Multi-Scale Models of Granular Magnetic Materials at High Temperatures

Author
Jonathon Waters

Supervisory Team
Hans Fangohr, Denis Kramer and Ondrej Hovorka

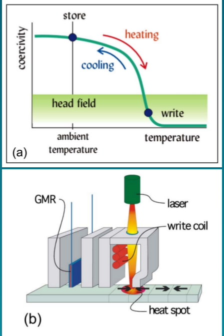
EPSRC
Engineering and Physical Sciences Research Council

UNIVERSITY OF Southampton

Introduction

In HAMR[1]:

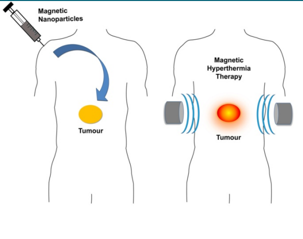
- T_C distribution affects the noise performance



E. Dobisz et al. Proc IEEE 96.11, 1836 (2008)

In Magnetic Hyperthermia[2]:

- Low T_C reduces tissue damage



Ângela Andrade et al. Coating Nanomagnetic Particles for Biomedical Applications (2011)

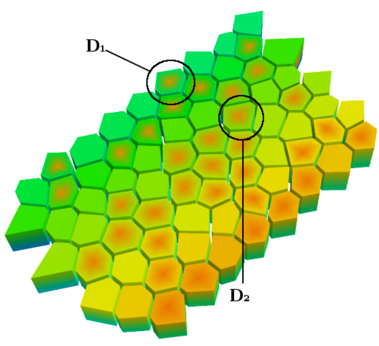
[1] D. Weller et al. IEEE Transactions on Magnetics 50.1, 3100108 (2014)

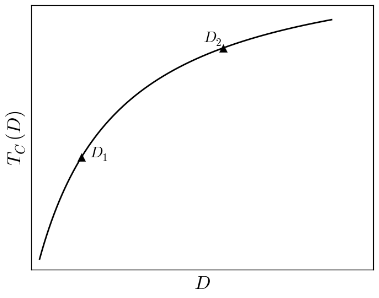
[2] I Apostolova et al. Solid State Communications 149.25, 986 (2009)

Defining Finite Sized T_C

Correlation length $\propto |T - T_C^b|^{-\nu}$

Grain size, $D \propto |T_C(D) - T_C^b|^{-\nu}$





Distribution in D leads to distribution in T_C

$$f_D(D) \implies f_{T_C}(T_C)$$

Currently Used Methods

- Explicit measurement of individual grains.[3]
  - Switching temperature is measured by a laser system set up. This is related to T_C
  - Very little agreement between methods
  - Currently only applicable to HAMR
- Identification from macroscale measurements[4]
  - Single measurement with magnetometer
  - Integral measure
  - But uses bulk relations

[3] S. Pisana et al. IEEE Transactions on Magnetics 51.4, 1 (2015)
[4] A. Berger et al. J. Appl. Phys. 91.10, 8393 (2002)

9 Month Objectives

- Develop a universal method to identify the T_C distribution which incorporates the finite size effects of the individual grains
- Test the method against a well quantified benchmark (2D Ising system) in order to verify it's effectiveness for different distributions.

Our Method

Magnetisation for Ensemble of Grains:

$$\mathrm{M(T)} = \mathrm{M_0} \int_0^{\infty} \mathrm{D^d m(D,T) f_D(D) dD}$$

Single Grain Magnetisation:

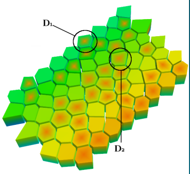
$$\mathrm{m(D,T)} \propto \mathrm{D}^{-\beta/\nu} \tilde{\mu} \left(\mathrm{D}^{1/\nu} \frac{\mathrm{T} - \mathrm{T_C^b}}{\mathrm{T_C^b}} \right)$$

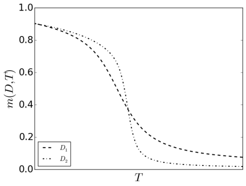
Change of Variables:

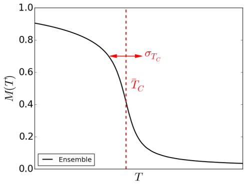
$$\mathrm{D} = \mathrm{d_0} \left(\frac{\mathrm{T_C^b} - \mathrm{T_C(D)}}{\mathrm{T_C^b}} \right)^{-\nu}$$

Final Result:

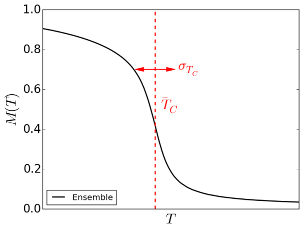
$$\mathrm{M(T)} = \mathrm{M_0^*} \int_0^{\mathrm{T_C^b}} \mathrm{t}^{-\mathrm{d}\nu+\beta} \tilde{\mu} \left(\frac{\mathrm{T} - \mathrm{T_C^b}}{\mathrm{t}} \right) \mathrm{f_t(t) dt}$$

