IEC/TR 62518

Edition 1.0 2009-03

TECHNICAL REPORT

Rare earth sintered magnets – Stability of the magnetic properties at elevated temperatures

IEC/TR 62518:2009(E)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland
Email: inmail@iec.ch
Web: www.iec.ch

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

- Catalogue of IEC publications: www.iec.ch/searchpub

The IEC on-line Catalogue enables you to search by a variety of criteria (reference number, text, technical committee,…). It also gives information on projects, withdrawn and replaced publications.

- IEC Just Published: www.iec.ch/online_news/justpub

Stay up to date on all new IEC publications. Just Published details twice a month all new publications released. Available on-line and also by email.

- Electropedia: www.electropedia.org

The world's leading online dictionary of electronic and electrical terms containing more than 20 000 terms and definitions in English and French, with equivalent terms in additional languages. Also known as the International Electrotechnical Vocabulary online.

- Customer Service Centre: www.iec.ch/webstore/custserv

If you wish to give us your feedback on this publication or need further assistance, please visit the Customer Service Centre FAQ or contact us:

Email: csc@iec.ch
Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00

IEC/TR 62518

Edition 1.0 2009-03

TECHNICAL REPORT

Rare earth sintered magnets – Stability of the magnetic properties at elevated temperatures

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE U

ICS 29.030

ISBN 978-2-88910-753-7

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

RARE EARTH SINTERED MAGNETS – STABILITY OF THE MAGNETIC PROPERTIES AT ELEVATED TEMPERATURES

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.

4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC provides no marking procedure to indicate its approval and cannot be rendered responsible for any equipment declared to be in conformity with an IEC Publication.

6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 62518, which is a technical report, has been prepared by IEC technical committee 68: Magnetic alloys and steels.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
68/376/DTR	68/383/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

$SmCo_5$ was the first sintered rare earth magnet to be developed (1967) [1][1], followed by Sm_2Co_{17} [2, 3, 4] and Nd-Fe-B [5]. These magnets are used in a wide variety of applications. Recently, these magnets have been used in higher temperature applications such as in heavy duty permanent magnet motors. For these high temperature applications, the temperature stability of the permanent magnet has to be considered along with the design of the magnetic circuit. This is particularly relevant for the relatively inexpensive Nd-Fe-B magnetic material which has a comparatively low Curie temperature. The temperature stability of the rare earth sintered magnets has a critical influence on the reliability of high temperature motors and this will, in turn, contribute to energy savings in the future.

Therefore, the subject of this technical report will be of considerable interest to the manufacturers of this type of motor and to the developers of permanent magnet materials.

1 The figures in square brackets refer to the Bibliography.

RARE EARTH SINTERED MAGNETS – STABILITY OF THE MAGNETIC PROPERTIES AT ELEVATED TEMPERATURES

1 Scope

The scope of this technical report is to describe the temperature behaviour of rare earth sintered magnets in detail for use in designing magnetic circuits exposed to elevated temperatures. The temperature behaviour of $SmCo_5$, Sm_2Co_{17} and Nd-Fe-B sintered magnets is described.

The various changes of open circuit flux which can occur due to temperature are discussed in Clause 4. The long term stability of the magnets is discussed in Clause 5. The experimental procedures are described in Clause 6. Results of the measurements of the flux loss occurring at the ambient temperature after heating isothermally at 50 °C, 75 °C, 100 °C, 125 °C, 150 °C and 200 °C for up to 1000 h are given in Clause 7. The effect of length to diameter ratio (*L/D*) of the magnet samples and the influence of H_{cJ} on the flux loss were also studied. The results are discussed in Clause 8.

The data in this technical report was provided by the Institute of Electrical Engineers of Japan (IEEJ) and its subcommittees. This data has been gathered from the members of these sub-committees.

The temperature stability correlated with the complex corrosion behaviour and the spin re-orientation phenomena at cryogenic temperatures will not be given in this technical report.

2 Normative references

IEC 60050-121, *International Electrotechnical Vocabulary – Part 121: Electromagnetism*

IEC 60050-151, *International Electrotechnical Vocabulary – Part 151: Electrical and magnetic devices*

IEC 60050-221:1990, *International Electrotechnical Vocabulary – Chapter 221: Magnetic materials and components*
Amendment 1 (1993)

IEC 60404-8-1, *Magnetic materials – Part 8-1: Specifications for individual materials – Magnetically hard materials*

3 Terms and definitions

For the purpose of this document, the following terms and definitions apply. In addition, most of the technical terms used in this document are defined in IEC 60050-121, IEC 60050-151, and IEC 60404-8-1(the product standard).

