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TECHNICAL SPECIFICATION

colour inside

Nanomanufacturing – Key control characteristics – Part 9-1: Traceable spatially resolved nano-scale stray magnetic field measurements – Magnetic force microscopy

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FOREWORD

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IEC TS 62607-9-1 has been prepared by IEC technical committee 113: Nanotechnology for electrotechnical products and systems. It is a Technical Specification.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
113/584/DTS	113/606/RVDTS

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

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts of the IEC TS 62607 series, published under the general title *Nanomanufacturing – Key control characteristics*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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- withdrawn,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

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INTRODUCTION

Measurements of magnetic fields that are homogeneous over macroscopic volumes can be made traceable to the SI standards, and traceable calibration chains from the national metrology institutes to the end users are well-established.

However, many important industrial applications such as magneto-resistive position, angle, or motion control rely on precision sensing of spatially varying magnetic fields. Such spatially varying magnetic fields can, for example, be generated by a magnetic bit pattern of a magnetic encoder scale. Today, magnetic encoder bit patterns have typically a lateral periodicity above 100 µm. Based on stray field interpolation, such encoders are applied, for example, for precision positioning systems with sub-micrometre resolution. However, such precision positioning requires reliable local field measurements which are not yet underpinned by any suitable standards.

Today, local magnetic stray field measurements with resolutions from above 50 µm down to below 500 nm can be realized by scanning magnetic field detection (SMF) methods with different field sensors such as Hall sensors, magneto-resistive (MR) sensors and magnetically coated tips on an oscillating cantilever (magnetic force microscopy (MFM)), or with imaging techniques like Kerr and magneto-optical indicator film (MOIF) microscopy. Achievable spatial resolution and typical scanning area are compared in Figure 1.

MFM provides a significantly higher resolution than other SMF techniques and MOIF (see Figure 1) and can therefore be considered as the standard tool for nano-scale investigations of the local magnetic properties of magnetic nanostructures, thin films and devices [1][1]. However, despite its wide use, MFM measurements per se only deliver purely qualitative stray field images that cannot be applied for quantitative data analysis. This results from the fact that the measured signal strongly depends on the properties of the magnetic tip, the mechanical properties of the cantilever and the sensitivity of the detection device. Hence a calibration that includes the characterization of the magnetic tip and the microscope is needed if the MFM method is to be used to provide values of key control characteristics (KCCs) which are ultimately traceable to national calibration standards.

This document aims to provide industry end users, instrument manufactures and calibration laboratories with a description of traceable calibration procedures based on reference materials with well-defined local stray field distributions. This document includes the description of suitable reference samples, the evaluation of MFM key parameters required for the method, and the determination of the instrument calibration function (ICF). Due to the finite dimension of the tip, a spatial broadening of the MFM signal is unavoidable. Mathematically this broadening can be described by the convolution of the ICF and the real magnetic field structure of the sample to be measured. Vice versa, a quantitative analysis of the measured data is achieved by a deconvolution of the MFM measurement data using the ICF. The description of this process is the key part of this document.

[1] Numbers in square brackets refer to the Bibliography.

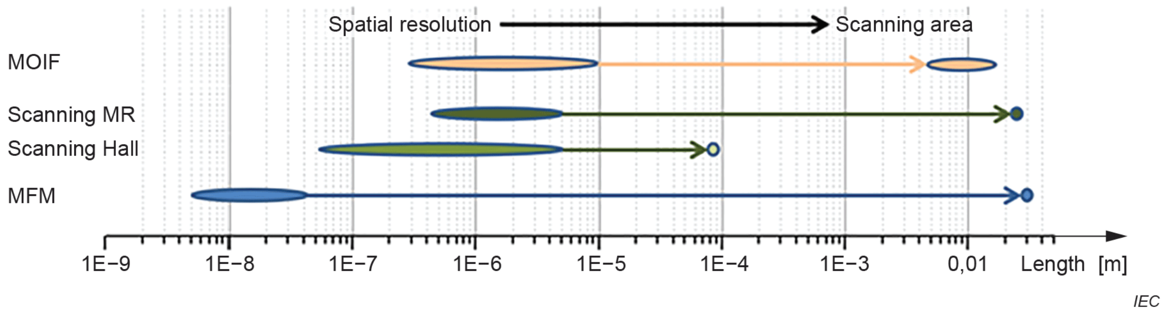

Figure 1 – Spatial resolution of magnetic stray field characterization techniques and their possible maximum scan area

