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Pulsed field magnetometry

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PULSED FIELD MAGNETOMETRY

FOREWORD

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IEC 62331, 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
68/299/DTR	68/303/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- withdrawn;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

In order to measure the full magnetic characterization of magnetically hard (permanent magnet) materials, it is necessary to apply a magnetic field sufficient to saturate the test specimen of magnetic material.

The generation of this magnetic field can become a practical limiting factor and can determine the appropriate measurement techniques.

Super-conducting magnets can generate very high static or slowly changing magnetic fields but their complexity, high capital outlay and running costs, requiring cryogenic gases make them far from ideal. It is necessary to change fields slowly to avoid "quenching" the super-conducting magnet.

Conventionally wound electro-magnets with slowly changing magnetic fields have a significant heat generation problem through I^2R loss. This can be alleviated through the use of a high relative permeability "iron yoke". However, saturation of the iron prevents maximum characterization of the loop of rare earth permanent magnet materials to be determined.

A pulsed field system utilizing conventional conductors minimizes heating effects by limiting field durations and by limiting heat generation to acceptable levels. Fields up to 40 Tesla (T) can be generated in this way.

Careful consideration, however, must be given to the instrumentation and method to take account of dynamic effects due to the short duration of the magnetic field.

While work on pulsed field magnetometry is carried out in many parts of the world, the two main groups are MACCHARETEC [ref. 29][1] in Europe and EMAJ [ref. 30] in Japan. The approach adopted in Japan is one of supporting a standard with fixed specimen sizes, magnetic field strengths and frequencies in a limited number of configurations.

1 References in square brackets refer to the bibliography.

PULSED FIELD MAGNETOMETRY

1 Scope and object

This Technical Report reviews methods for measuring magnetically hard materials using pulsed field magnetometers.

The methods of measurement of the magnetic properties of magnetically hard materials have been specified in IEC 60404-5 for closed magnetic circuits and in IEC 60404-7 for open magnetic circuits. The measurement result of the magnetic properties of magnetically hard materials at elevated temperatures is given in IEC 61807.

Pulsed field magnetometers have been developed to provide rapid measurement facilities to match high speed production rates with 100 % quality control.

The object of this report is to describe the principles and practical implications of pulsed field magnetometry in order to enable the full potential of the technique to be considered, including its application using small and large magnets of varying geometries, to various magnetic field strengths and frequencies.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60404-5:1993, *Magnetic materials – Part 5: Permanent magnet (magnetically hard) materials – Methods of measurement of magnetic properties*

IEC 60404-7:1982, *Magnetic materials – Part 7: Method of measurement of coercivity of magnetic materials in an open magnetic circuit*

IEC 61807:1999, *Magnetic properties of magnetically hard materials at elevated temperatures – Methods of measurement*

IEC 60404-14:2002, *Magnetic materials – Part 14: Methods of measurement of the magnetic moment of ferromagnetic material specimen by the withdrawal or rotation method*

3 Pulsed field magnetometer (PFM)

A pulsed field magnetometer consists of the following parts:

a) The magnetic field strength generator consisting of
   i) the power supply (usually a capacitive discharge system)
   ii) magnetizing solenoid
b) Magnetization and magnetic field strength sensors (pick-up coils)
c) Instrumentation for transient processing and digitizing hardware
   i) integration
   ii) digitization
d) Data processing facilities to enable the processing of

i) zero signal

ii) *M*(*H*) loop positioning

iii) self-demagnetization correction

iv) low band pass filtering

v) calibration factors

vi) eddy current correction.

3.1 General principles

The basic principle of operation of the pulsed field magnetometer depends upon an intense transient magnetic field being generated by the magnetic field strength generator and being applied to the test specimen to be measured. The magnetic field strength and resultant magnetization of the test specimen are recorded and processed.

During a measurement cycle, the test specimen in the *J* coil increases flux. The output voltage of this coil is the time derivative of the flux *Φ* coupled to that coil. This flux is due largely to the magnetization of the specimen but also to the zero signal (see 7.1.1) and possible eddy currents (see the eddy current correction techniques in 7.1.6) etc. As a consequence the coil is usually referred to as the "*J*coil," or on occasions the "*M* coil." It is however, truly a d*Φ*/d*t* coil. In this standard it will be referred to as the "*J* coil."

