Magnetic Susceptibility Imaging as a New Approach towards Characterization and Testing of Para- and Diamagnetic Materials

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Abstract. Magnetic nondestructive testing (NDT) methods are mainly applied to characterize and inspect ferromagnetic or, at least, electrically conductive materials. However, all materials interact with a magnetic field to some extent. This interaction is generally quantified by the magnetic susceptibility χ, which is the proportionality factor between magnetization M and applied magnetic field strength H. In the group of non-ferro- and non-ferrimagnetic materials, one can distinguish between para- ($0 < \chi < 1$) and diamagnetic ($-1 < \chi < 0$) behavior. This group comprises (besides many others) all kinds of plastics, glass, carbon and non-ferrous metals. It is legitimate to assume that there is a correlation between local χ value and local anomalies of material composition, deformation and stress, which makes it interesting to explore related sensor principles with a potential for NDT application. The challenge is that for para- or diamagnetic materials, c can be ten orders of magnitude smaller than in the case of ferromagnetic materials, which significantly restricts the choice of sensors. The most sensitive options are either SQUIDs (superconducting quantum interference devices) that require cryogenic cooling and are expensive, or precision balances that measure the magnetic force acting upon the substance under test when it is exposed to a magnetic field gradient. The effect in principle is well known and has already been used for levitation experiments.

This contribution however concerns a novel magnetic force based sensor for laterally resolved susceptibility measurement and demonstrates the possible range of NDT applications on the example of different non-ferromagnetic material samples.

1. Introduction

Micromagnetic materials characterization is a well-known discipline of nondestructive evaluation and testing (NDE/NDT). It is based on the interaction of magnetic domain walls (Bloch walls) with microstructure, which is similar to the interaction of dislocations with microstructure [1 – 3]. The resulting correlation between magnetic and mechanical material properties is the basis of magnetic measuring principles that are applied in order to indirectly determine mechanical material properties from nondestructively determined micromagnetic parameters. The correlation between these parameters and mechanical hardness, strength and stress has been thoroughly studied to date, and there are commercial nondestructive testing devices for solving the inverse problem of measured quantity estimation using micromagnetic testing parameters as input [4]. As of today, a high number of non-destructive magnetic techniques for the characterization of ferromagnetic materials have been developed and currently are applied throughout industry and research.

However, not only ferromagnetic materials may be characterized by their magnetic properties. Every material interacts with a magnetic field to some extent, depending on its internal composition and structure. The interactions which define the material's behavior in a magnetic field take place on the micro- and nanometer scale and are partially quantum mechanical in nature. The magnetic susceptibility χ describes how a material interacts with a magnetic field. It indicates the magnetizability, i.e. the relation between magnetization M and applied magnetic field strength H.

It is legitimate to assume that a correlation exists between micro- or electromagnetic and mechanical properties in para- and diamagnetic materials as well. The electrical conductivity of aluminum does reveal some information about material properties which can be assessed non-destructively using eddy current impedance measurements [5]. There is less information regarding the correlation between the mechanical properties and magnetic susceptibility of non-ferromagnetic materials such as graphite, aluminum and plastics. This contribution presents an approach for magnetic susceptibility imaging and its applications in the field of NDE/NDT.

2. Background and approach

The magnetic characterization of para- and diamagnetic materials requires very precise magnetic field sensors such as Superconducting Quantum Interference Devices (SQUIDs), fluxgates, or magnetic force scales. SQUIDs require cryogenic cooling and cause high maintenance costs [6]. High-sensitivity fluxgate magnetometers are already used for susceptibility measurement in the field of geo-exploration [7,8], but they are large and not designed for measurements at a specific position close to a small object, as required for NDT purposes.

Magnetic force scales precisely determine the magnetic attraction or repulsion force between a magnet and a sample, which allows for a very accurate susceptibility measurement. Such devices exist in different implementations, but all of them are designed and used for integral substance analysis only. In Guoy's scale, the test object is held in a way such that the one end of it is suspended near the center of the gap in between the parallel magnet pole pieces where the magnetic field is strong and uniform. The other end of the object lies in a region where there is a gradient in the field just near the gap between the edges of the pole pieces [9]. This gradient in the field and the susceptibility of the object / the displaced medium determine the force on the test object, which is moved by the force. In Faraday's scale, the pole pieces of an electromagnet are placed and shaped in such a way that they produce a small region of linear magnetic field gradient in which a very small-sized test object is placed [9]. This method is not that easy to be used as an absolute method since it is difficult to determine the field and its gradient exactly at the position of the sample [10].