The MFM technique as described in this document has a resolution down to about 10 nm to 20 nm (depending on the signal-to-noise ratio of the instrument), which is at least one order of magnitude superior to other common characterization techniques for spatially varying magnetic fields. MFM systems operated at ambient conditions typically can achieve a resolution of around 50 nm [1]. With optimized tips, a resolution down to below 20 nm is possible [2]. The highest resolution in MFM is achieved in vacuum. With very precise tip–sample distance control [3] and high-resolution tips [4], a resolution down to 10 nm could be demonstrated.

While the MFM technique has the best precision and accuracy of the test methods (see Figure 1), as a scanning technique it is comparatively slow, requires specific ambient conditions such as stable temperatures and can only be used for samples which are flat and smooth on a micrometre scale (depending on the scanning unit). For routine statistical process control (SPC) of the manufacturing process, it may not be suitable in many use cases. Therefore, it is anticipated that the MFM technique needs to be complemented, for example, by:

- the magneto-optical indicator film technique (MOIF), which, as an imaging process, allows high throughput;
- scanning Hall or MR test methods, which can easily be calibrated in homogeneous external fields. In CMOS technique, arrays of parallel Hall sensors can be prepared and thus a high throughput can be achieved in a scanning process.

Wherever possible, existing relevant scanning probe microscopy (SPM) standards are referred to, especially those developed by ISO/TC 201 like ISO 18115-2 [5] and ISO 11952 [6].

In summary, this document provides a traceable method for nanometre-resolution measurements of magnetic field patterns, which is the basis for precise control of fabrication processes and final product qualification. The key control characteristics for those products are very product specific (see, for example, IEC TS 62622:2012 [7]).

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 9-1: Traceable spatially resolved nano-scale stray magnetic field measurements – Magnetic force microscopy

1 Scope

This part of IEC 62607 establishes a standardized method to characterize spatially varying magnetic fields with a spatial resolution down to 10 nm for flat magnetic specimens by magnetic force microscopy (MFM). MFM primarily detects the stray field component perpendicular to the sample surface. The resolution is achieved by the calibration of the MFM tip using magnetically nanostructured reference materials.

The objective of this document is to define and describe:

- reference materials for traceable high resolution magnetic stray field measurements;
- the calibration procedures to determine the instrument calibration function (ICF) and, if required, MFM key parameters entering the deconvolution process;
- the deconvolution process which allows to calculate quantitative stray field data from the measured MFM data using the ICF;
- the evaluation of the measurement uncertainty, including the prevention of potential artefacts which can occur during the measurement leading to a misinterpretation of the results.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1 General terms

3.1.1
key control characteristic
KCC
key performance indicator
measurement process characteristic which can affect compliance with regulations and quality, reliability or subsequent application of the measurement result

Note 1 to entry: The measurement of a key control characteristic is described in a standardized measurement procedure with known accuracy and precision.

Note 2 to entry: It is possible to define more than one measurement method for a key control characteristic, if the correlation of the results is well-defined and known.

Note 3 to entry: In IATF 16949 [8] the term "special characteristic" is used for a KCC. The term key control characteristic is preferred since it signals directly the relevance of the parameter for the quality of the final product.

3.2 General terms related to magnetic stray field characterization

3.2.1
magnetic-force microscopy
MFM
atomic force microscopy mode employing a probe assembly that monitors both atomic forces and magnetic interactions between the probe tip and a surface

[SOURCE: ISO 18115-2:2013, 3.15]

3.2.2
magneto-optical indicator film technique
MOIF technique
method of mapping the magnetic field above a sample surface by a thin magneto-optical indicator film

Note 1 to entry: The magnetic fields induce a perpendicular magnetization component in the active layer of the detector, which is recorded with the Faraday effect.

