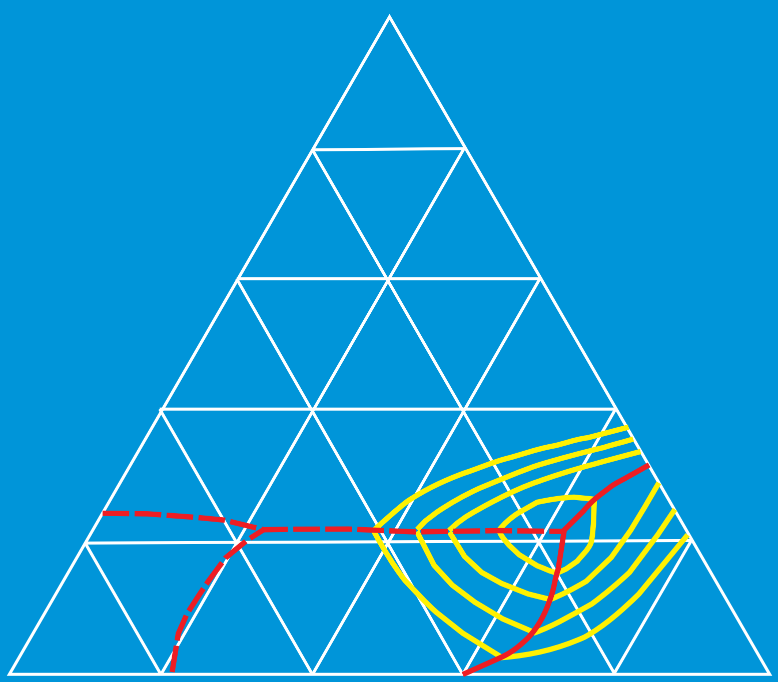
Ternary Alloys

A Comprehensive Compendium
of Evaluated Constitutional Data and
Phase Diagrams

Editor: Bernd Grieb

Volume 23

Magnet Systems for Applications in Windpower, Electromotors and Sensors



MSI
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Ternary Alloys

Volume 23

MSI
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Ternary Alloys Series

A Comprehensive Compendium of Evaluated Constitutional Data and Phase Diagrams

critically evaluated by MSIT®

"Ternary Alloys" is the result of an international assessment program performed by Materials Science International Services GmbH and its international Team (MSIT®).

The phase diagram evaluations in this publication have been carefully reviewed by the MSIT® review board on behalf of Materials Science International Services GmbH, and are presented as the most accurate and reliable information available on the subject.

The first 15 volumes of the Ternary Alloys series were published originally by VCH (1988-1995). In 1999, all rights and the previously published volumes were transferred to MSI GmbH, whose team (MSIT®) had produced the content. A new ISBN has been assigned to each of these volumes. From volume 16, MSI GmbH continues as publisher of the series.

List of published Ternary Alloys volumes:

Ag-X-Y category (vols. 1 & 2)
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Vol. 2: Ag-Cu-Pb to Ag-Zn-Zr

Al-X-Y category (vols. 3 to 8)
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Vol. 7: Al-Mg-Se to Al-Ni-Ta
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Vol. 20: Selected Systems for Lead-free Soldering and Brazing Applications
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Magnet Systems for Applications in Windpower, Electromotors and Sensors

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printed ISBN 978-3-932120-55-8
ebook ISBN 978-3-932120-56-5

Vol. 23. Magnet Systems for Applications in Windpower, Electromotors and Sensors – 2025

This volume is part of the book series:
Ternary Alloys: A Comprehensive Compendium of Evaluated Constitutional Data and Phase Diagrams/
Materials Science International Services GmbH, Stuttgart, Germany

Group ISBN for the Ternary Alloys book series: 978-3-932120-41-1

Published by
MSI, Materials Science International Services GmbH, Stuttgart (Federal Republic of Germany)
Am Wallgraben 100, D-70565 Stuttgart, Germany
Postfach 800749, D-70507, Stuttgart, Germany
https://www.msiport.com
https://www.msi-eureka.com/

Printed on acid-free paper.

Printing and binding:
WIRmachenDRUCK GmbH, Mühlbachstraße 7, 71522 Backnang

Printed in Germany

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About the *Ternary Alloys* book series

The book series *Ternary Alloys* provides reliable and comprehensive descriptions of materials constitution, based on the critical and intellectual evaluation of all relevant data available at the time. Data from different sources are carefully compared and assessed, and their compatibility with the accepted edge binary systems is checked in order to produce a single set of information that is internally consistent and represents the state of knowledge of that ternary system. Ternary systems are chosen mainly for their application in alloy development, but others are chosen because they have gained scientific interest in their own right. In any one ternary material system, however, one may find a number of alloys that can be used for a variety of different applications, depending on the chosen composition.

