-15, February 1999

Design Principles and Methods for Aircraft Gas Turbine Engines
MP-8, February 1999

Airframe Inspection Reliability under Field/Depot Conditions
MP-10, November 1998

Intelligent Processing of High Performance Materials
MP-9, November 1998

Exploitation of Structural Loads/Health Data for Reduced Cycle Costs
MP-7, November 1998

Missile Aerodynamics
MP-5, November 1998

EDUCATIONAL NOTES (EN)

Measurement Techniques for High Enthalpy and Plasma Flows
EN-8, April 2000

Development and Operation of UAVs for Military and Civil Applications
EN-9, April 2000

Planar Optical Measurements Methods for Gas Turbine Engine Life
EN-6, September 1999

High Order Methods for Computational Physics, Published jointly with Springer-Verlag, Germany
EN-5, March 1999

Fluid Dynamics Research on Supersonic Aircraft
EN-4, November 1998

Integrated Multidisciplinary Design of High Pressure Multistage Compressor Systems
EN-1, September 1998

TECHNICAL REPORTS (TR)

Verification and Validation Data for Computational Unsteady Aerodynamics
TR-26, October 2000

Recommended Practices for Monitoring Gas Turbine Engine Life Consumption
TR-28, April 2000

A Feasibility Study of Collaborative Multi-facility Windtunnel Testing for CFD Validation
TR-27, December 1999

Members of the AVT-060 Workshop

Chairman

Dr. Harold Weinstock
US Air Force Office of Scientific Research
Physics and Electronics
801 N. Randolph St., Room 732
Arlington, VA 22203-1977
Tel: 1-703-696-8572
Fax: 1-703-696-8481
harold.weinstock@afosr.af.mil

THE NETHERLANDS
Col. Ir. Willem Kauw
DMKLu/MXS
P.O. Box 20703
2500 ES The Hague
Tel: 31 70 339 6039
Fax: 31 70 339 6424
woklu@dmklu.af.dnet.miindef.nl

UNITED STATES
Dr. Richard McClelland
US Army Tank-Automotive & Armaments Command
Tank Automotive Res. Dev. & Eng. Crt.
Attn: AMSTA-TR-R
Mail Stop 202
Warren, Michigan 48397-5000
Tel: 1 810 574 5494
Fax: 1 810 574 6013
mcclellr@tacom.army.mil

WORKSHOP ORGANIZERS

Harold Weinstock
Air Force Office of Scientific Research
Washington D.C., USA

George Hadjipanayis
University of Delaware
Newark, Delaware, USA

Dimitris Niarchos
NCSR Demokritos
Athens, Greece

PROCEEDINGS EDITOR

Richard Fingers
Air Force Research Lab
Wright-Patterson AFB, Ohio, USA

1. INTRODUCTION

The principal objective of this Partners for Peace Workshop is to foster interaction between NATO and former Soviet Union engineers and scientists, leading to the development of advanced magnetic materials that are critical to the improved design and construction of military electric vehicles and electric pulse power systems. Workshop contributors provided design issues and magnetic material requirements for a variety of advanced power systems. Many topics and discussions were at the basic research level. The workshop forum was conducive to information exchange and a variety of research collaborations have resulted from the participant interactions. A list of the workshop participants and their respective contact information is included as Appendix A of this report. Appendix B is comprised of a complete collection of the presentation abstracts.

2. TECHNICAL PRESENTATIONS

Following a registration period and a Sunday evening reception, the technical sessions began Monday morning with a welcome address from the workshop organizers, Drs. George Hadjipanayis, Dimitris Niarchos, and Harold Weinstock. Dr. Weinstock of the U.S. Air Force Office of Scientific Research then gave opening remarks as an introduction to the technical sessions.

2.1 *Applications*

The aim of this first technical session, “Applications,” was to establish user requirements and motivation for the remaining sessions. Mr. Wolfgang Brand of Germany and Mr. Ghassan Khalil of the U.S. Army’s TACOM presented electric vehicle and weapon concepts and configurations along with potentially enhanced features such as electric drives, power supplies for external consumers, electric braking and auxiliary subsystems. Modular subsystems and the arrangement flexibility of the power distribution system afford further redundancy and the better utilization of space. The lack of hydraulics, homogeneous power supplies, automation and remote control options, and high reliability are system level benefits that arise from all electric vehicle configurations. Military vehicle requirements, and the application of advanced magnetic materials, and their impact on the vehicle cooling system were discussed. Dr. Francis Jamet of the French-German Research Institute of Saint Louis, France presented three types of electric weapons: high power microwaves, electromagnetic railguns, and electrothermalchemical guns. The energy, power, voltages, current intensities, and pulse duration characteristics of the electric weapons were discussed. Examples of weapon energy storage architectures and pulse forming networks based on the use of capacitor banks and superconducting coils were analyzed. Also, the needed characteristics of the weapon components such as high discharge capacitors, switching systems or connection parts were described and the expected technology improvements affording lower masses and volumes were examined.

Dr. Rick Fingers of the U.S Air Force Research Laboratory’s Propulsion Directorate presented the more electric aircraft initiative and related critical technologies. This advanced concept is based on utilizing electric power to drive aircraft subsystems that are currently driven by a complex combination of hydraulic, pneumatic, electric and mechanical power transfer systems. Predicted aircraft improvements, including a reduction in the required logistics support and an overall increase in available electrical power were presented. These improvements are to be realized with the further development of key technologies, including magnetic bearings, integrated power units, and starters and generators mounted internal to an aircraft main propulsion engine.

Dr. Herbert Leupold from the U.S. Army's Research laboratory discussed approximations to Halbach structures known as magic cylinders and magic mangles and presented them as novel applications of permanent magnets in electrical machinery. These designs, taking advantage of advancements in permanent magnet materials, have made possible electric generators and motors that are much more compact, have much less stray field and produce more energy per structured mass than do conventional ones. Dr. David Howe from the University of Sheffield, England gave the final presentation in this session, discussing a variety of novel applications of permanent magnets. Modular, fault-tolerant, permanent magnet brushless motors and multi-degree of freedom spherical actuators were discussed. Tubular, linear brushless motors, flywheel peak-power buffer applications, and reciprocating moving-magnet actuators for resonant electro-mechanical systems were presented.

The first day of the workshop ended with a group discussion on the needs of military vehicle and electric weapon system applications. Table I is a compilation of that open discussion. It was generally concluded that while there has been substantial progress made in magnetics over the last four years, as reflected in the remainder of this report, there is still a need for higher temperature materials capable of higher energy products or saturation levels. Corrosion resistance and the need for higher strength were also emphasized along with the need for improved fabrication and processing techniques.

Table 1 Magnetic material needs corresponding to the more electric aircraft, electric military ground vehicles, and electric weapon applications.

MAGNETIC MATERIAL NEEDS					
	LIFE	MAGNETIC	ELECTRICAL	MECHANICAL	PROCESSING
More Electric Aircraft (Soft Mag)	5000 Hours at ~600°C	B=2T with a Machine Core Loss of <480 W/Kg @5000 Hz, 500°C	Resistivity of 40 to 60 micro-ohm-cm at room temp	825 MPa yield strength at 300°C 700 MPa yield strength at 500°C	Improved Powder Metallurgy Techniques
More Electric Aircraft (Hard Mag)	5000 Hours at ~450°C	30 MGOe at 450°C		Improved Corrosion Resistance	Improved Compaction Techniques
Electric Military Ground Vehicles	250-300°C	35 MGOe at 250-300°C		Improved Corrosion Resistance	Improved Compaction Techniques
Electric Weapons	20-150°C	Improved Permeability	Fields of 5 – 10 T are required in a 20 – 80 mm gap between pole pieces.		

2.2 Fundamental and Technical Magnetism

The second technical session, "Fundamental & Technical Magnetism," began with an introduction to magnetism and magnetic interactions by Dr. Henryk Szymczak of the Institute of Physics, Polish Academy of Sciences in Warsaw, Poland. Dr. Szymczak illustrated some of the basic interactions governing the properties of magnetic materials at the atomic scale. The exchange interaction spin orbit coupling, and the crystal field action on the magnetic electrons are the essential interactions responsible for magnetic moments, the magnetic ordering temperature, and the type of magnetic order. Dr. Michael McHenry of Carnegie Mellon University in Pittsburgh, PA then introduced the physical basis for magnetic anisotropy, in terms of shape, magnetocrystalline structure and stress. He then presented the Landau theory of phase transformations and used it to describe important nanocomposites including HITPERM soft magnets, 2:17 and 3:29 phase hard magnets and spring exchange magnets. Dr. Alexandre Ermolenko of the Institute of Metal Physics in Ekaterinburg, Russia presented studies conducted over the last 50 years on rare earth intermetallics and the physical basis for their magnetic properties. He discussed the peculiarities of magnetic properties of 3d – 4f metals and binary intermetallics along with exchange interactions and regularities of the spontaneous formation of magnetic moments. Also, Dr. Vladimir Menushenkov of Moscow State Institute of Steel and Alloys, Moscow, Russia presented microstructural changes and coercivity mechanisms of rare-earth alloys and permanent magnets as a basis for the search for new phases of advanced magnets. In this effort phase transformations of NdFeB and SmCo alloys have been investigated with a focus on both the homogeneous and intergranular regions. A predictive scheme has been developed, based on an analysis of SmCo crystal lattice parameters, that provides a better understanding of the high coercivity mechanism obtained for enriched $SmCo_5$ alloys.

Professor Helmut Kronmuller of the Max-Planck Institute for Metallforschung in Stuttgart, Germany gave a detailed presentation on magnetic hysteresis to conclude this session by showing that optimized magnetic materials require suitable intrinsic material parameters but also well-defined microstructures. Spontaneous polarization, Curie temperature, anisotropy constants, and magnetostriction are intrinsic magnetic material parameters. Professor Kronmuller presented the extrinsic properties of the hysteresis loops as coercive field, remanence, initial susceptibility, and Rayleigh constant. All of these extrinsic properties depend heavily on the microstructure of the magnetic material. In the case of small particles or thin platelets, particle size and shape must also be considered as important extrinsic properties. In soft magnetic materials, crystalline or amorphous, the interaction between domain walls and the microstructure plays the dominant role for the hysteresis loop. Either a domain wall displacement or a rotational process dominates the hysteresis loop. In hard magnetic materials the hysteresis loops depend closely on the perfection of the grains and the type of coupling between them.

2.3 Characterization

Characterization was the focus of Wednesday's technical session. Dr. Mihail Mikhov of the University of Sofia, Bulgaria presented the classical magnetic measurement techniques and discussed their associated advantages and disadvantages. He described the DC Faraday magnetometer, alternating gradient force magnetometer, and the torque magnetometer as the most popular techniques for measuring magnetic anisotropy and magnetization levels. He also presented the vibrating sample magnetometer, SQUID magnetometer, AC susceptometer, and the hysteresis loop tracer as tools used for magnetic analysis based on flux measurements.