3.1
magnetic flux loss
the reduction due to an external influence, primarily temperature, in the flux of permanent magnets in a magnetized state, unit of Wb. Three kinds of flux loss, reversible flux loss, irreversible flux loss and permanent flux loss, are used to discuss the temperature stability of rare earth sintered magnets.

3.2
reversible flux loss
a magnetization change which is recovered by the removal of a disturbing influence such as temperature. Irreversible flux loss is the partial demagnetization change caused by the temperature changes. The irreversible flux loss is fully recovered by remagnetization. Permanent flux loss is caused by permanent change in the metallurgical state and is generally time and temperature dependent. The permanent loss cannot be recovered to the initial magnetization value by remagnetization.

3.3
uniformity field strength
$\boldsymbol{H_k}$
the uniformity field strength (of a magnetically hard material) as defined in IEC 60050-221-02-62 (Amendment 1 (1993)) was originally called "knee field" [6]. H_k is the negative value of the magnetic field strength when the magnetic polarization of a magnetically hard material is brought from saturation to 90 % of the value of the remanent magnetic polarization by a monotonically changing magnetic field.

3.4
reversible temperature coefficient
the reversible temperature coefficient of magnetic flux is the percentage changes in flux per degrees Celsius by the change in temperature, which is reversible. The temperature coefficient is expressed as %/°C. The temperature range must be stated to make them quantify. The reversible temperature coefficient of magnetic flux (denoted as $\alpha(\phi)$) is the quotient of the percentage change of magnetic flux by that change in temperature:

$$\alpha(\phi)=(\phi_\theta-\phi_{ref})/\phi_{ref}\cdot 1/(\theta-\theta_{ref})$$

where ϕ_θ and ϕ_{ref} are the flux at temperature θ and θ_{ref} respectively.

Generally rare earth sintered magnets exhibit a non-linear change of flux with temperature.

"Temperature coefficient of B_r (denoted as $\alpha(B_r)$)" can be defined from the temperature dependence of B_r in the temperature range to have the quantitative values. The temperature coefficient of B_r is the quotient of the relative change of B_r due to a change in temperature by that change in temperature:

$$\alpha(B_r)=(B_{r\theta}-B_{rref})/B_{rref}\ B_{r\theta}\cdot 1/(\theta-\theta_{ref})$$

where $B_{r\theta}$ and B_{rref} are the B_r at temperature of θ and θ_{ref} respectively. "Temperature coefficient of H_{cJ} (denoted as $\alpha(H_{cJ})$)" can be also defined as mentioned above.

The revised evaluation method for temperature coefficients of B_r and H_{cJ} are given in IEC/TR 61807(1999) in which the temperature dependence of B_r and H_{cJ} is expressed by a quadratic function of temperature, see Annex B. To define the "temperature coefficient" the temperature range must be stated because of the non-linearity of the temperature dependence.

3.5
anisotropy field
$\boldsymbol{H_A}$
the anisotropy field (denoted as H_A) is the field required to rotate into the hard direction or the field to saturate the material in the hard direction, and it is a measure of the anisotropy. The relationship between H_A, K_u (crystalline anisotropy constant) and M_s (saturation magnetization) is as follows:

$$H_A=2K_u/\mu_0 M_s$$

4 Classification of magnetic flux loss due to temperature

4.1 Reversible flux loss

The reversible change in the magnetic properties of rare earth magnets as a function of temperature originates from the change in saturation magnetization. Reversible flux loss is a magnetization change which is recovered by the removal of a disturbing influence such as temperature.

4.2 Irreversible flux loss

With irreversible flux loss, after the removal of the disturbing influence, the magnetization does not return to its original value. Examples of the disturbing influence are temperature changes, local temperature fluctuations and magnetic fields. The irreversible flux loss is fully recovered by remagnetization.

4.3 Permanent flux loss

Permanent flux loss is caused by a permanent change in the metallurgical state and is generally time and temperature dependent. Examples are precipitation and growth, oxidation, the annealing effects and radiation damage. The permanent flux loss cannot be recovered to the initial magnetization value by remagnetization.

The various flux losses mentioned above are shown in Figure 1. The figures were schematically presented by R. Tenzer [7, 8]. In Figure 1 the magnetic flux density B vs temperature and demagnetization curves at various temperatures with a certain load line are given to explain the three kinds of losses.

The curves in Figure 1(a) apply only for short temperature excursions, for example from 25°C to θ °C. Magnetic flux density B changes reversibly along a demagnetization curve at various temperatures. $B_d(25)$ - $B_d(\theta)$ is called the "reversible flux loss". This flux loss is fully recovered by returning the magnet to room temperature.

