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So, You Need Reliable Magnetic Measurements You Can Use With Confidence? How the Magnetic Measurement Capabilities at NPL Can Help

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The magnetic field standards, facilities and capabilities available at NPL for the calibration of magnetometers and gradiometers and the measurement of the magnetic properties of materials will be introduced. The details of the low magnetic field facility will be explained and the capabilities this facility enables for the characterisation and calibration of ultra-sensitive room temperature magnetic sensors will be presented. Building on core material capabilities that are compliant with the IEC 60404 series of written standards, the example of a standard permeameter that has been modified for the measurement of strips for real world conditions is discussed. This was incorporated into a stress machine to measure the DC properties of the soft magnetic materials used by the partners of a collaborative industry led R&D project at stress levels of up to 700 MPa. The results for three materials are presented and the changes in the properties with applied stress compared to establish which material exhibits favourable properties.

Keywords : ambient field cancellation, magnetic noise, magnetic capability, properties with stress

1. Introduction

To develop and use with confidence high sensitivity magnetic sensors it is necessary to establish a low magnetic noise environment along with traceable measurement systems to perform the characterisation and calibration [1]. NPL have for over 50 years, and continue today, to develop the facilities and capabilities needed. One such facility is the NPL low magnetic field laboratory in which the ambient magnetic field is reduced to less than 1 nT with a noise level of 15 pT/√Hz at 1 Hz. The measurement capabilities used to calibrate magnetometers in this and associated facilities will be summarised and the best measurement uncertainties presented.

Material measurement facilities that provide capabilities for the full range of the IEC 60404 series of written standards are available in the same group. The facilities are UKAS accredited and provide the core capability for developing real world measurement methods. An example is the need to measure the properties of soft magnetic materials at stress levels up to 700 MPa. The measurement setup is described. The results for three materials are presented and the changes in the properties with applied stress compared to establish which material exhibits favourable properties for the specific application being considered.

2. NPL Low Magnetic Field Facility

The Low Magnetic Field Laboratory is based in Bushy House on the NPL site in Teddington, UK. Unlike modern buildings, when built in 1663 no magnetic materials were used in the construction. As a consequence, the magnetic signature of the building is very small. This made the building suitable for a low magnetic field laboratory based on coil systems and a remote three axis reference magnetometer to reduce the ambient magnetic field to the required level. The 3 m diameter Helmholtz Coil established is shown in Fig. 1.

Shown in Fig. 2 is the magnetic field variation in the laboratory before and after cancellation. The origins of the variations with time before the cancellation system is operated (black curve) are mainly due to the electric train system used in the area. The electrical return of the circuit is not insulated and so earth leakage currents are generated. These currents then produce the very small mag-

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Fig. 1. (Color online) 3m diameter Helmholtz coil used to reduce the ambient magnetic field at NPL. A 1 m diameter Helmholtz coil used to calibrate magnetometers can be seen in the centre.

netic fields shown in Fig. 2. Other sources of disturbance in the ambient magnetic field are from the Earth's daily diurnal variation, 'Sun Spot' activity and the effect of vehicles and other nearby ferromagnetic items.

The cancellation achieved allows the calibration of magnetic field standards with a reduced uncertainty due to the improved measurement repeatability.

3. Magnetic Field Capability

Shown in Table 1 is the NPL capability for DC magnetic field measurements from 1 nT to 13 T.

By using a Proton resonance magnetometer, traceability is achieved through a frequency measurement. The CODATA [2] value for the gyromagnetic ratio of the proton is used to convert this frequency to a magnetic field. NPL took part in an International comparison organised by Euromet (made up of European National Measurement Institutes) for magnetic field values in this range [3]. The NPL measurement agreed with the comparison reference value. This provides an independent check of the NPL best measurement method and uncertainty.

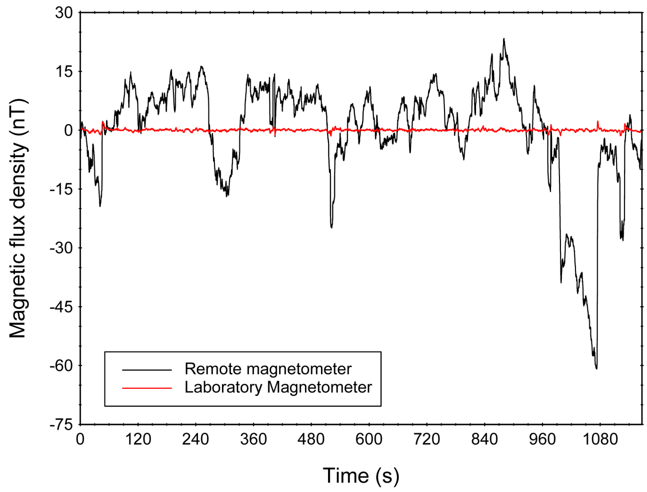

Fig. 2. (Color online) Cancellation achieved with existing system.

4. Magnetic Properties with Stress Applied

The same group at NPL provides comprehensive material measurements. Building on the material measurement capabilities established for standard conditions, new methods can be developed that produce operational conditions. For soft magnetic materials these include the measurement of the DC properties at stress levels up to 700 MPa. This is important in high speed rotating machines such as those being developed for embedded generators to be used in gas turbines for MORE electric aircraft.