Dr. Bhanu Chelluri of IAP Research Inc. in Dayton, OH gave an overview of the dynamic magnetic compaction process, which is an innovative net shape powder processing technology that uses magnetic pulses as the compaction force. Full density in several material systems has been achieved and the resulting magnet properties, part size and shape, and dimensional tolerances were discussed. With a compaction time of less than one millisecond, special microstructures and grain sizes of the starting powders can typically be preserved. Both hard and soft magnetic powders have been compacted for DOD and commercial applications.

Dr. Josef Fidler of the Vienna University of Technology in Wien, Austria discussed micromagnetic modeling as a methodology to predict the shape and detailed spatial arrangement of domains and domain boundaries to determine the magnetic hysteresis loop behavior. The hysteresis loop is an illustration of the average magnetization of a magnetic material as a function of external field. The micromagnetic modeling of the magnetic reversal process of magnetic nanoelements, which are patterned structures at the submicron level, show that the shape of the elements becomes an important factor controlling the hysteretic behavior. In the final briefing of the session Dr. Yuri Pastushenkov of Tver State University in Tver, Russia discussed magnetic domain structures and the spin reorientation process based on observed domain configurations and domain wall density calculations. He presented potential volume magnetization distribution models along with the possibility of the formation of new type of domain walls.

2.4 Materials

The "Materials" session on Thursday began with a very detailed presentation of a comprehensive study on rare earth 2:17 permanent magnets by Dr. George Hadjipanayis of the University of Delaware in Newark, DE. The four-year systematic study on precipitation hardened $Sm(Co, Fe, Cu, Zr)_Z$ magnets has resulted in a complete understanding of the effects of composition and processing on their hard magnetic properties. The ratios of elemental constituents were varied and the associated effects were related to resulting complex microstructures and quantified in terms of coercivites and temperature dependencies. Processing parameters were also varied and presented along with the corresponding microstructures and magnetic behaviors.

Dr. Tony Arrott provided the subsequent presentation, which focused on the importance of iron to the history of soft magnetic metals for power applications. Iron has the highest magnetic moment per unit volume or per unit mass and it is readily available. Comparatively speaking it is almost free. Therefore, the challenge is how to make iron better without making it a significant portion of the cost of the motor, generator, or transformer. The primary approach over the past 50 years has been to purify it and to enlist the help of other cheap elements such as silicon to improve metallurgical properties with minimal degradation to magnetic behavior.

Dr. L. Varga of the Research Institute for Solid State Physics and Optics in Budapest, Hungary then discussed nanocrystalline soft magnetic alloys and their application in power electronics. Two families of nanocrystalline alloys were investigated: Finemet type and Nanoperm type. Special tailoring of the hysteresis loop characteristics is necessary for electronic applications. Field annealing and stress annealing were two methods discussed to accomplish transversal or longitudinal induced anisotropy leading to the desirable tailored hysteresis loops. Dr. Sara Majetich from Carnegie Mellon University in Pittsburgh, PA described how the AC magnetic properties of nanoparticles are related to those of nanocomposites made by compaction. An AC version of the Stoner-Wohlfarth model was used to predict the hysteresis curve depending on particle size, anisotropy, and temperature. A modified version of this model was used to describe the compacted nanocomposites as well, despite the presence of interactions among the grains. Dr. Karl Unruh of the University of Delaware in Newark, DE discussed fiber reinforced soft magnetic alloys. He presented them as an approach to obtain both superior magnetic and mechanical properties for high temperature applications. Iron-cobalt coated continuous fibers were prepared and analyzed. The current project emphasis is to expand this promising approach in order to fabricate larger test specimens and components. Dr. Siu-Tat Chui of the Bartol Research Institute, University of Delaware in Newark, DE gave the final presentation of the session and focused on optimizing the energy product of nanocomposite magnets at finite temperature. He discussed an approach to model the coercive behavior of nanocomposite hard and soft multi-layer magnets.

2.5 Novel Processing

The final technical session, “Novel Processing” was comprised of two presentations. The first, given by Dr. H. Chiriac of the National Institute of Research and Development for Technical Physics in Iasi, Romania, pertained to magnetic annealing as a method for inducing a macroscopic magnetic anisotropy with a predetermined easy direction. This anisotropy is characterized by a preferred direction that is parallel with the direction of an applied field during annealing. Dr. Chiriac also presented magnetic annealing techniques for amorphous and nanocrystalline materials in the shape of ribbons, wires, and glass covered amorphous wires. Dr. Michel Trudeau of Emerging Technologies, Quebec, Canada has investigated and presented electrodeposition processes and suggests that for iron and iron-nickel alloys, this technique can be used to synthesize dense samples with a crystalline size as low as 5 to 7 nanometers. By controlling various electrodeposition parameters this electrolytic process can be a major fabrication technique for large-scale development of dense nanostructured materials.

3. MAGNETIC MATERIAL NEEDS

Magnetic material and property needs, based on the various power applications, were discussed and segregated into soft electromagnet and permanent hard magnet behavior. Even though an attempt was made to avoid qualifying statements such as, “better…stronger…higher,” when describing the needed magnetic material improvements, we found that it was often difficult to specify autonomous performance characteristics. Typically, engineering trade-off analyses must be conducted to examine the complete system, or subsystem, and compromises are made between core loss, strength, thermal stability, and creep resistance to obtain an optimized system. With an overall improvement in mechanical, electrical, and magnetic behaviors in mind, some specific quantities were established as important characteristics to target and some approaches were suggested as potential methods to meet the requirements of advanced electric air, ground, and weapon systems. Table 2 lists many of the research focus areas that may help to afford these advanced magnets.

The bottom-line needs for both permanent and soft magnetic materials are coupled to the specific high temperature applications discussed during the first day of the workshop. As listed in Table 1, soft magnets must maintain their structural and magnetic integrity for at least 5000 hours at nearly 600°C to satisfy some of the more stringent requirements of the more electric aircraft. Machine core loss is obviously a function of the operating parameters as well as the geometry and material properties.

A core loss goal of 480 W/Kg at a frequency of 5KHz, an induction of 2 T, and an operating temperature of 500°C has been established for some the more electric aircraft applications. As resistivity is inversely proportional to the eddy current loss component of the total core loss, an increase from 40 to 60 micro-ohm-cm at room temperature has been stated to contribute to the overall machine loss reduction. Frequency range needs to be considered for all of the applications and the loss mechanisms need to be considered. Individual eddy current and hysteretic loss components and their respective contributions to the total core loss need to be understood for each application. Hysteresis loop tuning is a needed capability to achieve a magnetic material's response tailored to a specific application. Advancements in bulk amorphous magnets are needed to explore the possibility of attaining higher operating frequencies suitable for electronic device applications.

Improved overall mechanical properties are needed for many of the advanced applications discussed at the workshop. A soft magnet yield strength need of 700 MPa at 500°C has been established as well as a yield strength of 825 MPa at about 300°C. The limited capacity for radial growth of the rotor, due to the small air gap distances between machine rotor and stator poles, allows for minimal tolerance for time dependent creep deformation. Although creep characterization and modeling of various rotor configurations is continuing, the initial limit for steady-state creep deformation has been established as 2×10^{-6} hr^{-1} for a life of 5000 hours at 600 MPa and 550°C. Corrosion resistance is also a requirement for many of the applications involving hot humid air and salt water environments. Better protective coatings are needed for corrosion resistance as well as for electrical insulation within laminated structures and also for high temperature winding insulation systems.

Compaction techniques need to be further studied and advanced in order to fabricate better magnets from nanomaterials, ribbons, and fibers. Scaling is also an issue pertaining to both hard and soft magnetic materials. Techniques need to be explored to extend magnet producibility and improve affordability when transitioning from the laboratory specimens to useful component-sized magnets. Magnetic and microstructural modeling and simulation is also needed to optimize the final magnet synthesis and fabrication processes.

Specific permanent magnet needs were emphasized at the workshop. All electric wheeled and track ground vehicles require higher energy product magnets than currently available to be used to deliver more torque at the drive wheels. A 35 MGOe magnet is needed for a relatively large diameter pancake motor. The rotor diameter is approximately 60 cm and rotates at about 3000 rpm, which corresponds to the vehicle maximum ground speed. The desired operating temperature is between 250°C and 300°C. Corrosion resistance is also a key issue for these ground vehicle applications. Magnetic bearing systems could benefit from the lower weight and reduced feedback controls associated with permanent magnet designs if the high temperature capabilities were increased. The bottom line need for hard magnets is an energy product of 30 MGOe, at an operating temperature of 450°C, for a life of 5000 hours, without degradation to mechanical behavior.

Reproducible soft and permanent magnets with these specified performance characteristics would meet current magnetic material needs, while increasing significantly the number of potential applications throughout the Department of Defense as well as commercial markets. Table 2 highlights some of the specific technology areas suggested during the final discussion period of the workshop as potential approaches to meet some of the military specific needs. In the past emphasis has been on advancing the state of the art of magnetics by improving the magnetic characteristics. Today, many designers are placing emphasis on maintaining the magnetic properties while increasing maximum operation temperatures. Instrumentation needs are for higher temperature characterization capabilities. Also, the associated instrumentation is needed for new processing techniques and advanced modeling and simulation. With emerging microstructure control processes and nanoengineering techniques, it may be feasible to design an application dependent magnet. The best magnet at room temperature may not necessarily be the best magnet at the desired operating temperature. New magnets being developed for many of today's advanced applications must be characterized at elevated temperatures.

Table 2 Magnetics research and development focus areas suggested as opportunities to address specific military applications.

MAGNETICS RESEARCH STILL NEEDED			
MATERIALS NEEDS	MAGNETIC PROPERTIES NEEDS		INSTRUMENTATION NEEDS
	HARD	SOFT	
• Improved mechanical properties • Improved corrosion resistance • Compaction of nanomaterials, ribbons, and fibers • Scaling technologies • Higher resistance • Protective coatings • Simulation and modeling tools	• Higher energy product (BH) • Lower required magnetizing fields • Hybrid magnets (shape anisotropy) • Simulation and modeling tools	• Frequency range (study loss mechanisms) • Hysteresis loop tuning • Bulk amorphous materials • Simulation and modeling tools	• High temperature characterizations • New processing technologies • Modeling and simulation tools

4. POTENTIAL COLLABORATIONS

4.1. Mikhov-Niarchos

Drs. Mihail Mikhov and Dimitris Niarchos will collaborate on an investigation of magnetic properties of new rare-earth intermetallics that are promising hard magnetic materials. Dr. Mikhov's research team from the University of Sofia, Bulgaria, will be responsible for the synthesis of single crystals of fine particles of the alloys as well as for investigating the magnetic anisotropy by Forrier decomposition of the associated hysteresis loops. Dr. Dimitris Niarchos' research team at the Demokritos Institute of Athens, Greece will be mainly engaged with the production, X-ray and electron microscopy characterization, and low temperature magnetization investigations of the samples.