Reliable phase diagrams provide scientists and engineers with basic information of critical importance for fundamental research and for the development and optimization of materials. So, collections of such diagrams are extremely useful, if the data on which they are based have been subjected to critical evaluation, as in these volumes. Critical evaluation means: where contradictory information is published, data and conclusions are analyzed, broken down into firm facts and re-interpreted in the light of all present knowledge. Depending on the information available this can be a very difficult task. Critical evaluation establishes descriptions of phase configurations and related data that are reliable.

The evaluations are performed by MSIT®, the Materials Science International Team, a group of scientists working together since 1984. Within this team, skilled expertise is available covering a broad range of methodologies, materials and applications. This joint competence is employed in the critical evaluation of the often-conflicting literature data. A particularly useful tool at the disposal of the MSIT is the ability to perform targeted thermodynamic and atomistic calculations for individual equilibria, driving forces and also for complete phase diagram sections, that can provide additional insight when trying to reconcile conflicting data.

Conclusions on phase equilibria may be drawn from direct observations, *e.g.* by microscopy, from monitoring caloric or thermal effects, or measuring properties such as electrical resistivity, electro-magnetic or mechanical properties. Other examples of useful methods in materials chemistry are mass-spectrometry, thermo-gravimetry, the measurement of electro-motive forces, and X-ray and microprobe analyses. In each published case the applicability of the chosen methodology has to be validated, the way of actually performing the experiment or computer modeling has to be assessed as well and the interpretation of the results with regard to the material chemistry. Thus, an understanding of the materials constitution and phase reactions is gained from many distinctly different types of experiments, calculations and observations. Intellectual critical evaluations which interpret all data simultaneously reveal the chemistry of the materials system best.

An additional degree of complexity is introduced by the material itself, as the state of the material under observation depends heavily on its history, in particular with regard to homogenization, thermal and mechanical treatments. All of this is taken into account in an MSIT® expert evaluation.

To include binary data in a ternary evaluation is mandatory. Each of the three-dimensional ternary phase diagrams has edge binary systems as boundary planes; their data have to match the ternary data smoothly. At the same time each of the edge binary systems A-B is a boundary plane for many other ternary A-B-X systems. Therefore, combining systematically binary and ternary evaluations increases confidence and reliability in both ternary and binary phase diagrams. This began systematically for the first time in the frame of the MSIT® Evaluation Program. The degree of success, however, depends on both the nature of materials and scientists!

The multitude of correlated or inter-dependent data requires that special care be taken. Within MSIT® an evaluation routine has been established that is knowledge driven, and applies both human based expertise and electronically formatted data together with software tools. MSIT® internal discussions take place during almost all of the evaluations. In this way, the efforts of the individual are supplemented with the expertise of a team. In some cases, the authors of earlier publications have contributed to the whole knowledge base by making their original data records available for re-interpretation. All evaluation reports published here have undergone a thorough peer-review process in which the reviewers had access to all the original data.

In its publications, MSIT® has adopted a standard format that presents the reader with the data for each ternary system in a concise and consistent manner, as applied in the MSI Eureka data base. The standard format and special features of the *Ternary Alloys* compendium are explained in the Introduction to this volume.

In spite of the skill and labor that have been put into this volume, it will not be faultless. All criticisms and suggestions that can help us to improve our work are very welcome. Please contact us *via* evaluation@msiport.com. We hope that this volume will prove to be as useful for materials scientists and engineers as the other volumes of *Ternary Alloys* and all previous works of MSIT® have been. We hope that this volume will be well received by our colleagues in research and industry.

Starting with the Volume 19, MSI has changed slightly the concept of the series "*Ternary Alloys*". Instead of exploring alphabetically all ternary systems based on one chemical element, such as Al-X-Y or Mg-X-Y, the subsequent volumes are dedicated to particular classes of materials or particular application areas, as volume 23 "Magnet Systems for Applications in Windpower, Electromotors and Sensors" with the guest editor Dr. Bernd Grieb (ppm Intl. GmbH, Tübingen, Germany).

Preface

Ancient people learned about magnetism from lodestones (or magnetite) which are naturally magnetized pieces of iron ore. Lodestones, suspended so that they could rotate, were the first magnetic compasses. The earliest known surviving descriptions of magnets and their properties are from Anatolia, India, and China around 2,500 years ago.

The term *magnet* is typically reserved for objects that produce their own persistent magnetic field even in the absence of an applied magnetic field, called permanent magnets. Only certain classes of materials can do this.

The difference between magnetic materials is related to their atomistic structure. When the spins interact with each other in such a way that the spins align spontaneously, the materials are called ferro- or ferrimagnetic. These include metals and alloys out of iron, cobalt and nickel, as well as the ceramic ferrite. The overall magnetic behavior of a material can vary widely, depending on the structure of the material, particularly on its electron configuration. These materials are the only ones that can retain magnetization and become magnets.