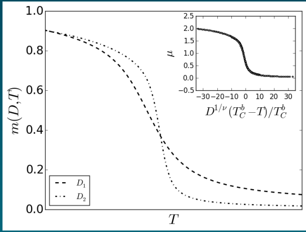






Finding f_t





$$M(T) = M_0^* \int_0^{T_C^b} t^{-d\nu+\beta} \tilde{\mu}\left(\frac{T - T_C^b}{t}\right) f_t(t) dt$$

- $M(T)$: To be fitted
- d, ν, β, $\tilde{\mu}$: Known information about the material
- T_C^b: May be known, otherwise taken from fit
- M_0^*, f_t [$\bar{t}$, σ_t]: Taken from the fit

$$\bar{T}_C = T_C^b - \bar{t} \qquad \sigma_{T_C} = \sigma_t$$

Test Case: 2D Ising Model

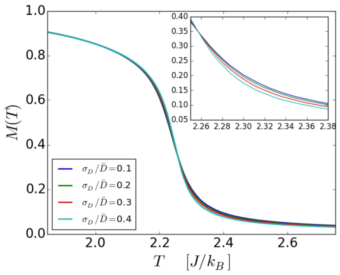
$$M(T) = M_0^* \int_0^{T_C^b} t^{-d\nu+\beta} \tilde{\mu} \left(\frac{T - T_C^b}{t} \right) f_t(t) dt$$

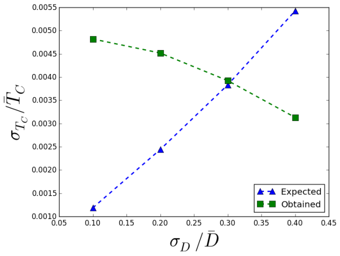
Used 2D Ising model as a benchmark:

- Simulated using Monte Carlo
- Analytical results for β, ν, T_C^b
  - $\beta = 1.25$
  - $\nu = 1$
  - $T_C^b \approx 2.269$

Tested against different f_D:

- All mean $\bar{D} = 100$
- Standard deviation $\sigma_D = 10, 20, 30, 40$





Test Case: 2D Ising Model

Introduce constraint[5]:

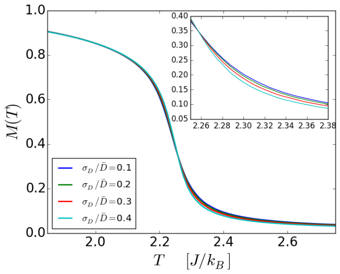
$$\Rightarrow \sigma^2_{\mathrm{T_C}} = (\mathrm{T^b_C} - \bar{\mathrm{T}}_\mathrm{C})^2 \left(\left(1 + \frac{\sigma^2_\mathrm{D}}{\bar{\mathrm{D}}^2} \right)^{1/\nu^2} - 1 \right)$$

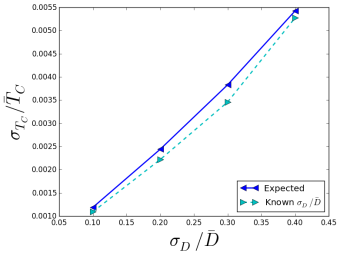
In the Ising model:

$$\nu = 1$$

$$\Rightarrow \sigma_{\mathrm{T_C}} = (\mathrm{T^b_C} - \bar{\mathrm{T}}_\mathrm{C}) \frac{\sigma_\mathrm{D}}{\bar{\mathrm{D}}}$$

Fitted results far better!





5 O. Hovorka et al. Appl. Phys. Letters 101.5, 052406 (2012)

Conclusions

- Universal method to find size dependent $\mathrm{T_C}$ distribution based upon fitting ensemble magnetisation:

$$\mathrm{M(T)} = \mathrm{M}_0^* \int_0^{\mathrm{T_C^b}} \mathrm{t}^{-\mathrm{d}\nu+\beta} \tilde{\mu} \left(\frac{\mathrm{T} - \mathrm{T_C^b}}{\mathrm{t}} \right) \mathrm{f_t(t)dt}$$

- Successfully tested against 2D Ising model (without a loss in generality) and found a strong parameter correlation which can be solved by the constraint:

$$\sigma_{\mathrm{T_C}}^2 = (\mathrm{T_C^b} - \bar{\mathrm{T}}_\mathrm{C})^2 \left(\left(1 + \frac{\sigma_\mathrm{D}^2}{\bar{\mathrm{D}}^2} \right)^{1/\nu^2} - 1 \right)$$

Acknowledgements

In the completion of this work, we acknowledge financial support from the EPSRC Centre for Doctoral Training grant EP/L006766/1.

We also acknowledge the use of the IRIDIS High Performance Computing Facility, and associated support services at the University of Southampton.

Contact: J.M.Waters@soton.ac.uk