4.2. McHenry-Varga

Drs. Michael McHenry and L. Varga have made preliminary arrangements for a collaborative effort on the investigation of new early transition metal substations for Zirconium in the recently developed HiTPerm soft magnetic materials. Dr. Varga and his research team at the Research Institute for Solid State Physics and optics in Budapest, Hungary are well known for their investigation of Finemet type and Nanoperm type nanocrystalline alloys and also for their expertise rapid solidification processing. Dr McHenry and his research team at Carnegie Mellon University in Pittsburgh, PA have developed the HiTPerm soft magnetic alloy and are well known for their investigation of nanocrystalline alloys. Together the teams will develop the new HiTPerm derivations; cast wider melt spun ribbons and investigate stress induced pair order anisotropy.

4.3. Chelluri-Varga

Drs. Bhanu Chelluri and L. Varga have initiated a collaborate effort to compact Nanoperm type soft magnetic materials for high frequency applications. Dr. Varga and his research team at the Research Institute for Solid State Physics & Optics at the Hungarian Academy of Sciences, Budapest, Hungary have much experience with Nanoperm type alloys as well as with high frequency power electronics. Dr. Bhanu Chelluri of IAP Research Inc. Dayton, Ohio has become an internationally recognized expert in the area of dynamic magnetic compaction. Together, the research teams plan to synthesize a Nanoperm type material and investigate the magnetic and mechanical behaviors of a bold magnet fabricated by the DMC process.

4.4. Hadjipanayis-Ermolenko

Drs. George Hadjipanayis and Alexandre Ermolenko are planning a collaborative effort on exchanged-coupled, high-coercivity hard magnets using mechanical alloying and ball milling. Dr. Hadjipanayis' research team at the University of Delaware has gained international recognition for their complete understanding of the effects of composition and processing on permanent magnet properties. Dr. Ermolenko and his research team at the Institute of Metal Physics in Ekaterinburg, Russia are well known for their study and development of intermetallic magnetic alloys and the corresponding physical properties. The scientific objective of the collaboration is to obtain new information about the physical mechanisms responsible for the formation of mechanically induced, non-equilibrium, metastable structural states of ferromagnetic materials. Also, the formation of defects and their evolution in crystalline materials during and after heat treatment will be investigated. Structural, phase, and chemical transformations at the various stages of mechanical alloying and ball milling will be studied. This information is important to increase the energy products of exchanged-coupled magnets.

4.5. Chiriac-McHenry

Drs. H. Chiriac and Michael McHenry have discussed a collaborative opportunity in which field annealed protocols would be determined for HiTPerm soft magnetic material. Dr. H. Chiriac and his research team at the National Institute of Research and Development for Technical Physics in Iasi, Romania are very well know for their expertise in BMI applications, sensors, and wire fabrication. Dr. McHenry and his group at Carnegie Mellon University in Pittsburgh, PA have developed the HiTPerm soft magnetic alloy and are well known for their investigations of nanocrystalline alloys. Together, the research teams will develop further the HiTPerm soft magnetic alloy by developing field annealing protocols and studying the BMI effect in HiTPerm wires.

4.6. Menushenkov-Fingers

Drs. Vladimir Menushenkov and Richard Fingers are considering a collaborative effort to search for new high performance hard magnetic materials. Dr. Menushenkov and his research team are internationally recognized for their phase transformation research at the Moscow State Institute of Steels and Alloys, in Moscow, Russia. Dr. Fingers and his researchers have experience with both soft magnetic FeCo alloys as well as Sm-Co and Nd-Fe-B based alloys and sintered magnets. Together, the research teams will further study the evolution of microstructure and coercive force of Sm-Co and Nd-Fe-B based alloys. Attempts will be made to increase both energy product and operation temperature of these sintered magnets.

This page has been deliberately left blank

Page intentionnellement blanche

APPENDIX A – PRESENTATION ABSTRACTS

1. All Electric Vehicle

Wolfgang Brand
BWB-Koblenz, Germany

Abstract

Benefits of electrical energy and progress in electrical technologies:
The main characteristic of the "All Electric Vehicle" (AEV) is the overall use of electric energy for all functions of the vehicle. If there are combat missions involved like survivability and lethality, we talk about an "All Electric Combat Vehicle" (AECV). Hereafter, the abbreviation AEV for both applications will be used.
The AEV systems may have the following configurations:

- Pure electric: only electric supply components are used (e.g. battery or fuel cell)
- Diesel or turbo electric: the prime mover is a diesel engine or gas turbine
- Hybrid electric: a vehicle with the capability to run either by generated or stored electrical energy.

In principle these AEV features and performances to be addressed are:

- electric drive of the vehicle
- supply of command, control, communication and information systems,
- electric brake and regeneration of braking energy,
- electric supply of auxiliary subsystems like fan drives and actuators,
- electric supply of additional electric consumers within the vehicle,
- electric power supply of external consumers,
- electric power supply for electric weapons like electric guns or directed energy like Laser, High Power Microwave and electric armor.

Why are great efforts made to investigate the field of AEV?
The reason is the growing importance of electrical systems based on the physical characteristics of electric energy allowing:

- elementary electrical conversions, distribution, control,
- simple and effective interaction with chemical processes (e.g., ignition of internal combustion engines or ammunition),
- simple transformation (e.g. into force, heat, light).

Thus, many benefits arise, e.g., for components like

- power distribution and power summation at will (allowing free arrangement of components),
- modular subsystems (redundancy and better utilization of space),
- lack of hydraulics (no hazardous liquids, clean compartment);

and for systems like

- homogeneous power systems,
- energy management including peak-power,
- manifold growth potential,
- automation, remote control, robotics,
- high reliability, internal diagnostics,
- beneficial life-cycle costs (maintenance free, low wear, high efficiency),
- less training,
- auxiliary power supply.

These benefits have been well known for more than 100 years. Many applications and technical solutions have been created since the beginning of the industrial age, but a real success and breakthrough could not be achieved for a long time. Thanks to the progress made in the fields of electronic controllers, computers, permanent magnets and power electronics during the last thirty years, new electrical technologies now allow electrical equipment with sufficient power and energy density for use in vehicles. In addition, electrical storage components also have improved tremendously. New electro-chemical storage media such as improved batteries, as well as flywheel energy storage systems with electrical input and output provide an improved basis to supply electrical vehicle systems.

Following are some examples of this progress:
We all are aware of the tremendous worldwide use of electronic controllers, processors and computers. They are essential to take full advantage of the AEV. Concerning magnetic materials the maximum energy density (given by the BH product) has improved by a factor of 40 in comparison to steel. Nearly within the same time frame, power electronics also have improved by a similar amount. A further big step in performance will be expected utilizing the emerging SiC technology.

Components/Concepts for AEV:
Electrical machines base on permanent magnet (PM) material for excitation have been in use for quite some time. But their insufficient energy density did not allow for beneficial vehicle integration. This also applied to power electronics. Improved technologies now permit the realization of high-power and hi-energy drive components such as electric generators, motors, power converters, controllers and power management units.

The DC power link plays a very important role in the electric architecture of the AEV. Here, the electric energy is available to its largest extent. First, there must be energy storage to start the prime mover. Once the engine is running, the full power of the generator can be used for driving. A multi-engine concept also is feasible. The processor control unit governs the operation and additionally provides power management for the AEV.

This describes the common AEV system. But regenerative braking and the high-energy/high-power storage system, either a flywheel or a battery, provides additional power. Only an electrical system allows the easy combination of these power sources, creating new AEV features and performances which are not feasible with conventional vehicle systems. Additional subsystems for AC and DC power units, such as those needed for weapons-naturally being very important for the mission-only participate as consumers.

The essential components for mobile systems using new magnetic materials and several AEV concepts-wheeled or tracked-are discussed in terms of their benefits for weight, volume, efficiency, and technical and military performance.

Finally, examples of actual electric vehicles are presented.

Conclusion

The AEV system utilizes a single form of energy and provides one basic technology in a homogeneous design for power generation and regeneration, and for the power supply of all subsystems. The drive and mission components, even the control elements and sensors, form a homogeneous system structure assuring direct interaction with power management and mission-control devices. In addition, new high-power energy storage systems allow for new features such as peak-power management for highly-improved dynamic mobility, survivability and silent watch.

Several commercial vehicles and military prototypes are already on the road being tested in order to evaluate and improve electric-drive technologies. New magnetic materials are an essential key element for those AEV systems. But additional effort is still necessary to improve the design and performance of Permanent Magnet machines. Therefor, the following areas for further work are addressed.

Requirements

- high remanence B_r[t]
- high intrinsic coercive force H_{CJ}[kA/m]
- high specific energy product (B*H)[kJ/m^3]
- high thermal resistance
- high electrical resistivity
- high resistance against humidity and reagents
- low dependence on temperature of:
- remanence B_r
- intrinsic coercive Force H_{Ci}
- beneficial mechanical features (e.g. sturdiness, flexural strength)

Consequences

- high torque M [Nm]
- high stability against demagnetizing fields
- high power capability or low construction volume
- demagnetization only at high temperatures
- low losses by eddy currents
- long life and corrosion resistance
- decrease of temperatures causes lower:
- reversible reduction of the B-field
- irreversible damages of magnets at higher temperatures
- long life, simple mechanic construction

It is hoped that this workshop will give beneficial inputs to accelerate adequate Permanent magnet material development programs.

2. Electric Weapons

Dr. F. JAMET and Dr. P. LEHMANN
French-German Research Institute of Saint-Louis

Abstract

The presentation will be devoted to three types of weapons:

- High power Microwaves (HPM),
- ElectroMagnetic Railguns (EM),
- ElectroThermalChemical (ETC) guns.

The characteristics of the weapons, in the frame of conventional military applications will be examined in order to determine the specifications for the electric pulsed power supplies: energy, power, voltages, current intensities, pulse duration/rise/decay time, etc.

For HPM weapons, 1µs to 10µs current pulses of ore than 10kA and voltage levels of 100kV to 1 MV are necessary. For EM railguns the electrical energy necessary for one shot ranges between 1 MJ and 50 MJ, depending on the military application, and the current reaches several MA. Examples of energy/power storage architectures and pulse forming networks based on the use of capacitor banks and superconducting coils will be analyzed.

The needed characteristics of the components such as high discharge capacitors, switching systems or connection parts will be described and the expected technology improvements allowing to lower the masses and volumes will be examined.

Finally, we shall describe in details the 10 MJ ISL railgun facility in order to give an overview about the main issues of such weapons. The electrical sliding contact studies, the barrel technology as well as the used measurement techniques will be presented. We also shall show examples of numerical simulation of the EM behavior of the rails-armature coupling.

3. Thermal Management in Power Systems

Ghassan Khalil
U.S. Army TACOM
Warren, MI

Abstract

Electric drives have been investigated through the 20th century for their potential advantages in vehicle propulsion. In every attempt military and commercial vehicle developers always concluded that electric power is adequate but presents challenges that must be overcome prior to application. With the evolution of the technology several advances have been made which have placed electric and hybrid electric drives in the forefront of the candidates of future power and energy alternatives.

Two of the most important achievement-promoting advancements for electric drives are advanced magnetic materials with high energy product, thus high torque and power densities and power semiconductors. Devices with higher power density, higher efficiency, better thermal performance, improved reliability and lifetime, and better control characteristics have recently been developed. However, the silicon-based power devices have a limited operating temperature range (less forgiving than the magnetic materials) and require a relatively low temperature coolant. This adds a cooling burden to the powertrain and presents a great challenge to the vehicle integrators.