Ferrites are made of a sintered composite of powdered iron oxide and barium/strontium carbonate resulting after sintering and shape processing in a non-corroding but brittle material and must be treated like other ceramics.

Alnico magnets are made by casting or sintering a combination of aluminium, nickel and cobalt with iron and small amounts of other elements added to enhance the properties of the magnet. Sintering offers superior mechanical characteristics, whereas casting delivers higher magnetic fields and allows for the design of intricate shapes.

In **Rare-Earth Magnets** rare-earth elements (REE) have a partially occupied *4f* electron shell (which can accommodate up to 14 electrons) and interacts with the *3d* electron shell of the transition metals (TM) Fe, Co or Ni. The spin of these electrons can be aligned, resulting in very strong magnetic fields, and therefore, these elements are used in compact high-strength magnets where their higher price is often not a concern. The most common types are samarium-cobalt (SmCo) and neodymium-iron-boron (NdFeB) magnets.

As everybody knows, NdFeB-magnets were detected in **1981** by M. Sagawa (Sumitomo, Japan) and J. Croat (General Motors, USA). In **1979** scientists from L‘viv in Ukraine (Chaban *et. al*) investigated the ternary system Nd-Fe-B and documented a phase with app. Nd(15 at.%)-Fe(80 at.%)-B(5 at.%). This was clearly the magnetic phase, which started to change the magnetic world some years later.

Main applications are served by Ferrites or RE-Magnets, depending on performance and cost relation. Ferrites are comparatively cheap and therefore used in high volumes for lower performance applications such as sensors, speakers, electric motors, toys, white goods and industrial equipment.

RE-Magnets are significantly more expensive due to the REE used and higher cost in processing. However, due to their higher power and magnetic stability, better efficiency, and reduced weight and volume - both the magnets themselves and the overall devices - they are used in large quantities and are, globally, the most economically important types of magnets. The magnet market size is seen in tens of billions and therefore key factors for many strategic applications. Caused by the limited availability due to limited mining and processing capabilities the REE became of geopolitically strategic importance and used as pressure medium by governments such as China and USA. With this background the connection between magnet technology and REE is close and essential to understand the rising dependency of the industrial societies from these raw materials and technologies.

The main applications of RE-Magnets are electrical motors and generators for automotive and bikes, wind-power, automation, robotics, pumps, industrial engines and server applications. Besides these, we see high volumes in sensors, medical equipment (MRI), chemistry (NMR, couplings), energy storage (Flywheel), separation, levitation, recording, and many more.

Today, global reserves of around 200 Mio. tons of RE ores are explored, but mining and processing present technical challenges combined with tremendous investment costs. Even though they are present in all continents, only China started these activities in strategic manner in the 1980^{th} and could take other mining locations in USA and other countries out of business by very competitive production of RE oxides and metals, followed by the production of magnets.

New activities in Australia, USA, Brazil, Chile, India and several other countries in Asia are undertaken to reduce the dominance of China, but still in 2025 more than 70% of the REE mining and 90% of REE containing magnets are sourced in China.

To use the expensive raw material at best efficiency, the constitution of the material systems is a key for improving performance and cost. Whereby the ferrites are established in principle, we see the beneficial impact of adding lanthanides in small amounts to influence the structural interaction of the iron and lanthanum electron configurations with only minor impacts on phase relations.

This is very different to the metallic systems of REE, TM and boron phases. In the last decades the complex systems of the basically ternary system (Fe,Co)-(Nd,Pr,Dy,Tb)-B and (Co,Fe,Cu)-Sm with the magnetic phases $TM_{14}RE_2B$, TM_5Sm and $TM_{17}Sm_2$ were investigated intensively. Looking at magnetic energy product $(BH)_{max}$ and coercivity H_c (magnetic stability), magnetization behaviour, electrochemical and corrosion stability and cost(!) the sensitivity to changes in compositions turned out and resulted in thousands of publications around these materials.

Magnets are functional materials with complex structures and physical, chemical and mechanical properties, which all must be understood and considered to get best performance and economical value.

On behalf of the participating authors, the Editor likes to thank all those who have contributed their comments and insight during the review process. In particular, we thank reviewers - Lesley Cornish, Guillaume Deffrenes, Iuliia Fartushna, Hari Kumar, Mario Kriegel, Ales Kroupa, Lorenzo Fenocchio, Shuhong Liu, Martin Palm, Alex Pisch, Frank Stein, Maria Ilatovskaya.

In addition, the Editor gratefully acknowledges the dedicated scientific editorial work undertaken by Oleksandr Dovbenko and Liya Dreval, who ensured that the high standards expected of MSI publications were maintained.

Specific thanks are due to MSI and the Managing Director, Svitlana Iljenko, who granted, organized the review, and managed the publication.

Bernd Grieb June 2025

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