By simplifying a more generalized representation used by Peyman, Geim et al. [11,12] down to one dimension (which is legitimate for a mechanical setup with only one degree of freedom), an equation of the magnetic force F_P acting upon a particle P in a magnetic field gradient can be given as follows:

$$F_P = \frac{\chi_P V_P}{\mu_0} B_x \frac{dB_x}{dx} \quad , \qquad \text{(Eq. 1)}$$

where B_x represents the magnetic flux density in one dimension, V_p represents the volume of a particle, χ_p is the susceptibility of the particle and $\mu_0 \approx 4\pi \cdot 10^{-7}$ Vs/Am in air. Since an actual object is composed of many particles of very small volume dV, the total force F_{total} acting upon the object, assuming that it has homogenous susceptibility χ, is given by the following equation:

$$\mathrm{F_{total}} = \frac{\chi}{\mu_0}\int_V \mathrm{B_x}\frac{\mathrm{dB_x}}{\mathrm{dx}}dV \qquad \text{(Eq. 2)}$$

Even though a bulk object is composed of many particles which are exposed to any distribution of B_x, the total force will therefore always be proportional to χ, and it can be increased by increasing B_x or its gradient. This means that magnet strength and shape determine the effectiveness of the sensor. This is an important factor for sensor design improvement and interpretation of the results.

None of the principles mentioned above are used in industrial NDT today. Existing magnetic force susceptimeters have significant limitations regarding size or shape of the test object. In some devices, only liquids can be tested, while others require a specific geometry. These instruments are designed for materials analysis in the laboratory environment.

This paper proposes a susceptibility sensor principle (patent pending) based on magnetic force measurement which has high potential for industrial application. NDT-related results obtained with a sensor prototype are presented and discussed.

3. Experimental set-up

The novel magnetic force sensor includes a capacitive distance sensor in order to determine the deflection of a cantilever carrying a sensing magnet (Fig. 1). This way, the magnetic force sensor can theoretically be used with common eddy current inspection equipment. The cylindrical sensing magnet has a height and diameter of 10 mm. Under the influence of the sample, the magnet is either repelled or attracted, which leads to a deflection of the cantilever. The output voltage change of the capacitive sensor electronics when approaching a material is proportional to the deflection of the cantilever. When investigating practical materials such as plastics or aluminum, the deflections are so small that the distance between the sample and the magnet changes to a very small extent. In this case, the deflection (or voltage change) is almost proportional to the susceptibility of the material. In order to cover a wider range of susceptibilities with linear response, an actuator with feedback loop would be required in order to bring the magnet back to a zero position.

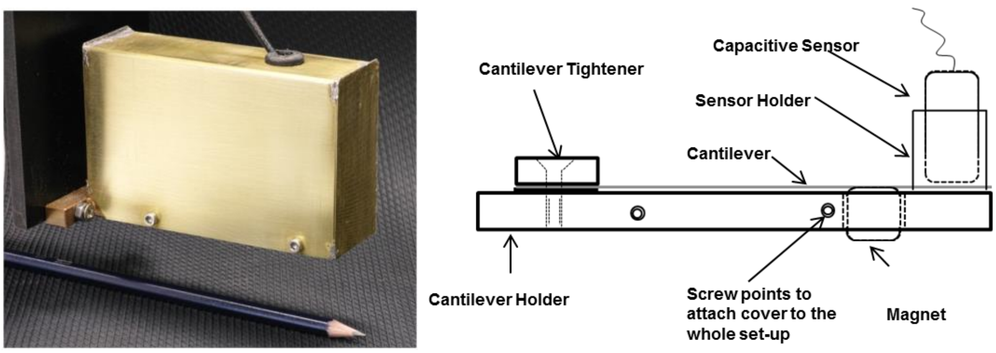

Fig.1. Magnetic force sensor prototype (to the left) and schematic (to the right)