This paper discusses the military vehicle requirements, the application of advanced magnetic materials and their impact on the cooling system. It also covers the promising approaches to overcoming the cooling issues.

4. More Electric Aircraft

Drs. R. T. Fingers and A. M. Janiszewski, USAF
Propulsion Directorate, Air Force Research Laboratory
Wright-Patterson Air Force Base, OH

Abstract

A national initiative is underway to develop and test more electric aircraft (MEA) technologies and is being led by the U.S. Air Force Research Laboratory at Wright-Patterson Air Force Base, Ohio. The MEA concept is based on utilizing electric power to drive aircraft subsystems which are currently driven by a combination of hydraulic, pneumatic, electric and mechanical power transfer systems. A major objective of this effort is to increase military aircraft reliability, maintainability and supportability and to drastically reduce the need for ground support equipment. Conventional aircraft secondary power systems, addressing the auxiliary, starting, and emergency power requirements are comprised of complex, high maintenance, hybrid subsystems. Mechanical, electrical, hydraulic, and pneumatic power systems are used to transfer power from the point to generation to the final utilization. The combined logistics to support these subsystems is substantial. Based on rapidly evolving power electronics, fault tolerant electrical power distribution systems, and electric driven flight control actuator systems, increasing the use of electric power is seen as the direction of technological opportunity. Predicted aircraft improvements, including a reduction in required logistics support and an overall increase in available electrical power, will be presented. These improvements will be realized with further advancement of key MEA technologies, including magnetic bearings, aircraft integrated power units (IPU), and starter/generators (IS/G) internal to an aircraft main propulsion engine. These advanced developments, as well as ground and space power applications, will be discussed, as they are the driving force for the new emphasis on high temperature and high strength magnetic materials for power applications.

5. Novel Applications of Permanent Magnets to Electrical Machinery

Dr. Herbert A. Leupold
Department of Physics
U.S. Army Research Laboratory
West Point, NY

Abstract

Advances in permanent magnet materials and design technology have made possible electrical generators and motors that are much more compact, have much less stray field and produce more energy per structural mass than do conventional ones. The simplest of these are essentially rotating Halbach structures (or magic cylinders) with electric coils in their interior cavities. Slightly more complex are counter-rotating, nested Halbach structures which feature less eddy current loss than the simpler configurations of the same mass and output.

Approximations to Halbach structures known as magic mangles afford consideralbe reduction in the movements of inertia of the rotating parts thereby resulting in greater rotational responsiveness. Also brittle magnet materials are subject to much less stress in mangles that in equivalent cylinders thus affording much higher rotational frequencies. Magic mangles are much easier to manufacture than the equivalent magic rings though at the expense of small losses of magnetic field. Comparisons made with more conventional structures favor the magic mangles. In one case a magic mangle generator produces seventy five percent more voltage with only one fourth the structural mass of a comparable conventional configuration. Similar advantages exist for the other cylindrical and mangle type embodiments indicating potential advantageous applications in missiles, spacecraft, airborne vehicles, and portable surface devices.

Also discussed in this presentation is a variety of other promising electro-mechanical devices and components such as field-gradient activators, permanent magnet rotors with gradual azimuthal periodicity in orientation, and novel magnetic bearings.

6. Novel Applications of Magnets

Professor David Howe
Department of Electronic and Electrical Engineering
University of Sheffield
Sheffield, United Kingdom

Abstract

As a consequence of recent advances in permanent magnet materials, as well as developments in power electronics and digital control technology, many new and novel designs of machine/actuator are emerging for applications in different market sectors. The presentation will focus on research which is being undertaken at the University of Sheffield on some specific permanent magnet machine/actuator systems.

- **Modular, fault tolerant, permanent magnet brushless motors:** The phase windings are magnetically, electrically and physically isolated, and can be designed to limit the short-circuit current to the rated full-load current of the machine, which is conducive to fault tolerance. Further, since only alternate stator teeth carry coils, such motors are conducive to low cost modular construction. Thus, they are appropriate for both safety critical and cost-sensitive applications, such as aircraft flight control surface actuation, integrated start-alternator and traction drives, and marine propulsion. However, precautions have to be taken to minimize rotor induced eddy currents.
- **Multi-degree-of-freedom-spherical actuators:** Controlled motion of a spherical permanent magnet rotor with multi-degrees-of-freedom is achieved by employing a diametrically magnetized rotor and three orthogonal pairs of stator coils-to facilitate ‘pan and tilt’ excursions of +/-45°, or a 4-pole parallel magnetized rotor and four sets of non-orthogonal coils- to additionally facilitate continuous rotation. By elimination the need for a separate motor/actuator for each axis, as is generally required for multi-degree-of-freedom actuation systems, the dynamic performance is improved, whilst the system is both lighter and more efficient. Potential applications include robotics, flexible manufacturing, active vision systems and force-feedback joysticks.
- **Halbach magnetized permanent magnet brushless motors:** The combination of a multiple Halbach magnetized rotor and a stator with a non-overlapping (concentrated) winding offers several potential advantages, such as an inherently sinusoidal airgap field distribution and emf waveform, and a very low cogging torque. Thus, likely applications include servo motors, for which a potentially low cost manufacturing route is the injection moulding of Halbach orientated anisotropic bonded NdFeB ring magnets from HDDR-derived moulding compound.
- **Tubular, linear brushless motors:** Tubular motors comprise a multi-pole permanent magnet thrust rod and a moving coil thrust block. By employing a two-phase iron-cored thrust block, both a high thrust force capability and a high closed-loop position bandwidth can be achieved, enabling direct-drive linear motors to complete with more traditional methods for generating controlled linear motion, in applications such as high-speed packaging/manufacturing. Tubular motors impose negligible net radial force on the bearing system and have no end-windings, which is conducive to low copper loss. However, design optimization is required to minimize the cogging force which results from slotting (slot-pitch

equals pole-pitch) and the finite length of the laminated iron cores of the thrust block, whilst consideration should be given to the level of the eddy current loss which is induced in the thrust rod during high speed operation.

- **Flywheel peak-power buffer for electric/hybrid vehicles:** The incorporation of a peak-power buffer in the power-train of electric/hybrid vehicles could significantly enhance their performance and improve consumer acceptance, by making acceleration/regenerative braking largely independent of the state-of-charge of the batteries, extending the cycle-life of the batteries and increasing the vehicle range-by enhancing power-train efficiency. One potential technology is a high-speed flywheel, based around a cylindrical fibre composite rim, with an integral brushless motor/generator for converting kinetic energy to electrical energy, and vice-versa, and which is supported on active/passive magnetic bearings. However, particular consideration must be given to minimizing power losses so as to obtain a high 'round-trip' efficiency and to limit the temperature rise of the rim, which rotates in a high vacuum so as to minimize the aerodynamic loss.
- **Reciprocating moving-magnet actuators for resonant electro-mechanical systems:** 'By matching the system compliance to the total moving mass, and thereby making the mechanical resonant frequency coincident with the electrical excitation frequency maximum displacement of the moving-magnet armature and the coupled load and maximum system efficiency are achieved. The high-energy product to mass ratio of rare-earth magnet materials can be exploited to advantage in such actuators. Potential applications include air-compressors, fuel pumps, artificial heart devices, etc.

7. Introduction to Magnetism-Magnetic Interaction

Henryk Szymczak
Institute of Physics, Polish Academy of Sciences
Al. Lotnikow 32/46, Warsaw, 02-668, Poland

Abstract

Some basic interactions governing the properties of magnetic materials at the atomic scale are discussed on an introductory level. The essential interactions determining the magnetic moments, the temperature of magnetic ordering and the type of magnetic order are the exchange interactions, spin-orbit coupling and the crystal field action on magnetic electrons. The relative importance of each interaction term may strongly differ from one system to another due to different behavior of magnetic electrons. It will be shown that all magnetic interactions can somehow depend on the lattice distortions and therefore contribute to the magnetoelastic energy (and consequently- to the magnetostricition). The two non-local effects related to the demagnetizing fields and to the magnetostrictive self-energy are shown to have strong effect on the magnetic domain structure and on extrinsic properties of magnetic materials.

8. Magnetic Anisotropy

Dr. Michael McHenry
Materials Science and Engineering Department
Carnegie Mellon University
Pittsburgh, PA

Abstract

The physical basis for magnetic anisotropy, in terms of shape, magnetocrystalline, and stress (magnetostrictive) aminsotropies will be introduced with emphasis on the quantum mechanical origin of magnetic anisotropies. The Landau theory of magnetic phase transformations will be introduced. Within the language of the Landau theory energy density, terms describing magnetocrystalline and magnetoelastic anisotropies will be illustrated. Each of these will be developed with an example of a current magnetic material which is important to power application (or actuation). The temperature dependence of magnetic anisotropy will be developed within this framework. A local Landau theory will be described and used to illustrate important magnetic nanocomposites (soft/soft, hard/hard, and hard/soft). These illustration will include HITPERM soft magnets, 2:17 and 3:29 phase hard magnets, and spring exchange magnets. Surface and interfacial anisotropies will be discussed using nanocomposite ideas.

9. Rare Earth Intermetallic Compounds

Dr. A.S. Ermolenko
Institute of Metal Physics, Ural Brunch of RAS
Sofia Kovalevskaya St., 18, Ekaterinburg, 620219, Russia

Abstract

The studies of the physical properties of rare earth intermetallics began in 1950-th years, and the interest to this subject does not weaken up to now. The intermetallics between rare earth and 3d transition metals occurred to be especially interesting and attractive. The permanent magnets and the magnetostriction materials with outstanding properties were developed on their base. These properties are realized due to the confluence of two kinds of ions with 3d and 4f unfilled electron shells into one 3d-4f intermetallic. Namely this kind of rare earth compounds is a main subject to consideration in the present lecture.
The following topics will be touched:
1. The peculiarities of magnetic properties of 3d-4f metals.
2. The main types of the binary 3d-4f intermetallics.
3. Two-sublattice magnetic structures of 3d-4f intermetallics.
4. Exchange interaction and regularities of spontaneous magnetic moment formation.
5. The magnetocrystalline anisotropy and the magnetostriction.
6. The orientational magnetic phase transitions.
7. Alloyage influence on magnetic properties of 3d-4f intermetallics.

10. Microstructural Changes And Coercivity Or Rare-Earth Alloys And Permanent Magnets (The Search For New Phases For Advanced Magnets)

Drs. V.P. Menushenkov, A.S. Lileev, A. G. Savchenko
Moscow State Institution of Steel and Alloys (Technological University),
117936, Moscow, Leninsky prospect 4

Abstract

The influence of the phase transformations in Sm-Co and Nd-Fe-B based alloys and sintered magnets during heat treatment on their hysteresis properties are discussed. The main attention is focused on both the homogeneity regions of the phases and the intergranular regions. After an analysis of the crystal lattice parameters of the $SmCo_{5-x}$ alloys and sintered magnets a hypotetic scheme of phases transformations and the boundary of homogeneity region are proposed. This scheme is compared and discussed wit that previously obtained in other studies. The use of this scheme provides the better understanding of the structural mechanism of high coercivity obtained for the $SmCo_5$ based alloys enriched in Sm or Co. The evolution of the microstructure and coercive force during heat treatment are considered.

