Investigating the three-dimensional structure of stray fields in the boundary layer at micron scale using angled volumetric scanning

Robert GIBBS, Turgut MEYDAN, Paul WILLIAMS

Wolfson Centre for Magnetics, School of Engineering, Cardiff University, Cardiff, United Kingdom

A new versatile magnetic sensor scanning hardware, developed to volumetrically scan the thin boundary layer fields above a given sample has been developed. Scans of a 25×25 mm sample of Grain-oriented (3% Si) electrical steel have been successfully achieved at resolutions of 50 µm/pixel and 10 µm/pixel indicating domain and micro-domain structures. A new 3D printed sensor head and scanning methodology has been developed to investigate the three-dimensional shape of the stray fields. Initial results show promise in quantifying the extent, shape and amplitude of stray fields in the boundary layer. The fields (±25 A/m at the height of the scan) are initially shown not to extend much beyond 300 µm from the sample surface.

1 Introduction

Observation of magnetic domains using the Bitter technique [1] highlight the domain boundaries due to the presence of stray magnetic fields between domains. The Kerr effect [2] reveals the body of domains through their interaction with polarized light. It might be expected that magneto-resistive sensors in a scanning microscope, measuring stray fields, also highlight the edges of domains where the stray fields are strongest. A three-dimensional scanning magnetic imaging system has been developed based on a *Micromagnetics STJ-020* tunneling magneto-resistance (TMR) sensor with a 5 µm^2 active sensing footprint, with a *Philtec RC20* reflection-compensated fibre-optic displacement sensor for topology tracking. Both are mounted on a custom 3D-printed head assembly. Similar systems have been used to study geological samples [3] and custom permanent magnetic structures [4], but not for domain imaging at this resolution. Successful scans of a 25×25 mm^2 sample of 3% Si Grain-oriented electrical steel, with stray field strength of ± 25 A/m, show clear remanent domain structure at 50 µm/pixel (Fig. 1(b)) and evidence of internal micro-domain structure at 10 µm/pixel resolution (Fig. 1(c)).

Unexpectedly, these domain images have greater similarity to Kerr effect observations than to observations using the Bitter technique. To better understand this, a new methodology is being developed to distinguish and quantify the components of the stray field tangential and normal to the sample surface. The intention is to develop a system for investigating the three-dimensional shape of stray fields in the surface boundary layer; to quantify how stray fields vary spatially with the underlying domain structure. Preliminary results of this methodology are presented here.

2 Hardware Development and Initial Results

A new 3D-printed head assembly has been designed, Fig. 1(a), which facilitates the tilting of the *STJ-020* TMR sensor ±5° about the z-axis (normal). The scanner head assembly is mounted on a *Parker Automation* 3-axis plotter system which has been calibrated to a positioning accuracy of ± 1 µm. Initially the limitations of the prototype 3D-printed head assembly reduces confidence in positioning to ± 50 µm, but future precision mechanics will bring this uncertainty in line with the ± 5 µm limitation of the sensor itself. The system allows for a full volumetric scan of the boundary layer to be made. In Fig. 1(e) a 2×2×0.4 mm^3 volumetric scan of the sample is presented at 100 µm/voxel resolution. A further 10 µm/pixel repeated scan of the first (z_o) layer is presented in Fig. 1(f). The individual z- and x-axis components of the field are calculated from two corresponding scans of the sample with the sensor tilted ±5° about the normal.