An advantage over regular magnetic field sensors is that far-field influences are suppressed quite well since not only their amplitude but also their gradient is small, which leads to small magnetic forces according to Eq. 2. Nevertheless, additional consideration of these influences is required in order to obtain clean images when scanning sample surfaces. As a downside, the results are highly distance dependent, so precise lift-off control is mandatory. A solution for far-field suppression and drift compensation applied in this context was to scan the sample from two distances, here 1 mm and 7 mm, in each lateral coordinate and then to subtract the two measured voltages from each other. The two distances mentioned above were chosen because at around 7 mm lift-off, there was no noticeable signal any more, and 1 mm was a practically feasible close-up distance for scanning. Fig. 2 shows, using glass slides as an example material, that the (in this case, repulsive) force decays over distance with an exponential law. This also means that maintaining a constant distance throughout the scan is crucial to the image quality, with increasing demands to accuracy as the distance is decreased. The ideal distances and the decay curve depend on the size of the magnet.

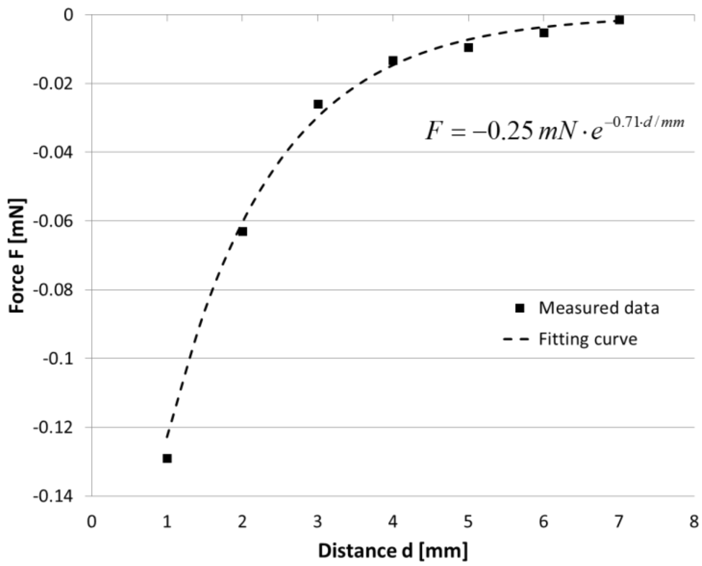

Fig. 2. Diamagnetic repulsion force as a function of distance between magnet and sample (in this case, a stack of glass slides with a total thickness of 5 mm)

4. Results and Discussion

Graphite is one of the most diamagnetic substances at ambient temperature. Images of pyrolytic graphite slivers hovering over neodymium magnets are well known. Fig. 3 shows the results of a scan on a block of (regular, non-pyrolytically grown) graphite (dimensions: 40x40x10 mm). The slight gradient of the measured signal is due to a small distance variation because the sample was not perfectly aligned with the scanning plane. A peak force of about 1.6 mN is observed.

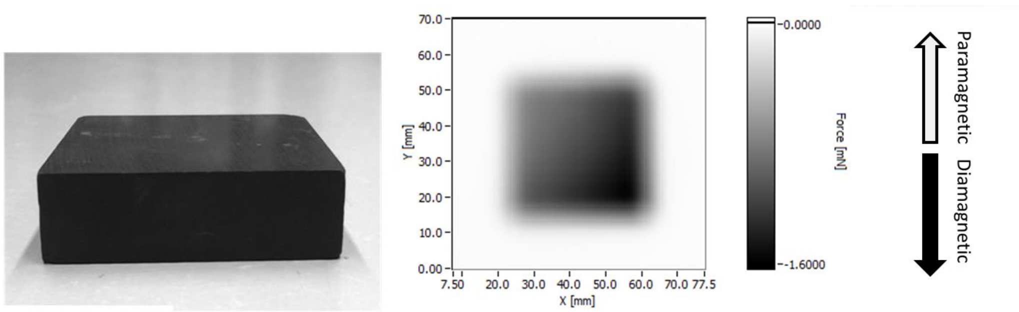

Fig. 3. Magnetic force scan of a graphite block shows diamagnetic behavior

Technical aluminum grades usually are alloyed with other elements in order to optimize them for machining or forming. Some Al alloys were found to be paramagnetic, some were diamagnetic. This may be the basis of aluminum identification systems for recycling and deformation characterization. A block of a typical aluminum alloy sized 40x40x10 mm was scanned using the magnetic force sensor (Fig. 4). The results show that this material is approximately 5 times less paramagnetic than the graphite block is diamagnetic. Moreover, surface-near impurities (probably ferromagnetic dust) are observed. Since the gradient of the magnetic field is strongest at the circumferential edge of the magnet (which is circular), small particles of deviating susceptibility appear as circles in the scan. It has to be noted that the signal/noise ratio still is sufficiently high to produce no apparent noise in the image.

