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Traveling Wave Magnetic Particle Imaging for determining the iron-distribution in rock

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Abstract

Determining the composition of solid materials is of high interest in areas such as material research or quality assurance. There are several modalities at disposal with which various parameters of the material can be observed, but of those only magnetic resonance imaging (MRI) or computer tomography (CT) offer a non-destructive determination of material distribution in 3D.

A novel non-destructive imaging method is Magnetic Particle Imaging (MPI), which uses dynamic magnetic fields for a direct determination of the distribution of magnetic materials in 3D. With this approach, it is possible to determine and differentiate magnetic and non-magnetic behaviour.

In this paper, the first proof-of-principle measurements of magnetic properties in solid environments are presented using a home-built traveling wave magnetic particle imaging scanner.

Keywords

Traveling Wave Magnetic Particle Imaging, iron-distribution, non-destructive imaging method, solid materials

Introduction

Several modalities are at the material researchers', geologists' or archaeologists' disposal to determine different parameters of solid materials. These include radiologic, acoustic and various diffraction experiments. For example, the iron-content in a sample can be determined by x-ray diffraction, for which the sample must be crushed. Often it is desirable to determine the iron-content or iron-distribution inside solid materials like antique rocks or meteorites without destroying them. MRI or CT provides a non-destructive imaging of the structural composition in 3D. Computer tomographic (CT) devices offer the opportunity to take a close look inside solid materials with high resolution. Because of the differences in the absorption cross section of different materials CT allows to display structural distribution of the atoms. The high absorption cross section of heavy atoms, which rocks typically consists of, requires CT devices capable of producing high-energy x-rays. As a drawback, different phases of one and the same element cannot be differentiated. For example, for iron magnetite and hematite, with magnetite being a magnetic material, yield the same CT signal. In MRI differences in the magnetic behaviour of the material are detectable as negative contrast (they can be used as contrast agents). Unfortunately the very short T_2 relaxation in solid materials often renders MRI a non-optimal method for this kind of studies [1].

In 2005 a novel non-destructive imaging method, Magnetic Particle Imaging (MPI), has been published by Gleich and Weizenecker [2]. It is based on the nonlinear response of ferro- and superparamagnetic materials to varying magnetic fields. A preferably small region of almost zero magnetic field, the so-called field free point (FFP), with a strong gradient (1-7 T/m) is generated by two permanent magnets, which are assembled in a Maxwell configuration. The FFP is driven by electromagnets over the whole sample in order to scan it point by point. Only in the vicinity of the FFP can a MPI signal be detected. Outside the FFP, the magnetic field is sufficiently strong to saturate the magnetic material and supress the generation of MPI signal. The MPI signal created by the resulting changes in magnetic field contains higher harmonics of the excitation frequency, which is due to the nonlinear magnetization response of magnetic material in strong magnetic fields described by the Langevin function.

An alternative MPI scanner design for a fast three-dimensional localization of the distribution of magnetic materials is traveling wave MPI (TWMPI) [3]. It uses an array of electromagnetic loop-coils, the so-called dynamic linear gradient array (dLGA), for the generation of the required strong gradient and the FFP required for scanning the sample [4] (fig. 1 a). In a TWMPI scanner the FFP is moved linearly along the symmetry axis of the dLGA as part of a traveling wave (fig. 1 b). This allows scanning and encoding one line of the sample. Two additional saddle coil systems, which are oriented perpendicular to the main field of the dLGA, can arbitrarily shift the FFP through the field of view (FOV) to cover a full 3D volume [3] (fig. 1 c & d). The proposed TWMPI scanner is designed as a small animal scanner and therefore takes into account the limitations (specific absorption rate – SAR) for tissue [5].

The theory of (TW)MPI and the hardware is based on superparamagnetic iron-oxide nanoparticles, which can be found in contrast agents like Resovist® (Bayer, Germany). Solid magnetic materials inside the scanner distort the magnetic fields and make it difficult to reconstruct the (TW)MPI signal with established reconstruction methods [3][6]. In this paper the feasibility of examining iron-distribution in solid materials is investigated on a rock sample. For validation, the sample is also scanned with a micro-CT device with sufficiently high radiation strength.

Methods and Results

The traveling wave MPI scanner used for this measurements provides a field of view (FOV) of about 65 x 25 x 25 mm³ and can accommodate a mouse-sized sample to be examined in a single scan. It operates at a gradient strength of about 4 T/m generated by the dLGA and yields an intrinsic resolution of about 1-2 mm using superparamagnetic iron-oxide nanoparticles [7].

The dLGA contains 16 electromagnets, which are driven at an excitation frequency f_1 and a phase shift between adjacent elements of 22.5° to create a sinusoidal magnetic field, and also the FFP, traveling along the symmetry axis through the scanner. Two additional coil elements on either side decouple the system electrically to run the dLGA in a stable way at high currents.

