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COMMUNICATIONS

CALIBRATION OF A MEASURING DEVICE TO DETERMINE SPECIFIC SATURATION MAGNETIZATION BY A SPECIAL COIL

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Specific saturation magnetization σ_S is an important parameter of ferromagnetic materials. It is in principle independent of the structure and shape of the sample. There are two ways to calibrate devices for determining σ_S: the standard method, using a calibrated magnetic moment standard, or an alternative method, using a special moment coil. This paper presents a calibration method used at Czech Metrology Institute for calibration of Koerzimat 1.096 using a special moment coil. Special attention is given to a description of the special moment coils used for Koerzimat 1.096 calibration, and to analysis of sources of uncertainty. Calibration expanded uncertainty of 0.4 up to 0.6 % can be achieved using this method.

K e y w o r d s: calibration, magnetic moment, magnetic moment standard, moment coil, saturation magnetization

1 INTRODUCTION

In many fields of metal processing (*eg* metallurgy, magnet and cemented carbide manufacturing, and magnetic material control), the saturation magnetization provides information on the properties and the composition of the material, and also on the quality of the material. Measuring devices for determining specific saturation magnetization σ_S, such as Koerzimat 1.096 and Sigmameter, work on the principle of magnetic moment measurement, according to [1]. The weight of the sample is first determined with precision scales. The sample is then positioned in the air gap of a saturation magnet (a shielded permanent magnet with a large air gap) and is pulled out. The magnetic moment is measured by means of a Helmholtz measuring coil, arranged in the air gap of the saturation magnet, and a fluxmeter. The weight-specific saturation magnetization σ_S is then calculated from the magnetic moment ratio to weight. According to [1], devices of this kind should be calibrated by a calibrated magnetic moment standard of suitable dimensions made of 99.99 % pure nickel. We present an alternative method for Koerzimat 1.096 calibration using a special moment coil.

2 THEORY

In calibration method using a magnetic moment standard the test systems can be calibrated to higher resolution without loss of accuracy by using nickel rather than iron. Since nickel is chemically stable, it will not rust or corrode, thus avoiding attendant changes in magnetic characteristics. High-purity nickel is well-suited for use as a magnetic reference material. A disadvantage of nickel, however, is that it is a very soft metal and thus requires reasonably careful handling. As long as it is not physically damaged, however, its properties do not change. If it is crushed or otherwise damaged, it can be ground or machined to a new shape and, if properly annealed for stress-relief, can be certified again to its original magnetic specifications.

The principle of the calibration method for Koerzimat 1.096 using a magnetic moment standard made from nickel consists in comparing the calibrated value of the magnetic moment standard with the value measured according to [1]. The magnetic moment standard must have proper dimensions (it usually has the shape of a disc). The magnetic moment of the nickel standard can be determined *eg* by a sampling technique using an absolute magnetometer based on the Faraday method (developed at NIST). The purity of the nickel at a level of least 99.99 % must be certified *eg* by a chemical laboratory. The advantage of this method is its simplicity. The disadvantage is that the magnetic moment standard has only one nominal value, so if you want to calibrate the device in more than in one measuring point, for example in five measuring points, you need to have five magnetic moment standards with different nominal values.

Calibration method, which has been used successfully at the Czech Metrology Institute is based on a special moment coil. Figure 1 presents a schematic diagram of the calibration aparatus. The moment coil, powered by current I and inserted into the measuring Helmholtz coils (inside the saturation magnet air gap) is to simulate a sample of ferromagnetic material. The magnetic moment of this coil is determined by its current I with K_S being the proportionality constant. Using this coil, the set saturation magnetization value can be found as

$$\sigma_{Sc} = \mu_0 \frac{K_S I}{m} = \mu_0 \frac{K_S U_N}{m R_n}, \qquad (1)$$

where μ_0 is the magnetic constant ($4\pi \times 10^{-7}$ H/m), m is the specimen weight, and U_N is the voltage drop on the standard resistor R_n measured by a digital multimeter (DMM).