Curves in Figure 1(b) apply for larger temperature excursions. In this case a part of the flux change will be recovered on cooling, $B_d'(25)$ - $B_d'(\theta)$. The other part, $B_d(25)$ - $B_d'(25)$, can be recovered by remagnetization and is called the "irreversible flux loss".

When the exposure temperature exceeds several hundred degrees Celsius, changes in the microstructure of the magnet, surface oxidation etc., cause an additional flux loss which will no longer be recovered by remagnetization. $B_d(25)$ - $B_d''(25)$ in Figure 1(c) is called the "permanent flux loss". The reversible B_d vs θ closely reflects the temperature variation of saturation magnetization and remanence. It is commonly approximated by a straight line and is called "the reversible temperature coefficient", see 3.4.

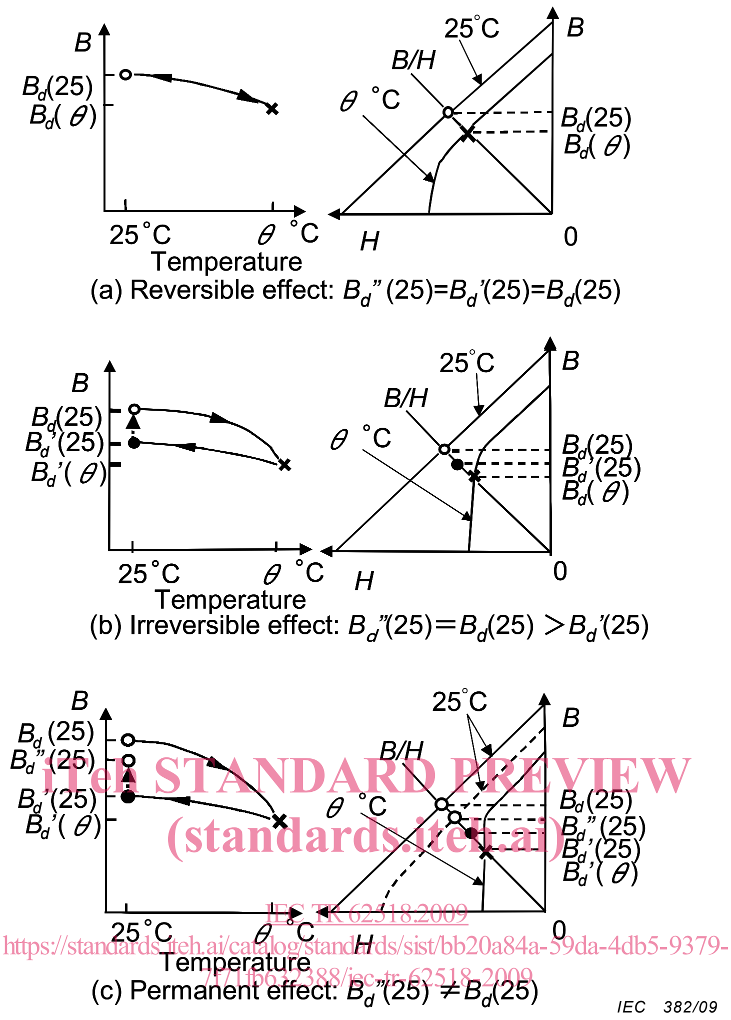

Figure 1 – Change of magnetic flux density operating on a load line during elevated temperature ageing after R. Tenzer (schematic) [7, 8]

5 Long term ageing of rare earth magnets

When a magnet is newly magnetized and the flux (open circuit flux or its operating-point induction) is observed for a long period of time, a slow decay is found to occur. It usually follows a time function. This behaviour is shown in Figure 2 schematically after K. J. Strnat [9].

The change can be separated into three stages. First, there is a relatively fast initial flux loss, ab. This is followed by a long period of increasing stability, marked the “plateau”, bc, during which there is often a constant irreversible flux loss per logarithmic time cycle on the plateau. This time dependency of *B* on the plateau is proportional to log *t* (*t* is time) from the result of the magnetic after-effect which was given by Street et al. [10]. To show this constant flux change, the “irreversible flux loss per decade” [the flux change per decade (%/decade)] is used. The irreversible flux loss per decade is the flux loss during the time period ranging from 1 h to 10 h, from 10 h to 100 h or from 100 h to 1 000 h.

At higher temperatures and for some magnets, the flux decline, cd, will later accelerate and is sometimes catastrophic. This was observed very clearly for rare earth bonded magnets with an improper surface treatment under harsh environment conditions. For rare earth sintered magnets only small flux changes were observed. The temperature stability correlated with the complex corrosion behaviour will not be given in this technical report.