In the case of the *H* coil, the output voltage is the time derivative of the magnetic flux that is coupled to that coil and is largely the magnetic field strength applied to the specimen. This coil is usually referred to as the "*H* coil," although it is truly a d*H*/d*t* coil.

The outputs of these two coils are integrated (see 6.2). In the case of the integrated signal from the *J*coil, the zero signal is removed and the result calibrated to generate an *M*' signal, that is, the magnetization of the specimen being measured in an open magnetic circuit. By combining this with the *H* signal, an *M*'(*H*) hysteresis loop is obtained (see Clause 7).

If the *M*'(*H*) loop is corrected for the self-demagnetization of the open magnetic circuit measurement, (see 7.1.3), the intrinsic *M*(*H*) or *J*(*H*) loop data can be obtained (or *B*(*H*) if required) by the usual conversion.

The two signal channels, that is, from pick-up coil, through integration, digitization and data collection and processing within the computer, are generally known as the "*J*" and "*H*" channels.

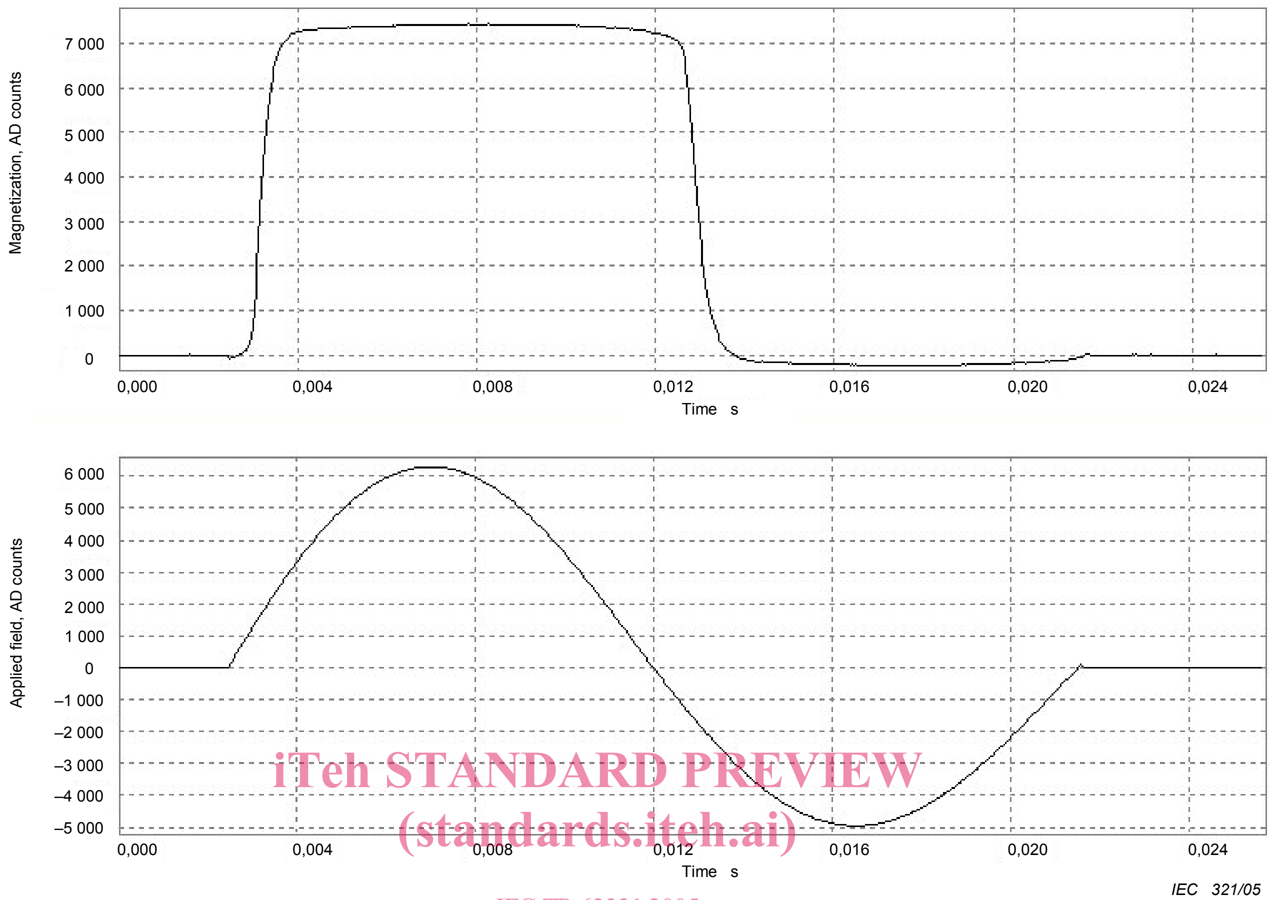

Figure 1 – *M*' and *H* time traces for a permanent magnet

The lower trace (above) is the time trace of the magnetic field strength (*H*) based upon the field generator configuration discussed in 3.2.2.1. The upper trace represents the time trace of the specimen magnetization; a specimen of sintered Neodymium Iron Boron; data obtained after initial integration and digitization of the *J* and *H* coil outputs, in arbitrary units [ref. 32].

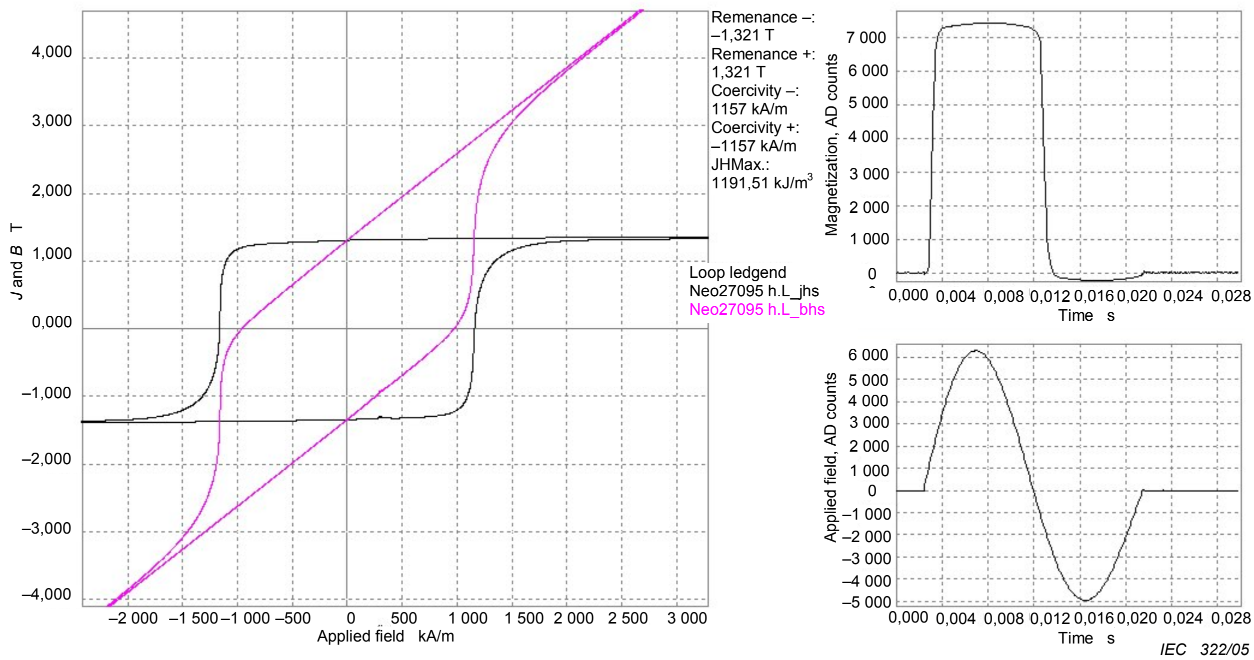

Figure 2 – *J*(*H*) and *B*(*H*) loop for a permanent magnet

The complete hysteresis loop is obtained by plotting the *J* data against the *H* data shown in Figure 1, without using the time domain data. The time domain *J* and *H* data are again shown to the right. [ref. 32]. The inner loop represents the *B*(*H*) loop.