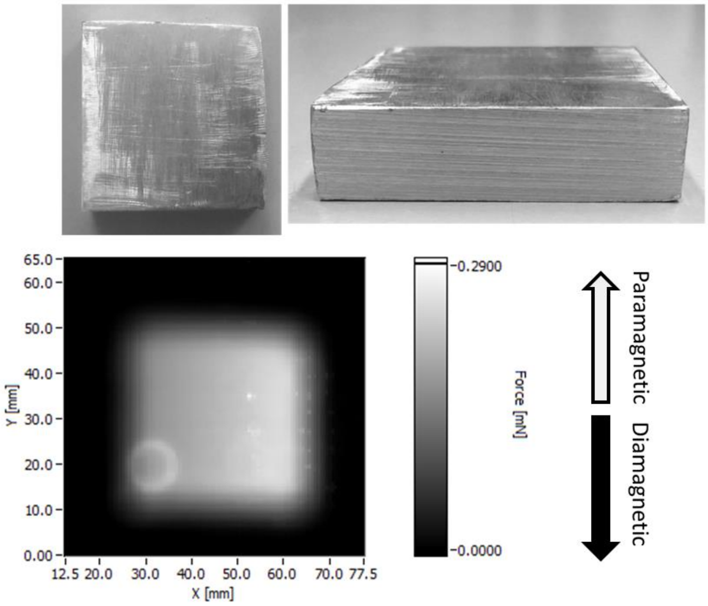

Fig.4. Magnetic force scan of an aluminum block shows paramagnetic behavior with impurities

In a next step, a series of plastics was investigated (Fig. 5). The samples were rectangular, strip-shaped and of different thickness. Most of them showed diamagnetic behavior, only a sample of phenol formaldehyde showed a strongly paramagnetic response, which is probably related to color pigments. Other phenol formaldehyde based materials such as Pertinax did not appear to be paramagnetic. The measurement was repeated three times in order to obtain a measure of accuracy.

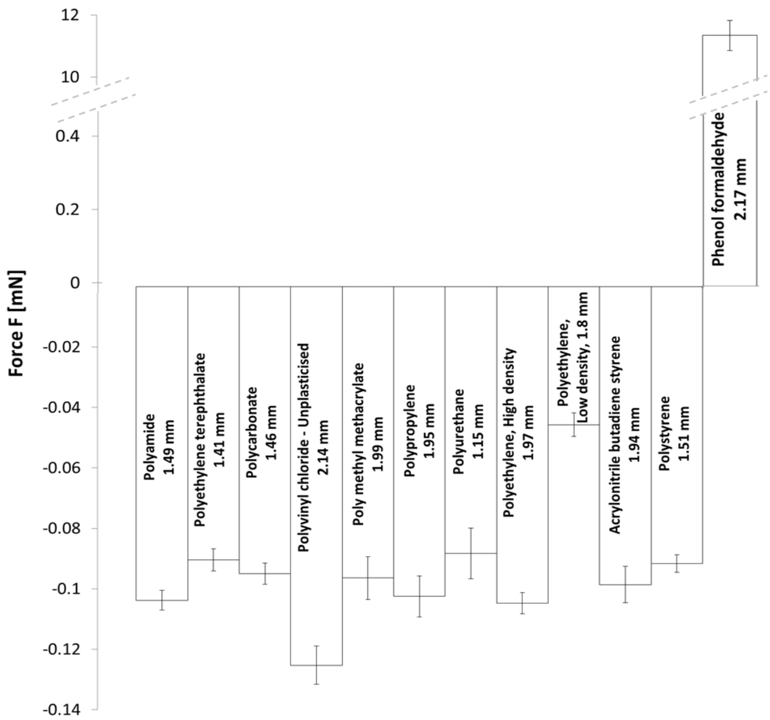

Fig.5. Magnetic force measurement on different plastic materials

Thickness and purity of the materials are reflected in the magnetic force scans as well. Fig. 6 shows a scan of a PVC plate with engraved letters “IZFP” on the back side that was pointing away from the sensor during the scan. The letters are clearly visible in the scan, confirming a thickness dependence of the results.