3.2.3
dynamic mode scanning force microscopy
scanning magnetic force microscopy mode in which the relative positions of the probe tip and sample vary in a sinusoidal manner in time at each point in the image

Note 1 to entry: The sinusoidal oscillation is usually in the form of a vibration in the z-direction and is often driven at a frequency close to, and sometimes equal to, the cantilever resonance frequency.

Note 2 to entry: The signal measured can be the amplitude, the phase shift, or the resonance frequency shift of the cantilever.

[SOURCE: ISO 18115-2:2013, 3.6, modified – The source uses the term "dynamic-mode AFM" instead of "dynamic mode scanning force microscopy" and the term "AFM mode" instead of "scanning magnetic force microscopy mode"]

3.2.4
intermittent contact mode
mode of scanning the probe where the probe is operated with a sinusoidal z-displacement modulation such that the probe tip makes contact with the sample for a fraction of the sinusoidal cycle

[SOURCE: ISO 18115-2:2013, 5.73]

3.2.5
non-contact magnetic-force microscopy
NC-MFM
dynamic mode scanning force microscopy (3.2.3) in which the probe tip is operated at such a distance from the surface that it samples the weak attractive van der Waals or other forces

3.2.6
scanning magnetic field microscopy
SMF microscopy
method of measuring and mapping the magnetic field from a sample surface by mechanically scanning a probe above the sample surface

Note 1 to entry: This generic term encompasses *scanning Hall probe magnetometry* (3.2.7) and *scanning MR magnetometry* (3.2.8).

3.2.7
scanning Hall probe magnetometry
SHM
scanning magnetic field microscopy (3.2.6) mode in which a Hall probe is used as the scanning sensor to measure and map the magnetic field from a sample surface by acquiring a Hall voltage

[SOURCE: ISO 18115-2:2013, 3.23, modified – The phrase "scanning magnetic field microscopy" is used instead of "SPM" and the phrase "by acquiring a Hall voltage" is added]

3.2.8
scanning MR magnetometry
SMR magnetometry
scanning magnetic field microscopy (3.2.6) mode in which a magneto-resistive sensor probe on a cantilever is scanned over a magnetic sample surface to measure the *magnetic field distribution* (3.3.1) by acquiring a magneto-resistive voltage

[SOURCE: ISO 18115-2:2013, 3.25, modified – The "phrase "scanning magnetic field microscopy" is used instead of "SPM" and the phrase "magnetic field distribution" is used instead of "two-dimensional magnetic images"]

3.3 Terms related to the measurement method described in this document

3.3.1
magnetic field distribution
spatially resolved magnetic field data array in the x-y-plane with the x-, y-direction in the sample plane and the z-direction along the sample surface normal with a spatial resolution dx, dy at a distance d above the surface of a test specimen

3.3.2
raw data distribution
spatially resolved MFM raw data array with the x-, y-direction in the sample plane and the z-direction along the sample surface normal at a distance d above the surface of a test specimen

3.3.3
magnetic force
force acting between magnetic volumes

Note 1 to entry: In SPM, the magnetic dipoles are usually incorporated as ferromagnetic material in the probe tip and it is the magnetic field of the sample that is measured.

[SOURCE: ISO 18115-2:2013, 5.8, modified – The phrase "magnetic volumes" is used instead of "magnetic dipoles in a magnetic field"]

3.3.4
magnetically coated probe tip
probe which is coated with a thin magnetic layer on the tip side of the cantilever

Note 1 to entry: The magnetic layer creates a magnetic volume that interacts with the sample magnetic field and thus probes it.

3.3.5
constant height mode
mode of scanning the probe tip over the sample surface at a constant height of the centre of the oscillation of the tip apex relative to the surface plane of the sample during the scan

[SOURCE: ISO 18115-2:2013, 5.34, modified –"over the surface" is replaced with "of the centre of the oscillation of the tip apex relative to the surface plane of the sample".]