One of the unsolved question in the understanding of the properties of Nd-Fe-B sintered magnets is the role of heat treatment in the 450-600°C range in developing of coercivity. Both the role of surface of the $Nd_2Fe_{14}B$ grains and the intergranular regions are analysed. Numerous investigations have been performed to study the phase composition and microstructure changes in the intergranular regions. The space lattice parameters of the $Nd_2Fe_{14}B$ phase vary unmonotonously with annealing temperature. After analysis of the hydrogen concentration in as-cast Nd-Fe-B alloys sintered and heat treated magnets the effect of hydrogen in $Nd_2Fe_{14}B$ and intergranular Nd-rich phases is discussed. The study of model alloys of Fe-Nd system showed that their high coercivity is attributed to the metastable highly anisotropic A_1 phase forming during eutectic reaction. The structural changes in Nd and Nd-Fe alloys and the influence of A_1 phase in coercivity of FE-Nd alloys and Fe-Nd-B magnets are considered.

The phase transformations in higher magnetic energy density Nd-Fe-B films with axial crystalline texture along the normal to the sputtering plane are discussed. The films were produced by ion-plasma sputtering of as-cast targets. The evolution of the microstructure and coercive force of the sputtering films during heat treatment are analyzed.

In the search for new high performance hard magnetic materials it is desirable to look for Fe-Co based alloys with higher than 83 at. % transition metal concentrations. The magnetic properties of some rare earth (Yb)-Co-Fe-Mn alloys are compared and discussed.

11. Magnetic Hysteresis

Professor H. Kronmuller
Max-Planck-Institut fur mMtallforschung
Heisenbergstr. 1,D-70569 Stuttgart, Germany

Abstract

During the last few decades a large number of high-performance magnetic materials have been developed covering a wide range of permeabilities and coercivities. Permeabilities up to~10^6 have been developed for nanocrystalline systems based on transition metals and coercivities up to 4 Tesla for sintered and nanocrystalline intermetallic compound of rare earth metals. The basic properties of magnetic materials are their intrinsic material parameters as spontaneous polarization Js, Curie temperature T_C. Anisotropy constants K_i and magnetostriction $\lambda_{s.}$ Usually, in general large values of J_S and T_C are required for all types of magnetic materials whereas K_i and λ_s should be as small as possible for soft magnetic materials and rather large for hard magnetic materials. The extrinsic properties of the hysteresis loop as coercive field H_C, remanence J_r, initial susceptibility χ_o and Rayleigh constant αR depend sensitively on the microstructure of the material and in the case of small particle and thin platelets also on the size and shape. The characteristic properties of the hysteresis loop χ_0, H_C, $\alpha$are the most exciting properties because their values may vary over 6 orders of magnitude, which results from the relation between intrinsic properties and the microstructure.

In soft magnetic materials, crystalline or amorphous, the interaction between domain walls and the microstructure plays the dominant role for the hysteresis loop. For the case of dislocation it is shown that these govern domain pattern as well as the magnetization processes.

In nanocrystalline magnetically soft materials as FINEMET, instead of domain wall displacements rotational processes dominate the magnetization process. Due to the random anisotropy effect in such systems a drastic decrease of the effective anisotropy constant takes place if the domain wall width exceeds the diameters of the grain size.

Whereas in crystalline soft magnetic materials the statistical theory of domain wall pinning give a quantitative interpretation of χ_o, H_c, α_R in the case of nanocrystalline materials the micromagnetic theory of the random anisotropy of statistically distributed easy directions allows a quantitative description of the properties of the hysteresis loop.

In hard magnetic materials as sintered and nanocrystalline magnets or individual single domain particles the hysteresis loops depend sensitively on the perfection of grains and the type of coupling between them. By means of computational micromagnetism on the basis of the finite Element Technique the demagnetization of three characteristic nanostructures have been simulated: i0 Magnetically decoupled grains due to a paramagnetic intergranular phase. ii) Magnetically exchange coupled grains with grain boundaries of reduced material parameters. iii) nanocrystalline composite systems where magnetically soft iron grains are magnetically hardened by exchange coupling with hard magnetic grains.

From these results detailed information for the tailoring of hysteresis loops by well-defined microstructures has been obtained. It shown that optimized magnetic materials requires suitable intrinsic material parameters but also well defined microstructures. Bu characteristic examples of modern magnetic materials the correlation between magnetization processes, magnetic structures and the microstructure are demonstrated.

12. Magnetic Measurement Techniques (Classical Methods)

Dr. Mihail Mikhov
Faculty of Physics, “St. Kl. Ohridski” University of Sofia
1164- Sofia, Bulgaria

Abstract

Mechanical forces on the magnetic moment placed in a homogeneous or non-homogeneous magnetic field and the magnetic field created in the space around the magnetic moment give the varieties of the direct methods for magnetic measurements. DC Faraday magnetometer (magnetic balance), Alternation Gradient Force Magnetometer and Torque Magnetometer are described as most popular techniques for magnetization and magnetic anisotropy studying, based on the force measurements. Vibrating Sample Magnetometer, SQUID Magnetometer, AC Susceptometer and Hysteresis Loop Tracer are given as examples of very commonly used methods, based on the flux measurements. The advantages and the limitations of the methods, such as sensitivities, accuracy, dynamic ranges, sample sizes, temperature and field ranges are noted. The influence of the demagnetizing field on the magnetization (m vs. H) curves is also briefly commented. The talk is not dealing with different methods for interpretation of the experimentally obtained quantities.

13. Dynamic Magnetic Compaction (DMC) of Soft and hard magnet Powders

Dr. Bhanu Chelluri
IAP Research Inc
2763 Culver Ave
Dayton, Ohio

Abstract

Dynamic Magnetic Compaction (DMC) is an innovative net shape powder pressing technology that uses magnetic pulse forces to achieve full density in several material systems. Since the compaction duration is less than 1 millisecond, important dynamic effects occur in the powders which, when combined with the full density, yield properties for high performance. Additionally, special microstructures and grain sizes of the starting powders can be preserved after DMC compaction. Different types of magnet powders are being compacted using this technology for DOD and commercial applications. Amongst soft magnet powders these include resin coated soft iron powders for ignition core applications and nano iron-cobalt powders for high temperature DOD applications. In the hard magnet area, powders of SmCo (2:17) are being investigated for better mechanical and magnetic properties for high temperature DOD applications, bonded neo magnets for higher performance commercial applications and compaction of nano magnet powders such as Pr_{19} Co_{81} powders. In this presentation, an overview of the process, the properties of various compacted materials, technology features such as size, shape and dimensional tolerances that can be achieved in finished parts will be described.

14. Microstructure and Magnetic Domains

Dr. Josef Fidler
Vienna University of Technology
Institute of Applied and Technical Physics,
Weidner Hauptstr. 8-14, A-1040 Wien, Austria.

Abstract

The development of new hard and soft magnetic material, the increasing information density in magnetic recording and the miniaturization in magnetic sensor technology lead to an increasing interest in the interaction between microstructure and magnetic domain structure. The shape and the detailed spatial arrangement of domains and domain boundaries determine the magnetic hysteresis or magnetization curve, which describes the average magnetization of a magnetic material as function of the external field. The trend towards nanocrystalline of magnetic materials and the improved availability of large scale computer power are the main reasons why micromagnetic modeling has been developing extremely rapidly in order to simulate the influence of the shape and the size of grains, of their magnetic intrinsic parameters, and of precipitates on the formation of magnetic domains.

Micromagnetic modeling of the magnetization reversal process of magnetic nanoelements which are patterned structures at the submicron level show that the shape of elements become an important factor controlling the hysteresis. The worldwide interest in these elements is their potential for possible future application in high-density magnetic data storage and microsensor applications. For use as patterned magnetic media each nanoelement would storage one bit. Thin films with exchange coupled nanocrystalline grains such as permalloy or cobalt will be used to fabricate the nanoelements. The physics of real magnetic materials and ultra small devices, such as patterned media, spin-valve devices and spin tunnel junctions, is complex, and the understanding of the magnetic switching behavior is of great interest. Over recent years the investigation of nanostructured elements has become more advanced due to improvements in numerical micromagnetic methods on the theoretical side and high accuracy fabrication methods, such as electron beam lithography and focused ion beam techniques.

The search for novel soft and hard magnetic materials for high temperature advanced power applications and for magnets with highest energy density values is worldwide an active area of research. The nucleation and expansion of reversed magnetic domains and the pinning behavior of the magnetic domain walls are the factors determining the coercive field or hysteresis of such materials.

This work is partly supported by the Austrian Science Fund projects P13260-TEC, 13433-PHY and Y132-PHY and the EC project HITEMAG (GRD1-199-11125).

15. Magnetic Domain Structure and Spin-Reorientation Process

Dr. Yu. G. Pastushenkov
Physical Department
Tver State University
Zheliabova St. 33, 17000 Tver, Russia

Abstract

Magnetic phase transitions, in general, are of considerable interest to the scientific community [1]. It is of great interest to study the phase transition occurring in the single crystals of intermetallic compounds since they offer other variety of magnetic for this type of study. From this point of view the tetragonal intermetallic compounds $Nd_2Fe_{14}B$, $R(Fe,Co)_{11}Ti$ (R=Tb,Dy) are of outstanding interest. By the change of magnetic constant they demonstrated all possible types of magnetic anisotropy (easy axis, easy cone, easy plane, easy axis +easy plane) and also the magnetic phase transition between them [2-4]. Therefore the intermetallic compounds $Nd_2Fe_{14}B$ and $R(Fe,Co)_{11}Ti$ are good models objects for study of the physical picture of magnetic phase transitions in tetragonal magnetic. On the other hand they are the main bases for the manufacturing of modern high-energy permanent magnets. In this sense the investigation of magnetic phase transition in tetragonal compounds is also very important for the best understanding of temperature dependence of demagnetization processes in Nd-Fe-B and Sm-Fe-Ti permanent magnets.

The domain structure was investigated in the spin-reorientation region on the (100) and (001) planes and arbitrary oriented surfaces of $Nd_2Fe_{14}B$ and $R(Fe,Co)_{11}Ti$ single crystals with nonuniaxial magnetocrystalline anisotropy by means of the magnetooptical Kerr effect. The magnetic phase diagram of a tetragonal magnetic is calculated theoretically and the effect of domain structure on the nature of the phase transition is investigated. Domain wall density calculations have been performed for the same domain wall orientations in tetragonal magnetics with all types of non-uniaxial magnetic anisotropy. On the basis of the observed domain configuration and domain wall density calculation the possible models for the volume magnetization distribution and possibility of new domain wall types formation in tetragonal magnetics with “easy cone” and “easy plane” anisotropy have been discussed [4].

It was found that in $Nd_2Fe_{14}B$ single crystal by low-temperatures the coercivity of different domain walls essentially depends on their type and orientation. The role of the new domain wall types in the low-temperature magnetization reversal process in Fe-Nd-B permanent magnets is discussed.