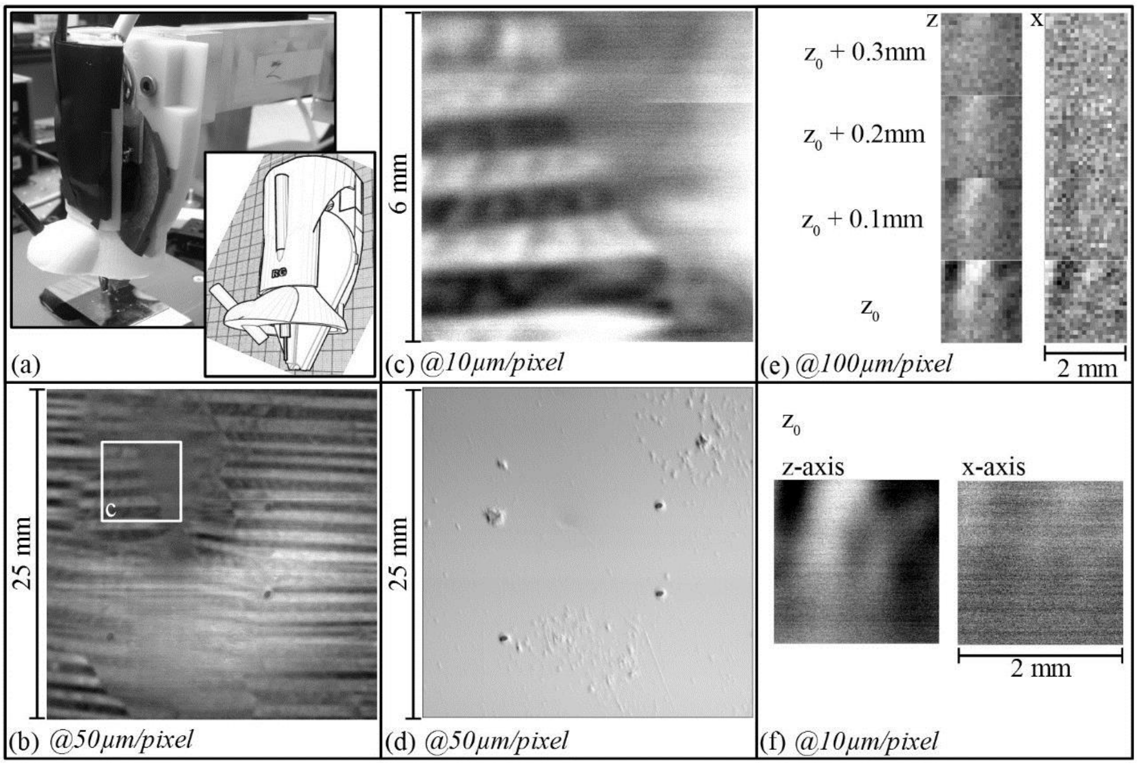

Fig. 1: (a) 3D printed scanner head assembly supporting a *Micromagnetics STJ-020* TMR sensor on a stage allowing ±5° tilt about z-axis and fixed *Philtec RC20* z-axis displacement sensor (b) Scan illustrating domains in 25×25 mm^2 of 3% Si Grain-Oriented electrical steel (c) 10 µm/px resolution scan of the 6×6 mm^2 subset, showing evidence of sub-domain structure (d) Topology scan showing four corresponding "pin-holes" and depressions in sample, height-range 0.35 mm (excluding holes) (e) Volumetric scan of 2×2×0.4 mm^3 of the boundary layer above the sample combining two ±5° tilt scans to calculate the z- and x-axis components (f) Repeat of the z_0 layer at 10 µm/px. Magnetic scans are grayscale mapped ±25A/m, x^+ towards right, z^+ out of page, white positive.

3 Conclusions

Although preliminary, the results show promise in quantifying the extent, shape and amplitude of stray fields in the boundary layer. The fields are shown not to extend much beyond 300 µm from the sample surface and have maximum strength ±25 A/m at the scanning height. The results are not yet clear enough to ascertain clearly whether the measured stray fields emanate from the domain boundaries or from the domain body. These initial results are noisy. The x-axis component is severely under-sampled by the ±5°, tilt which was chosen for ease of fabrication. Better mechanics will allow a greater angle of tilt and improve the positional accuracy and alignment of the two scans. The minimum distance from the sample surface (z_o) will be reduced from ~ 70 µm to < 7 µm by sensor lapping, which should greatly improve the resolving power of the micro-domain features in Fig. 1(c). Improvements to the shielding of the system will reduce background noise from the Earth's field and other external sources.

References

[1] Bitter, F. Experiments on the Nature of Ferromagnetism. *Physical Review* **41** (1932) 507-515

[2] Kerr, J. On the rotation of the plane of polarization by reflection from the pole of a magnet. *Phil. Mag. 5th Series* **3** (1877) 321-343

[3] Lima, E. A. *et al.* 2014. Scanning magnetic tunnel junction microscope for high-resolution imaging of remanent magnetization fields. *Meas. Sci. Technol.* **25** (2014) 1-14.

[4] Huber C. *et al.* 3D Print of Polymer Bonded Rare-Earth Magnets, and 3D Magnetic Field Scanning With an End-User 3D Printer. *Appl. Phys. Lett.* **109** (2016) 162401-1-162401-4