3.2 Size of test specimen

As the test specimens are measured in an open magnetic circuit, there is no immediate limit to the size of specimens that can be tested. Small and large test specimens can be measured providing that eddy current considerations, and the practical considerations of the instrumentation, are taken into account (see 7.1.6).

The results shown in this report are for cylinders of a maximum dimensions of 30 mm diameter and 25 mm length and minimum dimensions of 5 mm diameter and 5 mm length, although this is not a practical limitation for the PFM technique.

Cylindrical test specimens with diameters less than 3 mm and lengths of 3 mm have been measured while cylinders of NdFeB of 40 mm diameter and 30 mm length have also been measured.

The Japanese group EMAJ measure test specimens of a cylindrical shape of 10 mm diameter and 7 mm length and a cube of 7 mm x 7 mm x 7 mm (see Figures 14–16).

4 Field generator

4.1 General

The field generator consists of a system that enables the magnetic field to be applied to the test specimen.

This will consist of a power supply and a magnetizing solenoid. The power supply provides the magnetizing current to the magnetizing solenoid in order to generate the applied magnetic field.

4.2 Power supply

4.2.1 General

Power supplies normally have the capacity to apply an electrical potential (over the range of 400–10 000 V but more typically 1 000–3 000 V) at currents (with a current range of 1 000–40 000 A but more typically 5 000–20 000 A), in both positive and negative polarities.

This can be accomplished by one of two methods:

a) capacitive discharge;

b) direct mains supply.

4.2.2 Capacitive discharge

The capacitive discharge arrangement enables electrical energy to be accumulated in capacitors over an extended period of time, before being discharged in a short time period to provide high currents from the low impedance source.

The energy storage:

$$E = \frac{1}{2} C U_0^2 \qquad (1)$$

where

E is the energy, in joules;

C is the capacitance, in farads;

U_0 is the capacitor voltage, in volts.

For commercial PFM measurement systems, it is necessary to minimize costs and it is therefore, normally necessary to achieve the required magnetic performance with the minimum of capacitor energy. The capacitance and energy of the capacitive discharge system is matched with the magnetizing solenoid to provide the required magnetizing conditions of peak field strength, field volume, field homogeneity and period. The maximum magnetic field strength achieved is proportional to the current density; the proportionality factor being dependent on the geometry of the magnetising solenoid.

The discharge can be applied in the following forms:

a) sine wave (decaying);

b) unidirectional pulses (1/2 sine wave);

c) two unidirectional pulses (with decay).

4.2.2.1 Sine wave (decaying)

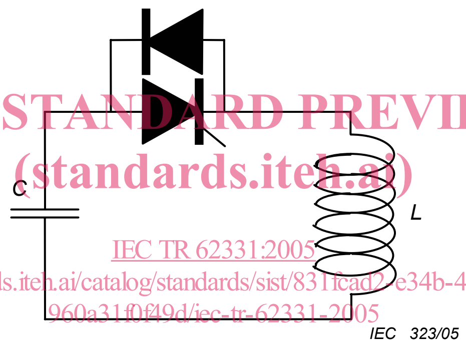

Figure 3 – Sine wave (decaying) electrical configuration

The current *I(t)*, and therefore the magnetic field strength is determined by:

$$I(t) = \frac{U_0}{\omega L} . e^{-\beta t} \sin \omega t \qquad (2)$$

where ω is given by

$$\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \qquad (3)$$

and is given by

$$\beta = R/2L \qquad (4)$$

Due to the resistive losses in the magnetizing solenoid, the peak field strength created in the magnetizing solenoid in the reverse direction is reduced, depending on the damping factor β. It is therefore necessary to apply a higher initial field, in order to achieve the necessary reverse field.

The sine wave technique has the advantage of a continuous process to apply positive and negative polarities and to avoid discontinuities. This is important in the testing of conductive materials where eddy current effects are taken into consideration (see 7.1.6).