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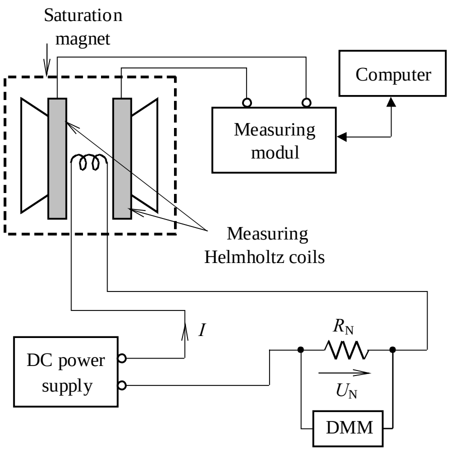

Fig. 1. Schematic diagram of Koerzimat 1.096 calibration using a special moment coil

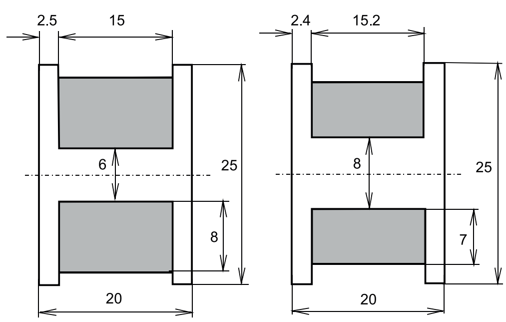

Fig. 2. Cross-section of the frame of the special coils EP 10/97 and EP 9/97 for calibration of Koerzimat 1.096

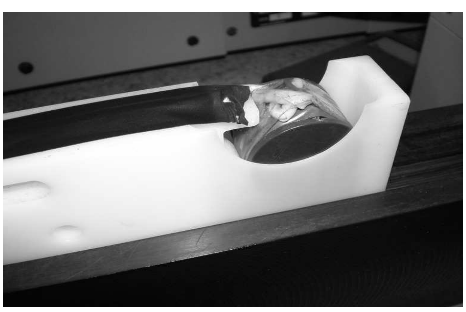

Fig. 3. Detail of moment coil EP 10/97 inserted into the test piece slide

3 SPECIAL MOMENT COILS

The system of axially symmetric conductive loops with area turns NA passed by current I can be described by the magnetic moment $m = I\,NA$, which is a vector quantity describing the magnetic dipole of the moment coil. In the real case of a system of loops, an accurate description is a series of multipoles with multipole constants p_0, p_1, $p_2, \dots, p_n$. A multipole with constant p_0 equals zero because of the absence of a magnetic monopole. A multipole with constant p_1 is a magnetic dipole; p_1 is the area turns for a coil. A multipole with constant p_2 is a quadrupole that equals zero as do all even multipole constants due to the symmetry of the system. The third multipole, with a constant of p_3, is an octupole, *etc.* The influence of the higher multipoles declines with distance. The influence can be significant in distances comparable with 5–10 times the dimensions of the coil. To suppress higher multipoles, especially p_3 of symmetrical cylindrical windins we choose the ratio of the coil's length to its diameter $\sqrt{3}/2$, [2]. This ratio can also be used for the multi-layer search coil.

With a coil having non compensated octupole constant - for example moment coil with small ratio of the coils length to diameter - the measurement error caused by an octupole placed in a short solenoid (not enough homogeneous external field) can be estimated to a few percent. If a compensated moment coil is placed into the magnetic field with a better homogeneity (*eg* Helmholtz coils) then the measurement error due to the octupole is reduced to a few tenths of a percent or less. Moreover, the moment coil with compensated octupole constant when placed into a homogeneous external magnetic field is also less sensitive to fabrication inaccuracies of a real coil.

Because the test piece slide for the saturation magnet has a limited space, the dimensions (and thus the area turns) of the moment coil are also limited. Two special moment coils EP 9/97 and EP 10/97 were designed with a cylindrical frame and with a suppressed octupole. The frame was made from textit, and is 25 mm in length and about 20 mm in diameter, as shown in Fig. 2. The idea was raised of using silver wire for the coil winding. Silver has a smaller resistivity value than copper, which means that when there are the same number of turns, the value of coil's power should be smaller than when using copper wire. Finally, after making calculations, we decided to use copper wire, because the power value would be only a few percent smaller, and would not justify the higher cost of silver. The winding of both coils is wound with enameled copper wire 0.5 mm in diameter. The moment coil constant value $(0.092682\pm0.000074)\,\mathrm{m}^2$ for EP 10/97 and $(0.066378\pm0.000053)\,\mathrm{m}^2$ for EP 9/97 was determined by a method with variable mutual inductance [3]. The maximum current value through the coils can be 1 A for a short time (*eg* few minutes).