[1] D.-X. Chen, V. Skumryev, H.Kronmuller Phys.Rev. B (1992). V.46. P.3496-3505.
[2] Yu. G. Pastushenkov, A. Forkl, H. Kronmuller: J. Magn. Magn. Mater.174 (1997), 278.
[3] Pastushenkov Yu. G., Suponev N.P., Dragon T., Kronmuller H. J.Magn.Magn.Mater, 196/197 (1999) 856-858.
[4]Pastushenkov Yu. G., Suponev N.P. Proceedings of Moscow International Symposium on Magnetism MISM’99, June 20-24, 1999. Part 1. P.384-387.
Keywords: Domain structure, Magnetic phase transition, Single crystal, Permanent magnet

Contact author: Yurij G. Pastushenkov, tel.: ++7 0822 487690; fax: ++7 0822 331274, e-mail: yupast@tversu.ru

16. Rare Earth 2:17 Permanent Magnets

Dr. George C. Hadjipanayis
Department of Physics and Astronomy
University of Delaware, Newark, DE

Abstract

During the last four years we have undertaken a comprehensive and systematic study on precipitation hardened $Sm(Co,Fe,Cu,Zr)_Z$ magnets and we are now in a position to completely understand the effects of composition and processing on their hard magnetic properties. Their high coercivity is due to a complex cellular/lamellar microstructure consisting of 2:17 R cells surrounded by 1:5 cell boundaries, superimposed on a thin lamella phase (Z phase). This microstructure causes domain wall pinning at the cu substituted 1:5 cell boundaries because of a reduction in their domain wall energy, due to the Cu substitution. Higher ratio z leads to larger cells as expected due to the larger amount of the 2:17 phase. For a fixed Cu content, this translates to a larger amount of Cu in the 1:5 cell boundaries, and therefore, to a higher coercivity. Magnets without cu, but with Zr, have the cellular/lamellar microstructure. However, the coercivity of the magnets is almost zero due to the lack of a large gradient in domain wall energy across the 1:5 boundaries. Cu substitution leads to a slight decrease in cell size. Magnets with higher Cu have higher room temperature coercivity but poor temperature dependence of coercivity. Zr is critical in the formation of uniform cellular and lamellar microstructures. In Zr free samples, the lamellar microstructure is not formed, and the larger amount of Cu is needed to form the cellular microstructure. For higher Zr, a 2:7 phase is formed leading to a deterioration of magnetic properties. Increasing Fe cont4ent results in the formation of uniform cellular/lamellar microstructures with a larger cell size. This translates to a larger Cu content in the 1:5 cell boundaries and thus to a higher coercivity. For higher Fe, the coercivity sharply drops because of the deterioration of the cellular microstructure and magnetic properties of the 2:17 PHASE. In general, the homogenized magnets have a featureless microstructure with the hexagonal 2:17 phase. However, for the homogenized magnets with higher Cu and Zr content, a microstructure consisting of 1:5 precipitates embedded in the 2:17 matrix is observe. In the latter magnets, a shorter aging at 850°C followed by subsequent quenching is enough to develop a high coercivity of over 22 kOe. The results of all of these studies clearly show that Cu and Zr are important elements in developing and stabilizing a uniform cellular microstructure, and the Cu mainly controls both the coercivity and its temperature dependence.

This work is supported by the Air Force Office of Scientific Research under Grant No. MURI F49620-96-0403

17. It All Starts With Iron

Dr. A. S. Arrott
Department of Physics
Virginia State University
Petersburg, VA

Abstract

Edison attributed progress to 2 percent inspiration and 98 percent perspiration. In the electrical power industry under Edison the inspiration may have been as high as that, but for most of the last century it has been almost entirely perspiration that has led to advances in the use of soft magnetic metals for motors, generators and transformers.

In technology there is a chain linking theory, phenomenology, experiment and practice. In principle each of these feeds into its neighbor in the chain, but in electrical machinery based on soft magnetic metals, it seems that the experiments feed outward sin both directions without much feedback. There are many reasons for this. There are matters of the many disciplines involved, the complexity of the problems and the extremely wide range of length scales to be considered. The electrical power industry concerns range from atoms to real estate, from Dirac's equation to Federal Regulatory Commissions. What ever happened to research in magnetism at (Over the past fifty years engineers and scientists have been replaced by lawyers at places like General Electric Westinghouse)?

The thesis of this presentation is that there is a fundamental cause for all of the above. It is iron. Iron has the highest moment per unit volume or per unit mass and it is so readily available that it is almost free. So the history of soft magnetic metals for power applications, to be reviewed, is that of how to make iron better without making it a significant part of the cost of the motor, generator or transformer. The main path has been to purify it to get rid of the bad guys and to enlist the help of other cheap elements such as silicon to improve the metallurgical properties with a minimal reduction in magnetic moment and a substantial increase in electrical resistivity. More recently another cheap element, boron, has been used to change the crystal structure from body-centered-cubic (slightly tetragonal) to amorphous to nanocrystalline composites from the partial recrystallization of amorphous iron alloys.

18. Nanocrystalline Soft Magnets

Drs. L.K.Varga[1] and F. Mazaleyrat[2]
[1] Research Institute for solid State Physics and Optics
1525 Budapest P.O.B. 49, Hungary
[2]LESIR, Ecole Normale Superieure de Cachan, 61
Av.Pres.Wilson 94235 Cachan, France

Abstract

Nanocrystalline soft magnetic alloys will be presented and their application in power electronics will be discussed. These nanocrystalline (nc) alloys are prepared by proper heat treatment of an amorphous precursor containing both grain nucleating (Cu) and grain growth inhibiting (early transition metal, ETM: Zr, Nb, etc.) elements. Two families of these nc alloys have been investigated so far; the Finemet type, ($Fe_{73.5}$ $Si_{22.5-x}B_xNb_3Cu_1$, x=7 and 9) and Nanoperm type, ($Fe(Co)_{92-x-y-z}Zr_xNb_yB_zCu_1$, x=2, 7, y=3.5, 4, z=2-8.5). (The version with Co replacement of Re is called HiTperm).

These two-phase granular magnets composed of magnetic nanosized crystallites embedded in residual amorphous matrix shows interesting magnetic phase transitions evolving through strongly-coupled ferromagnetic, weakly-coupled "super"-ferromagnetic, superparamagnetic and paramagnectic states as a function of temperature. These transitions will be exemplified by the characteristic changes in the hysteresis loop characteristics (saturation magnetization, remanence ratio, coercive field, initial permeability) as a function of temperature. Special attention is paid to the explanation of the Hopkinson peak of the initial permeability, which limits the applicability of these soft magnetic materials well below the Curie temperature of the residual amorphous matrix. We report here a large (300-400 K) increase of the decoupling (T_c^{am}) temperature with increasing crystalline fraction in Nanoperm type alloys. This is in contrast to the Finemet type alloys where T_c^{am} varies several 10 K only around the original as cast amorphous T_c when the amorphous precursor is annealed around the first crystallization peak.

For electronic applications special tailoring of the hysteresis loop characteristics is necessary, which can be accomplished by transversal or longitudinal induced anisotropy's. For Finemet type alloys, the activation energy of field induced anisotropy is around 3 eV while that of the stress induced anisotropy is around 4 eV. By field annealing a relatively small amount of induced anisotropy, Ku~10-50 J/m^3, can be introduced only, useful in suppressing the do bias sensitivity of transformer cores. By stress annealing however, a large induced anisotropy, up to Ku~4000 J/m^3, can be achieved, which beside excellent high frequency characteristics, makes possible the application in power electronics as well like fly-back converters and smoothing chokes where storing of magnetic energy is necessary.

It is attempted that the cheap iron based nanocrystalline alloys should replace part of ferrites in the forthcoming years.

19. From Nanoparticles To Nanocomposites

K. Humfeld, A. K. Giri, K. M. Chowdary, S. Yamamuro, and Dr. S. A. Majetich
Department of Physics
Carnegie Mellon University
Pittsburgh, PA

Abstract

Here we describe how the AC magnetic properties of nanoparticle are related to those of noanocomposites made by compaction. We start with an AC version of the Stoner-Wohlfarth model and show how the phase lag of the magnetization relative to the applied field leads to hysteresis or superparamagnetism, depending on the particle size, anisotropy, and temperature. These predictions are compared with experimental results for a 0.1% volume fraction sample of highly monodisperse 7nm Fe nanoparticles at low temperature.

In contrast to this system with isolated, non-interacting grains, we also investigated a nanocomposite made by compaction of similar Fe nanoparticles. The frequency dependence of the coercivity, permeability, and power loss for a sample with an average grain size of 10nm was measured between 77 and 473 K. Our AC magnetic model was modified to describe the nanocomposite as well, despite the presence of interactions among the grains. Here the volume was the exchange coupled volume rather than the particle volume, and the anisotropy was an effective value rather than the bulk magnetocrystalline anisotropy. The AC response of the nanocomposite is found to have two contributions, from magnetically isolated and magnetically coupled grains.

Related composites of $Fe_{10}Co_{90}$ nanoparticles were studied over a temperature range of 77-773K. Here Lorentz microscopy of sectioned nanocomposites shows evidence of magnetically coupled regions. The temperature dependence of the effective anisotropy and the exchange length found the fits to the experimental data are presented, and discussed in terms of the random anisotropy model. We conclude with predictions of requirements for improved high temperature soft magnetic materials based on nanocomposites.

20. Soft Magnetic Materials for High Temperature Applications - Bulk Alloys, Nanocrystalline Alloys, and Fiber Reinforced Composites

Dr. K.M. Unruh
Department of Physics and Astronomy
University of Delaware
Newark, DE

Abstract

Soft magnetic materials with superior high temperature magnetic and mechanical properties will play an important role in enabling a number of next generation aerospace technologies. Unfortunately, no known single phase material can simultaneously meet the anticipated requirements of a large saturation induction, large permeability, and low core loss in combination with high mechanical strength and creep resistance at temperatures as high as 600°C. As a result, it now seems likely that in order to meet this goal a composite material will be needed in which the necessary magnetic and mechanical properties are associated with different constituents.

After reviewing the status of the best currently available commercial FeCo alloys, the preparation and properties of two different classes of composite materials will be described: nanocrystalline FeCo based Finemet-type materials and FeCo coated continuos W fibers. While each of these materials exhibit superior high temperature magnetic properties, it appears that the FeCo coated W fibers offers the most promising approach for also achieving high temperature mechanical strength and creep resistance.

21. Optimizing the Energy Product of Nanocomposite Magnets At Finite Temperature

Dr. S. T. Chui
Bartol Research Institute
University of Delaware
Newark, DE

Abstract

We discuss the coercive behavior of nanocomposite magnets. The focus will be on optimizing the energy product of these systems. We discuss results of finite temperature Monte Carlo simulation for the switching field of multi-layers of hard and soft magnets. (J. Appl. Phy. August, 2000) These switching fields are usually larger than the depinning field of the domain walls in the same systems that we previously calculated (J. Phys. Conds. Matt.11, 2719 (1999)) and have a different dependence on the soft layer thickness. In the former case, the switching field goes down as the soft layer thickness is increased. In the latter case the depinning filed increases first and flattens off. Similar results also hold for three dimensional systems. In this case the depinning field exhibits a maximum as a function of the soft layer thickness. The implication of this on designing the maximum energy product will be discussed. The effect of finite temperature and the dipolar interaction will be included.