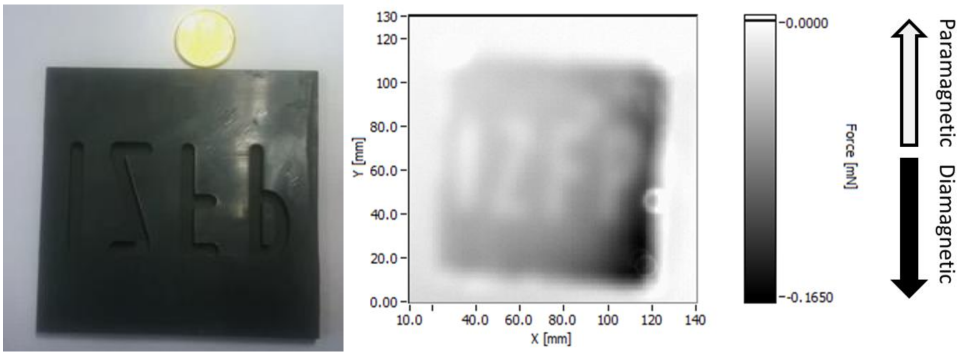

Fig.6. Magnetic force scan of PVC plate with milled letters “IZFP”.

Adhesive bonding becomes an increasingly important industrial technique for joining different materials. In most cases, the materials joined are non-transparent, which makes it difficult to inspect the bonding area for adhesive coverage. Magnetic force susceptibility imaging can display the adhesive distribution between layers of non-ferromagnetic material. As an example, a sandwich of two aluminum plates, each 1 mm in thickness, spaced 3 mm apart from each other, was joined by means of a silane-modified polymer adhesive. The adhesive was applied non-uniformly, representing a local lack of adhesive. Fig. 7 shows that the adhesive spots are clearly identified.

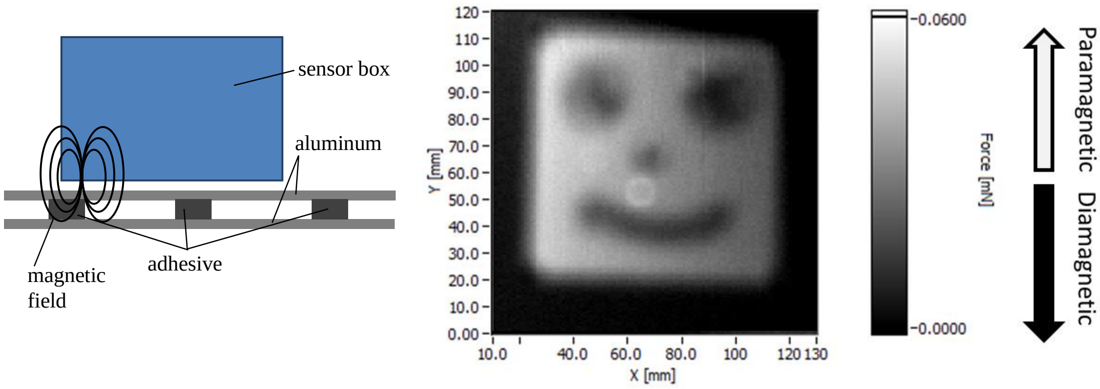

Fig.7. Schematic and scan of an aluminum plate sandwich, glued with silane-modified polymer adhesive

5. Conclusions

Magnetic susceptibility imaging of para- and diamagnetic materials was demonstrated by means of a magnetic force sensor with sensitivity in the low Micronewton range. The principle is based on measuring the force acting upon a permanent magnet in the proximity of the material to be inspected. A cantilever, which carries the magnet is deflected depending on the force. A capacitive sensor measures the deflection distance as output signal, which is then translated into force values. The lateral resolution depends on the size of the magnet, which was cylindrical with 10 mm diameter and a height of 10 mm. The sensitivity was sufficient for all plastics, metals, glass and adhesives investigated so far. Moreover, it was shown that (supposedly ferromagnetic) impurities are detectable.

Future work will focus on the improvement of lateral resolution and scanning speed, e.g. by increasing the magnetic field gradient and lowering the distance between magnet and sample. Possible applications are sensing and tracking of adhesives between opaque surfaces, material identification, inclusion detection and counterfeit identification.

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