As part of a collaborative R&D project involving 16 UK partners, an NPL standard permeameter used for measuring the properties of soft magnetic materials in rod form in accordance with IEC 60404 part 4 [4] was

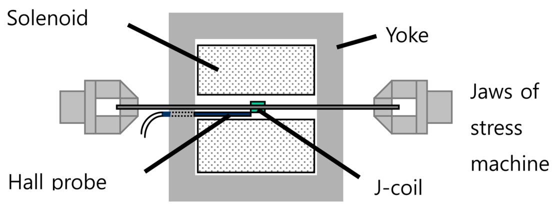

Fig. 3. Schematic of the NPL strip permeameter setup in a stress machine.

Table 1. NPL DC Magnetic Field Capability.

Range	Method for best measurement capability	Best measurement uncertainty ($k = 2$)
0.8 mA/m (1 nT) to 16 A/m (20 μT)	Fluxgate	0.15% + 0.5 nT
16 A/m (20 μT) to 72 A/m (90 μT)	Proton resonance	0.003%
72 A/m (90 μT) to 280 A/m (350 μT)	Fluxgate	0.05%
280 A/m (350 μT) to 40 kA/m (50 mT)	Hall effect gaussmeter	0.2%
40 kA/m (50 mT) to 10.5 MA/m (13T)	NMR gaussmeter	0.0015%

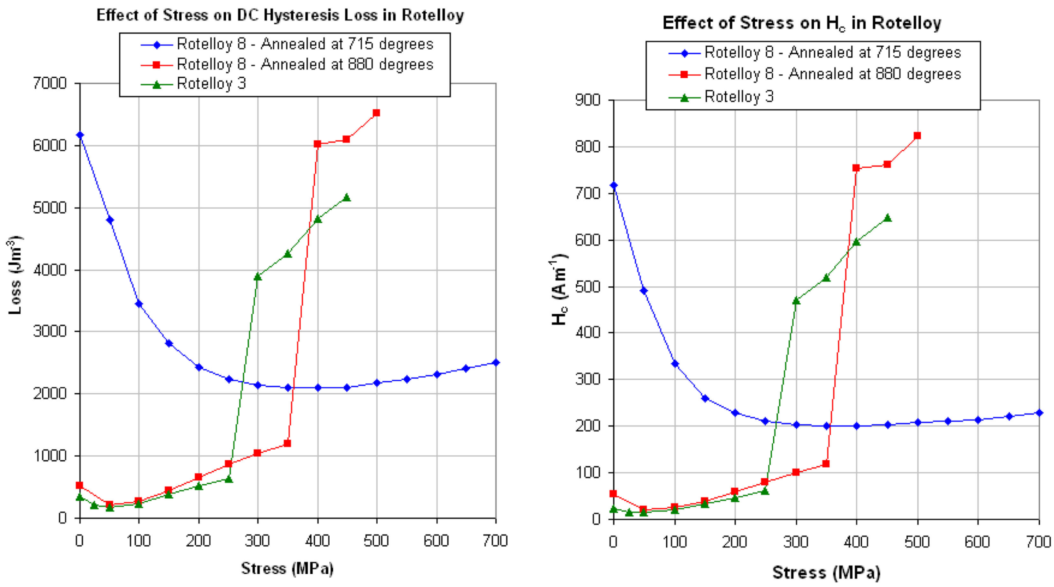

Fig. 4. (Color online) Change in the magnetic properties of three soft magnetic material test specimens with applied stress. In the right hand graph H_c is the coercivity.

modified to accommodate strips. The modified strip permeameter was then placed in a stress machine so that the DC magnetic properties could be determined with stress levels experienced in use applied during the measurement.

At NPL a horizontal stress machine has been developed for biaxial stress measurements on polymers and composites, and the positioning of the permeameter with the stress applied in a horizontal plane would be favourable. It was known from previous work, that supporting the weight of the yoke and the solenoid without stressing the material when mounting vertically was difficult. Shown in Fig. 3 is a schematic of the arrangement.

It is known that residual stress will change the properties of soft magnetic materials [5 and 6]. Previous to the work reported in this paper, the effect on the properties with such a large stress applied at the time of the measurements was not known. The DC hysteresis loops of strip geometry samples, 500 mm long, 20 mm wide and 0.3 to 0.6 mm thick, were measured. Rotelloy 3, Rotelloy 8 annealed at 880 °C (for improved magnetic properties) and Rotelloy 8 annealed at 715 °C (for improved mechanical properties) were investigated. The tensile stress was applied in 50 MPa steps up to the yield strength or 700 MPa, which ever was the smaller.

It can be seen in Fig. 4 that the Rotelloy 8 material heat treated at 715 °C for improved mechanical properties, is magnetically a better material for stress levels above 300 to 350 MPa. With no applied stress, the magnetic properties for this material are the worst. This behaviour is consistent with the heat treatment improving the mechanical properties. From Fig. 4, a heat treatment exists that would improve the observed magnetic behaviour and maintain performance at stress levels that are typically reached. The development of this optimised material is only possible using this NPL measurement method that applies the stress during the measurement of the properties.

These results show that the datasheet properties of the materials for standard measurement conditions [4] cannot always be used to select the appropriate material for operation in extreme conditions of stress.

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