Two additional perpendicular saddle coil systems can move the FFP arbitrarily through the FOV to cover a full 3D volume by scanning it line-by-line (line-scanning mode – LSM) [3].

The originally proposed LSM results in a resolution of about 4-8 mm [3], which is too low for small animal imaging.

To improve the resolution of the TWMPI scanner the FFP is moved on a sinusoidal trajectory along a plane (fig. 1 c) by driving one saddle coil system with a much higher frequency compared to the main frequency ($f_2 >> f_1$) [8]. This slice-scanning mode (SSM) results in a better in-plane resolution, which is usable for 2D imaging as well as higher signal gain due to the higher induction at higher frequencies.

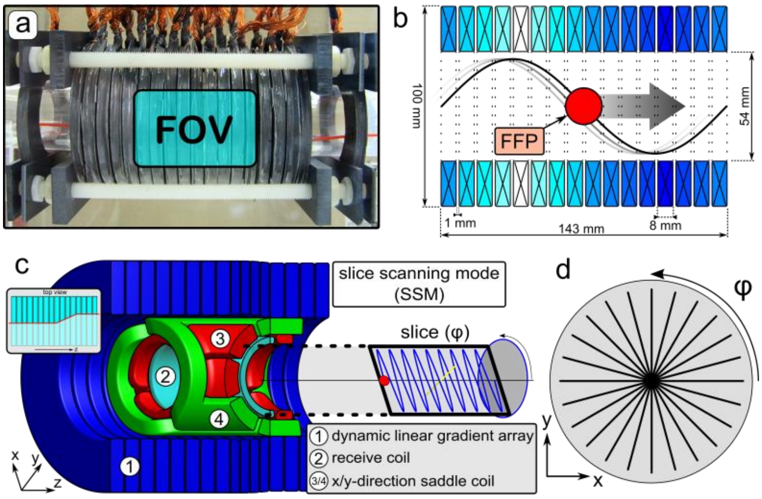

Fig. 1: **(a)** Picture of the home-built TWMPI scanner showing the dynamic linear gradient array (dLGA). **(b)** It contains 16 coil elements, which are driven with an increasing phase shift between adjacent elements to generate a sinusoidal magnetic field with a strong gradient (field free point – FFP). The FFP moves linearly along the symmetry axis through the scanner. **(c)** Sketch of the TWMPI scanner showing the dLGA **(1)** and the receive coil **(2)** surrounded by two perpendicular saddle coil pairs **(3/4)**, which can move the FFP arbitrarily through the volume. The slice-scanning mode (SSM) provides a sinusoidal trajectory of the FFP along a plane through the volume. **(d)** By rotating the scanning slices gradually around the z-axis it is possible to cover a full 3D volume with a high resolution.

For covering a whole 3D volume with a resolution of about 1.5 x 2 x 2 mm³ (z | x | y direction) the 2D scanning-slice is gradually rotated by a specific angle φ around the z-axis (rotating slice-scanning mode – rSSM) (fig. 1 d) [9].

The test sample is a beforehand unknown piece of rock containing ferrous material with a size of about 45 mm in length and about 22 mm in diameter. It was scanned using the TWMPI scanner and the radial technique. By rotating the sample at an angle increment of 7.5 degrees, the full 3D volume was covered by 36 single slices (over 180 degree). With 10 averages the total acquisition time was 7.2 s. In a first step each scanning-slice containing the data of one slice (φ), was processed separately. For that the datasets were gridded point-per-point onto a 2D image according to the trajectory of the FFP. After that a geometry-correction was performed to reduce the distortions caused by the dLGA. The resulting raw data images show the distribution of the magnetic material convolved with the system's point-spread-function (PSF). The PSF depends on the gradient strength of the scanner and the magnetic material examined. Because of the unknown effect of the solid material in the scanned rock, the deconvolution of the data was done using a standard deconvolution-kernel based on the Langevin function and the raw data images were deconvolved using Wiener deconvolution [10]. In a final step, the processed slices were re-gridded into a 3D dataset and reconstructed using a radon transformation [9].

The reconstruction of the TWMPI data shows a very inhomogeneous distribution of ferromagnetic material inside the rock, which can be seen as a 3D magnetization map of the magnetic material (fig. 2 a & b). The projections show the inhomogeneous areas inside the rock and give an idea of the distribution of the magnetic material.