4 UNCERTAINTY ANALYSIS

The A-type of uncertainty of the measurement is calculated from

$$U_{sA} = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}{n(n-1)}}, \quad \overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i\,. \qquad (2,3)$$

where n is the total number of measurements and $\overline{x}$ is the arithmetic mean of the individual measured values x_i

The B-type uncertainty of the calibration method has several components, as follows

$$U_{sB} = \sqrt{u_{SC}^2 + u_V^2 + u_R^2 + u_\varphi^2 + u_T^2 + u_H^2}\,, \qquad (4)$$

where u_{SC} is the standard uncertainty of the moment coil constant, u_V is the uncertainty of the voltage value measured on the standard resistor R_N, u_R is the uncertainty of the standard resistor, u_φ is the uncertainty of the directional dependence measurement of the moment coil, u_T is the uncertainty of the influence of the moment coil winding temperature, and u_H is the uncertainty of the influence of homogeneity inside the measuring Helmholtz coils in the saturation magnet air gap.

The uncertainty of the search coil constant determined by calibration with variable mutual inductance is 0.04 %. The uncertainty of the measured voltage on the standard resistor is dependent on the specification of the digital multimeter that is used. The value of u_V can be of order of thousandths of one percent. The maximum uncertainty value of the standard resistor usually varies in units to tens of ppm, so it can be neglected, because the other uncertainties are essentially higher. The value of the output voltage impulse from the measuring Helmholtz coils depends on the direction in which the moment coil is inserted into the measuring Helmholtz coils inside the saturation magnet air gap. In principle, the value depends on $\cos\varphi$, where φ is the angle between the axis of the moment coil and the axis of the measuring Helmholtz coils. The search coil must be set to the position where $\cos\varphi = 1$, which is the maximum value from the measuring Helmholtz coils. For example, there is a difference of about 0.02 % from the true value of the measured voltage impulse for $\varphi = 1^\circ$, there is a difference of about 0.06 % for $\varphi = 2^\circ$, and so on. This means that the value of u_φ can lie in the order of hundredths to tenths of one percent. The current through the moment coil causes the winding to heat up, and thus changes the area turns value. This means that the influence of the moment coil temperature winding must also be taken into account. The value of u_T can lie in the order of hundredths to tenths of one percent. The influence of homogeneity inside the measuring Helmholtz coils is small, due to the suppressed octupole of the moment coil that is used, but its value is non-negligible. The value of u_H was determined as 0.08 %.

The total (combined) uncertainty of the calibration method is then calculated as $U_s = \sqrt{u_{sA}^2 + u_{sB}^2}$.

5 MEASUREMENT RESULTS

The method described above was tested using Koerzimat 1.096 in the laboratory of Global Tungsten & Powders, Czech Republic. The calibration was performed for the sets weight value of 2.5 g, 5 g and 10 g. The moment coil EP 10/97 was used for calibration, and the results are presented in Tab. 1. The nominal current value through the moment coil was 0.5 A and 1 A. The real current was measured as a voltage drop by the HP 34401A-type multimeter on the Guildline 9221-type standard resistor with a calibrated value of $(2.000038 \pm 0.000011)\,\Omega$. Ten measurements were performed for each weight value. The values presented in Tab. 1 are the arithmetic mean of these measurements.

Table 1. Result of simulations

Weight (g)	Measured current (A)	Measured σ_S by Koerzimat 1.096 ($\mathrm{mTm^3/kg}$)	σ_{Sc} sets by moment coil ($\mathrm{mTm^3/kg}$)	Relative error of measured value (%)	Expanded uncertainty of calibration for k=2 (%)
2.5	0.52669	24.53	24.54	0.04	0.5
5	0.51238	11.91	11.94	–0.25	0.5
5	1.00317	23.36	23.37	–0.04	0.4
10	0.51615	6.007	6.011	–0.07	0.5

6 CONCLUSIONS

An alternate method for calibration of measuring device for determining specific saturation magnetization has been proposed. The construction and the parameters of the special moment coils have been described, and an uncertainty analysis is also presented. When a method with a special moment coil is used, the calibration uncertainty depends mainly on the uncertainty of the moment coil constant, on the uncertainty of the measured current, which is measured as the voltage drop on the standard resistor, and on the uncertainty of the placement of the moment coil in the measuring Helmholtz coils in the saturation magnet air gap. The influence of the homogeneity inside the measuring Helmholtz coils and the influence of the moment coil winding temperature must also be taken into account. The advantage of this calibration method is that we can make a calibration for more than one value of σ_{Sc} with a single moment coil and by changing the current and weight value. A calibration expanded uncertainty value of 0.4 up to 0.6 % can be achieved using this method.

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