22. Magnetic Annealing

Dr. H. Chiriac
National Institute of Research and Development for Technical Physics
47 Mangeron Blvd.
6600 Iasi, Romania

Abstract

Magnetic annealing-the thermal treatment of a magnetic material at a temperature below Curie temperature-generally results in the induction of a macroscopic magnetic anisotropy with a predetermined easy axis direction. The interaction between magnetic moments and micro-structural topology favors the formation of atomic pairs in a direction, which is related to the orientation of constituent magnetic moments.

The anisotropy induced by magnetic annealing is characterized by a preferred direction, which is parallel with the field direction during annealing. The magnitude of the induced anisotropy constant is a function of time and temperature of the treatment. Normally, this induced anisotropy is reversible and can be removed by other annealing applying the magnetic field in another direction. The origin of the field-induced anisotropy has been ascribed to the formation of atom pairs aligned along a preferred direction determined by the direction of the applied magnetic field during annealing.

The magnetic annealing can be applied by increasing the temperature of the sample, which is introduced in an oven and applying a magnetic field by means of one solenoid, coils or electromagnet. Another possibility is to heat the sample passing a current through it (Joule heating), used also for the production of a circumferential magnetic field or by applying from outside a supplementary one.

New results on the magnetic annealing in amorphous and nanocrystalline materials in the shape of ribbons, wires, and glass-covered amorphous wires are presented.

23. Nanostructureed Magnetic Material Using Electrodeposition Processes

Dr. Michel L. Trudeau
Emerging Technologies, Hydro-Quebec
1800 Boul. Lionel-Boulet, Varennes
Quebec, Canada

Abstract

The last ten years have clearly revealed the technological potentials of nanostructured materials. However, the developments in some technological fields are still in desperate need of synthesis processes that can generate large amount of fully dense nanostructured products. This is the case for instance for soft magnetic materials. It has been shown a number of years ago, that by decreasing the average crystal size of soft magnetic materials in the nanometer regime, it is possible to reduce drastically their magnetic losses. However, many studies done in recent years have demonstrated that large-scale soft magnets can not be obtained by the densification of nanostructured powders. On the other hand, a number of works have shown that by controlling the current profile during electrodeposition and through the addition of grain growth inhibitors, it is possible to control the nucleation and growth of the deposited materials. Dense samples, with a crystalline size as low as 5 to7 nm, can thus be synthesized. Compared to other techniques, pulse-electrodeposition has received little attention as a synthesis method for producing large quantities of fully dense nanostructured materials. In this work we will discuss the syntheses of soft magnetic materials, in particular Fe and Fe-rich Fe-Ni alloys obtained by controlling different electrodeposition parameters. These examples will demonstrate that electrolytic processes can be the major synthesis technique for large-scale development of dense nanostructured materials.

APPENDIX B – PARTICIPANT LISTING

Arrott, A. S.
Physics Department
Virginia State University
Petersburg, VA 23804, USA
PHONE: 804-524-5915
FAX: 804-524-5439
E-MAIL: arrott@sfu.ca

Brand, Wolfgang
BWB-Koblenz, Germany
PHONE: 49-261-400-7020
FAX: 49-261-400-6021
E-MAIL:WolfgangBrand%BWB@BWB.org

Chelluri, Bhanu
Sr. Research Scientist
IAP Research, Inc.
2763 Culver Avenue
Dayton, OH 45429-3723
PHONE: 937-296-1806
FAX: 937-296-1114
E-MAIL: bhanu@iap.com

Chiriac, H.
National Institute for Research and
Development for Technical Physics
47 Mangeron Boulevard
6600 IASI 3, ROMANIA
PHONE: 40-32-130680
FAX: 40-32-231132
E-MAIL: hchiriac@phys-iasi.ro

Christodoulou, Chris
Frederick Institute of Tech./Frederick Research Center
7, Y.Frederikkov Street
1036 Nicosia, CYPRUS
PHONE: 357-2-345159
FAX: 357-2-373595
E-MAIL: frederick@zenon.logos.cy.net

Chui, Siu-Tat
Bartol Research Institute
University of Delaware
217 Sharp Laboratory
Newark, DE 19716
PHONE: 302-831-8115
FAX: 302-831-1843
E-MAIL: chui@bartol.udel.edu

Ermolenko, Alexandre S.
Inst. of Metal Physics
Ural Brunch of Ras
Sofya Kovalevskaya St., 18
Ekaterinburg 620219, Russia
PHONE: 3432-744472
FAX: 3432-745244
E-MAIL: ermolenko@imp.uran.ru

Fidler, Josef
Institute of Applied Physics
Vienna University of Technology
Wiedner Haupstrasse 8
A-1040 Vienna, AUSTRIA
PHONE: 43-1-58801-13714
FAX: 43-1-58801-13798
E-MAIL: fidler@tuwien.ac.at

Fingers, Richard T.
United States Air Force Research Lab/PRPG
1950 Fifth Street
Wright Patterson AFB, OH 45433
PHONE: 937-255-6241
FAX: 937-656-4132
E-MAIL: richard.fingers@wpafb.af.mil

Hadjipanayis, George C.
University of Delaware
Dept. Of Physics & Astronomy
223 Sharp Lab
Newark, DE 19716
PHONE: 302-831-2736
FAX: 302-831-1637
E-MAIL: hadji@udel.edu

Howe, David
Dept.of Electronic & Electrical Engineering
University of Sheffield
Mappin Street
Sheffield S1 3JD, UNITED KINGDOM
PHONE: 44-114-222-5195
FAX: 44-114-222-5196
E-MAIL: s.j.gawthorpe@sheffield.ac.uk

Jamet, Francis
French German Research Institute
of St. Louis (ISL)
PHONE: 33-38-969-5015
FAX: 33-38-969-5162
E-MAIL: jamet@isl.tm.fr

Khalil, Ghassan
U. S. Army Tank-automotive and
Armaments Command
Research Business Group
Mobility Systems (AMSTA-TR-R)MS 121
Warren, MI 48397-5000
PHONE: 810-574-7989
FAX: 810-574-5054
E-MAIL: khalilg@tacom.army.mil

Kronmuller, Helmut
Max-Planck Institut fur Metallforschung
Heisenbergstr. 1
D-70569 Stuttgart, GERMANY
PHONE: 49-711-689-1910
FAX: 49-711-689-1912
kronm@physix.mpi-stuttgart.mpg.de

Leupold, Herbert A.
U. S. Army Research Laboratory
Department of Physics USMA
Bartlett Hall, Rm. 300 North Side
West Point, NY 10996
PHONE: 845-938-5800
FAX: 845-938-5803
E-MAIL: hH3416@exmail.usma.army.mil

Majetich, Sara
Department of Physics
Carnegie Mellon University
Pittsburgh, PA 15213
PHONE: 412-268-3105
FAX: 412-681-0648
E-MAIL: sm70@andrew.cmu.edu

McHenry, Michael E.
Materials Science and Engineering Dept.
Carnegie Mellon University
Pittsburgh, PA 15213-3890
PHONE: 412-268-2703
FAX: 412-268-3113
E-MAIL: mm7g@andrew.cmu.edu

Menushenkov, Vladimir P.
Laboratory of Permanent Magnets,
Moscow Institute of Steel & Alloys
(Technological University)
Leninsky Pr. 4
117936, Moscow, RUSSIA
PHONE: 095-339-6933
FAX:
E-MAIL: menush@nu.misa.ac.ru

Mikhov, Mihail
Faculty of Physics
St. Kl. Ohridski
University of Sofia
1126 – Sofia, BULGARIA
PHONE: 359-2-62-56877
FAX: 359-2-96-25276
E-MAIL: mikhov@phys.uni-sofia.bg

Niarchos, Dimitrios
NCSR "Demokritos"
Aghio Paraskevi, Attikis 153 10
Athens, GREECE
PHONE: 30-1-653-3706
FAX: 301-1-651-9430
E-MAIL: dniarchos@ims.demokritos.gr

Pastushenkov, Yurij G.
Head of Magnetism Department
Tver State University
Zheliabov Street, 33
170000 Tver, RUSSIA
PHONE: 7-0822-487690
FAX: 7-0822-331274
E-MAIL: yupast@tversu.ru

S.G. Sampath
European Research Office, U.S. Army
Edison House, 223-231 Old Marylebone Road
London NW1 5TH
United Kingdom
PHONE: 44-20-7724-1433
FAX: 44-20-7724-1433
E-MAIL: ssampath@usardsguk.army.mil

Szymczak, Henryk
Institute of Physics
Polish Academy of Sciences
al. Lotnikow 32/46
02-668 Warsaw, POLAND
PHONE: 48-22-620-3346
FAX: 48-22-843-0926
E-MAIL: szymh@ifpan.edu.pl

Trudeau, Michel L.
Technologies Emergentes
IREQ, Hydro-Quebec
1800, Boul . Lionel-Boulet
Varennes, Quebec, CANADA J3X 1S1
PHONE: 450-652-8265
FAX: 450-652-8905
E-MAIL: trudeau.michel@ireq.ca

Unruh, Karl
University of Delaware
Dept. Of Physics & Astronomy
223 Sharp Lab
Newark, DE 19716
PHONE: 302-831-6810
FAX: 302-831-1637
E-MAIL: kmu@udel.edu

Varga, L. K.
Head of the Metallurgy & Magnetism Group
Res. Inst. for Solid State Physics & Optics
Hungarian Academy of Sciences
H-1525 Budapest, P. O. B. 49
Konkoly Thege ut 29-33, HUNGARY
PHONE: 36-1-392-2220
FAX: 36-1-392-2220
E-MAIL: varga@power.szfki.kfki.hu

Weinstock, Harold
A. F. Office of Scientific Research
AFOSR/NE
801 N. Randolph St., Room 732
Arlington, Virginia 22203-1977
PHONE: 703-696-8572
FAX: 703-696-8481
E-MAIL: harold.weinstock@afosr.af.mil

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's References	3. Further Reference	4. Security Classification of Document
	RTO-TR-031 AC/323(AVT-060)TP/36	ISBN 92-837-1060-6	UNCLASSIFIED/ UNLIMITED

5. Originator Research and Technology Organization
North Atlantic Treaty Organization
BP 25, 7 rue Ancelle, F-92201 Neuilly-sur-Seine Cedex, France

6. Title
NATO East-West Workshop on Magnetic Materials for Power Applications

7. Presented at/sponsored by
the Applied Vehicle Technology Panel (AVT), organised by the US Air Force Office of Scientific Research, Arlington, VA, USA and held in Marathon, Greece, 25-30 June 2000.

8. Author(s)/Editor(s)	9. Date
Multiple	August 2001

10. Author's/Editor's Address	11. Pages
Multiple	58

12. Distribution Statement There are no restrictions on the distribution of this document. Information about the availability of this and other RTO unclassified publications is given on the back cover.