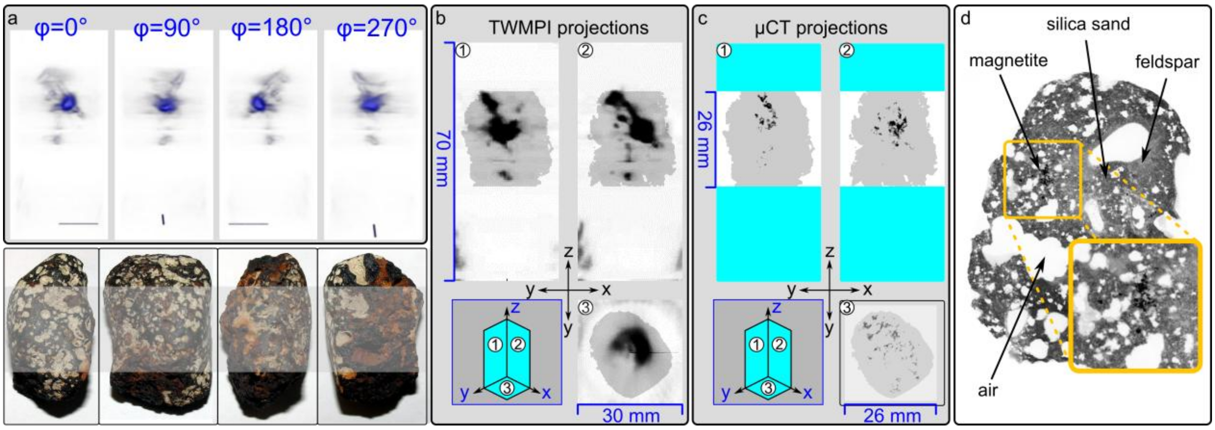

Fig. 2: (a) Reconstruction of the TWMPI dataset shows the magnetization inside the rock. **(b)** Projections of the TWMPI scan show a very inhomogeneous distribution. **(c)** Comparative measurements using a µCT device show in the same areas a high density material. **(d)** µCT section through the middle of the rock: light areas contain air. Darker regions represent feldspar, which absorption rate is lesser than silica sand. Black dots are spots of magnetite.

For comparison an additional 3D scan using a micro-CT device was performed. With an anode voltage of 225 kV and a current of 180 µA the device is strong enough to x-ray the rock. The 2 K detector (Perkin-Elmer flat-panel with columnar CsI-scintillators) acquires 1600 projections with an acquisition time of 999 ms per projection. An additional 0.5 mm copper plate was used to pre-filter the signal. The reconstruction of the 3D dataset (2048 x 2048 x 2048 pixels) using a standard back-projection algorithm results in a highly resolved 3D dataset with an isotropic resolution of 35.4 µm and shows high density material in form of small dots in the same area as the TWMPI data (fig. 2 c).

The rock consists mainly of silica sand and shows regions of feldspar, which can also contain small traces of iron (fig. 2 d). The dark regions are proposed to be magnetite and yield a strong TWMPI signal, as well as a strong attenuation in the µCT data.

Discussion

Contrary to superparamagnetic iron-oxide nanoparticles, which are well known as contrast agents in the MRI and which are used as tracers in the MPI, the behaviour of solid iron material is much less predictable and varies strongly in its magnetic properties. This influences the TWMPI signal quality significantly. Different phases of iron (magnetite, maghemite, or hematite) as well as the core size and the deviation of concentration of the magnetic material result in different behaviour of the TWMPI signal (higher harmonics). Also, anisotropy and relaxation effects influence the signal and distort the 2D point spread function (PSF) of the system. However, for deconvolution of a TWMPI dataset, it is necessary to know the exact shape of the PSF over the whole volume to achieve an intrinsic high resolution. Thus, making quantitative statements on the magnetic material is very difficult because of the PSF depends on the number and the amplitude and phase curve of the high harmonics, which in turn are influenced by the magnetic material under examination. Nevertheless the TWMPI scan shows a structural distribution of magnetic material inside the rock, which is verified by the µCT scan showing in the same areas material with higher absorption cross section with a much higher resolution.

A TWMPI scanner specifically designed for solid material could significantly increase resolution and signal-to-noise ratio (SNR) by increasing the gradient strength and the scanning frequencies.

To overcome the issue of different PSFs and reduce the degrees of freedom of the signal, it is possible to measure with different excitation frequencies. This allows differentiation among various core sizes of particles [11] and could also give in the case of solid material a better result by determining the distribution of several iron-phases in the sample.

Also a 3D magnetic particle spectroscopy (MPS) scanner is an option to acquire spectroscopic information from each voxel in the sample. This information can be compared with fingerprints of materials and allows differentiating between contrasting materials and giving quantitative information on the magnetic material.

Conclusion

In this preliminary test, the feasibility of determining the distribution of iron in solid materials like rocks using the rotating slice-scanning mode (rSSM) for TWMPI scanner was shown. A comparative measurement using a µCT device shows a good agreement for the distribution of the ferrous material inside rock, but cannot give a statement of the phase of the material with the high absorption cross section (e.g. magnetite or hematite). The TWMPI results otherwise show a similar structural distribution of magnetic material and give a first impression of the possibility of determining different iron-phases within solid materials.

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