3.3.6
measurement height
value of the constant height of the centre of the oscillation of the tip apex relative to the surface plane of the sample during a measurement in *constant height mode* (3.3.5)

3.3.7
measurement plane
plane at constant height above the surface where the raw data distribution is measured in *constant height mode* (3.3.5)

3.3.8
cantilever oscillation
sinusoidal z-displacement of the cantilever and thus the tip in *dynamic mode scanning force microscopy* (3.2.3)

Note 1 to entry: The z-displacement is typically induced by the oscillation of the cantilever by means of an excitation piezo, the driven frequency is close to the cantilever resonance frequency.

3.3.9
cantilever
thin force-sensing support for a *magnetically coated probe tip* (3.3.4) joined to the *cantilever chip* (3.3.10) at the end furthest from the probe tip

[SOURCE: ISO 18115-2:2013, 5.18, modified – The phrase "a magnetically coated probe tip" is used instead of "a probe tip".]

3.3.10
cantilever chip
small piece, usually of silicon, on which the *cantilever* (3.3.9) with the *magnetically coated probe tip* (3.3.4) has been fabricated and to which it is still attached as a convenient supporting structure in the probe assembly (3.3.12)

[SOURCE: ISO 18115-2, 5.26, modified – The phrase "with the magnetically coated probe tip" is added.]

3.3.11
chip holder
structure on which the *cantilever chip* (3.3.10) with the *cantilever* (3.3.9) and the *magnetically coated probe tip* (3.3.4) are mounted

Note 1 to entry: The chip holder, chip, cantilever, and probe comprise the *probe assembly* (3.3.12).

[SOURCE: ISO 18115-2:2013, 5.27, modified – The phrase "the magnetically coated" is added.]

3.3.12
probe assembly
structure comprising the *chip holder* (3.3.11), *cantilever chip* (3.3.10), *cantilever* (3.3.9) and *magnetically coated probe tip* (3.3.4) including a provision to drive a sinusoidal oscillation of the cantilever in the form of a vibration in the z-direction

Note 1 to entry: This provision typically is an excitation piezo, see ISO 18115-2.

[SOURCE: ISO 18115-2:2013, 5.20, modified– The phrase "magnetically coated probe tip" is used instead of "probe" and the phrase "including a provision to drive a sinusoidal oscillation of the cantilever in the form of a vibration in the z-direction" is added.]

3.3.13
excitation piezo
provision to drive a sinusoidal oscillation of the *cantilever* (3.3.9) in the form of a vibration in the z-direction exploiting the variation of a piezo active material induced by a sinusoidal electric drive signal

Note 1 to entry: See ISO 18115-2.

3.3.14
MFM observation variable
phase shift between sinusoidal cantilever drive signal and cantilever oscillation at fixed excitation frequency and excitation amplitude

Note 1 to entry: In principle, other measurands can also be exploited to detect the interaction between magnetic tip and sample stray field, e.g. the frequency shift of the resonance frequency of the oscillating cantilever.

3.3.15
phase shift signal
$\Delta\varphi$
MFM observation variable (3.3.14) defined as the phase shift between sinusoidal cantilever drive signal and cantilever oscillation at fixed excitation frequency and excitation amplitude

Note 1 to entry: The signal may be corrected by a constant offset.

3.3.16
signal detector
detector that transforms the amplitude and temporal course of the cantilever oscillation into an electrical signal

Note 1 to entry: In this case a light pointer combined with a sensitive photo detector (PSD).

3.3.17
signal analysis system
system to extract and record the *MFM observation variable* (3.3.14) as a function of the lateral displacement of the tip

Note 1 to entry: In this case a system to extract the phase shift between the cantilever driving sinusoidal oscillation and the signal detected by the signal detector. The phase shift may be offset corrected.

3.3.18
z-scanner
element for the realization of the vertical displacement of the specimen/probe distance during x-y-scanning

Note 1 to entry: See ISO 18115-2:2013, 5.136.

3.3.19
x-y-scanner
element for realization of the lateral displacement of the probe or of the specimen in the x-y-plane

3.3.20
data pre-processing
raw data treatment to remove known artefacts of the measurement process

3.3.21
data levelling
form of *data pre-processing* (3.3.20) to eliminate unwanted features from scan lines, such as drift and offsets