13. Keywords/Descriptors

Magnetic materials	Electric power
Electric vehicles	Electric drives
Magnetic properties	Electric brakes
Power supplies	Weapon systems
Electromagnetic pulses	High temperature
International cooperation	Mechanical properties
Military vehicles	Novel processing

14. Abstract

The NATO Workshop with Partners for Peace on Advanced Magnetic Materials for More Electric Vehicles and Electric Pulse Power Weapons (AVT-060) was organised with the aim of assessing the need for improved magnetic materials primarily in future generations of more electric vehicles and (to a lesser extent) in electric pulse power weapons. Scientists from eight NATO countries and five non NATO countries participated. Recent advancements and further improvements were discussed:

Applications
Fundamental and Technical Magnetism
Characterisation
Materials
Novel Processing

and foundations for future co-operation were established.

This page has been deliberately left blank

Page intentionnellement blanche

NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION
BP 25 • 7 RUE ANCELLE
F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE
Télécopie 0(1)55.61.22.99 • E-mail mailbox@rta.nato.int

DIFFUSION DES PUBLICATIONS
RTO NON CLASSIFIEES

L'Organisation pour la recherche et la technologie de l'OTAN (RTO), détient un stock limité de certaines de ses publications récentes, ainsi que de celles de l'ancien AGARD (Groupe consultatif pour la recherche et les réalisations aérospatiales de l'OTAN). Celles-ci pourront éventuellement être obtenues sous forme de copie papier. Pour de plus amples renseignements concernant l'achat de ces ouvrages, adressez-vous par lettre ou par télécopie à l'adresse indiquée ci-dessus. Veuillez ne pas téléphoner.

Des exemplaires supplémentaires peuvent parfois être obtenus auprès des centres nationaux de distribution indiqués ci-dessous. Si vous souhaitez recevoir toutes les publications de la RTO, ou simplement celles qui concernent certains Panels, vous pouvez demander d'être inclus sur la liste d'envoi de l'un de ces centres.

Les publications de la RTO et de l'AGARD sont en vente auprès des agences de vente indiquées ci-dessous, sous forme de photocopie ou de microfiche. Certains originaux peuvent également être obtenus auprès de CASI.

CENTRES DE DIFFUSION NATIONAUX

ALLEMAGNE
Streitkräfteamt / Abteilung III
Fachinformationszentrum der Bundeswehr, (FIZBw)
Friedrich-Ebert-Allee 34
D-53113 Bonn

BELGIQUE
Coordinateur RTO - VSL/RTO
Etat-Major de la Force Aérienne
Quartier Reine Elisabeth
Rue d'Evère, B-1140 Bruxelles

CANADA
Services d'information scientifique pour la défense (SISD)
R et D pour la défense Canada
Ministère de la Défense nationale
Ottawa, Ontario K1A 0K2

DANEMARK
Danish Defence Research Establishment
Ryvangs Allé 1, P.O. Box 2715
DK-2100 Copenhagen Ø

ESPAGNE
INTA (RTO/AGARD Publications)
Carretera de Torrejón a Ajalvir, Pk.4
28850 Torrejón de Ardoz - Madrid

ETATS-UNIS
NASA Center for AeroSpace Information (CASI)
Parkway Center
7121 Standard Drive
Hanover, MD 21076-1320

FRANCE
O.N.E.R.A. (ISP)
29, Avenue de la Division Leclerc
BP 72, 92322 Châtillon Cedex

GRECE (Correspondant)
Hellenic Ministry of National Defence
Defence Industry Research & Technology General Directorate
Technological R&D Directorate
D.Soutsou 40, GR-11521, Athens

HONGRIE
Department for Scientific Analysis
Institute of Military Technology
Ministry of Defence
H-1525 Budapest P O Box 26

ISLANDE
Director of Aviation
c/o Flugrad
Reykjavik

ITALIE
Centro di Documentazione Tecnico-Scientifica della Difesa
Via XX Settembre 123a
00187 Roma

LUXEMBOURG
Voir Belgique

NORVEGE
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25, NO-2007 Kjeller

PAYS-BAS
NDRCC
DGM/DWOO
P.O. Box 20701
2500 ES Den Haag

POLOGNE
Chief of International Cooperation Division
Research & Development Department
218 Niepodleglosci Av.
00-911 Warsaw

PORTUGAL
Estado Maior da Força Aérea
SDFA - Centro de Documentação
Alfragide
P-2720 Amadora

REPUBLIQUE TCHEQUE
DIC Czech Republic-NATO RTO
VTÚL a PVO Praha
Mladoboleslavská ul.
Praha 9, 197 06, Česká republika

ROYAUME-UNI
Defence Research Information Centre
Kentigern House
65 Brown Street
Glasgow G2 8EX

TURQUIE
Millî Savunma Başkanliği (MSB)
ARGE Dairesi Başkanliği (MSB)
06650 Bakanliklar - Ankara

AGENCES DE VENTE

NASA Center for AeroSpace Information (CASI)
Parkway Center
7121 Standard Drive
Hanover, MD 21076-1320
Etats-Unis

The British Library Document Supply Centre
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
Royaume-Uni

Canada Institute for Scientific and Technical Information (CISTI)
National Research Council
Document Delivery
Montreal Road, Building M-55
Ottawa K1A 0S2, Canada

Les demandes de documents RTO ou AGARD doivent comporter la dénomination "RTO" ou "AGARD" selon le cas, suivie du numéro de série (par exemple AGARD-AG-315). Des informations analogues, telles que le titre et la date de publication sont souhaitables. Des références bibliographiques complètes ainsi que des résumés des publications RTO et AGARD figurent dans les journaux suivants:

Scientific and Technical Aerospace Reports (STAR)
STAR peut être consulté en ligne au localisateur de ressources uniformes (URL) suivant:
http://www.sti.nasa.gov/Pubs/star/Star.html
STAR est édité par CASI dans le cadre du programme NASA d'information scientifique et technique (STI)
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
Etats-Unis

Government Reports Announcements & Index (GRA&I)
publié par le National Technical Information Service
Springfield
Virginia 2216
Etats-Unis
(accessible également en mode interactif dans la base de données bibliographiques en ligne du NTIS, et sur CD-ROM)

ST JOSEPH OTTAWA/HULL

Imprimé par St-Joseph Ottawa/Hull
(Membre de la Corporation St-Joseph)
45, boul. Sacré-Cœur, Hull (Québec), Canada J8X 1C6

NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION

BP 25 • 7 RUE ANCELLE

F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE

Telefax 0(1)55.61.22.99 • E-mail mailbox@rta.nato.int

DISTRIBUTION OF UNCLASSIFIED RTO PUBLICATIONS

NATO's Research and Technology Organization (RTO) holds limited quantities of some of its recent publications and those of the former AGARD (Advisory Group for Aerospace Research & Development of NATO), and these may be available for purchase in hard copy form. For more information, write or send a telefax to the address given above. **Please do not telephone**.

Further copies are sometimes available from the National Distribution Centres listed below. If you wish to receive all RTO publications, or just those relating to one or more specific RTO Panels, they may be willing to include you (or your organisation) in their distribution.

RTO and AGARD publications may be purchased from the Sales Agencies listed below, in photocopy or microfiche form. Original copies of some publications may be available from CASI.

NATIONAL DISTRIBUTION CENTRES

BELGIUM
Coordinateur RTO - VSL/RTO
Etat-Major de la Force Aérienne
Quartier Reine Elisabeth
Rue d'Evère, B-1140 Bruxelles

CANADA
Defence Scientific Information Services (DSIS)
Defence R&D Canada
Department of National Defence
Ottawa, Ontario K1A 0K2

CZECH REPUBLIC
DIC Czech Republic-NATO RTO
VTÚL a PVO Praha
Mladoboleslavská ul.
Praha 9, 197 06, Česká republika

DENMARK
Danish Defence Research Establishment
Ryvangs Allé 1, P.O. Box 2715
DK-2100 Copenhagen Ø

FRANCE
O.N.E.R.A. (ISP)
29 Avenue de la Division Leclerc
BP 72, 92322 Châtillon Cedex

GERMANY
Streitkräfteamt / Abteilung III
Fachinformationszentrum der Bundeswehr, (FIZBw)
Friedrich-Ebert-Allee 34
D-53113 Bonn

GREECE (Point of Contact)
Hellenic Ministry of National Defence
Defence Industry Research & Technology General Directorate
Technological R&D Directorate
D.Soutsou 40, GR-11521, Athens

HUNGARY
Department for Scientific Analysis
Institute of Military Technology
Ministry of Defence
H-1525 Budapest P O Box 26

ICELAND
Director of Aviation
c/o Flugrad
Reykjavik

ITALY
Centro di Documentazione Tecnico-Scientifica della Difesa
Via XX Settembre 123a
00187 Roma

LUXEMBOURG
See Belgium

NETHERLANDS
NDRCC
DGM/DWOO
P.O. Box 20701
2500 ES Den Haag

NORWAY
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25, NO-2007 Kjeller

POLAND
Chief of International Cooperation Division
Research & Development Department
218 Niepodleglosci Av.
00-911 Warsaw

PORTUGAL
Estado Maior da Força Aérea
SDFA - Centro de Documentação
Alfragide
P-2720 Amadora

SPAIN
INTA (RTO/AGARD Publications)
Carretera de Torrejón a Ajalvir, Pk.4
28850 Torrejón de Ardoz - Madrid

TURKEY
Millî Savunma Başkanliği (MSB)
ARGE Dairesi Başkanliği (MSB)
06650 Bakanliklar - Ankara

UNITED KINGDOM
Defence Research Information Centre
Kentigern House
65 Brown Street
Glasgow G2 8EX

UNITED STATES
NASA Center for AeroSpace Information (CASI)
Parkway Center
7121 Standard Drive
Hanover, MD 21076-1320

SALES AGENCIES

NASA Center for AeroSpace Information (CASI)
Parkway Center
7121 Standard Drive
Hanover, MD 21076-1320
United States

The British Library Document Supply Centre
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
United Kingdom

Canada Institute for Scientific and Technical Information (CISTI)
National Research Council
Document Delivery
Montreal Road, Building M-55
Ottawa K1A 0S2, Canada

Requests for RTO or AGARD documents should include the word 'RTO' or 'AGARD', as appropriate, followed by the serial number (for example AGARD-AG-315). Collateral information such as title and publication date is desirable. Full bibliographical references and abstracts of RTO and AGARD publications are given in the following journals:

Scientific and Technical Aerospace Reports (STAR)
STAR is available on-line at the following uniform resource locator:
http://www.sti.nasa.gov/Pubs/star/Star.html
STAR is published by CASI for the NASA Scientific and Technical Information (STI) Program
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
United States

Government Reports Announcements & Index (GRA&I)
published by the National Technical Information Service
Springfield
Virginia 22161
United States
(also available online in the NTIS Bibliographic Database or on CD-ROM)

Printed by St. Joseph Ottawa/Hull
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada J8X 1C6

ISBN 92-837-1060-6