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Invited paper

The past, the present and the future of soft magnetic materials

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Abstract

In this closing talk at SMM14, the *past* featured J.A. Ewing, the major figure in ferromagnetism a century ago, and his book *Magnetic Induction*. The book *Magnetic Domains* by Alex Hubert and Rudolf Schäfer provided the *present*. Visualizations of three dimensional magnetization patterns in a soft iron cube indicated a *future* direction and the need for webpages for communication of complex results. © 2000 Published by Elsevier Science B.V. All rights reserved.

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The organizers asked me to close the conference with a talk on 'The past, the present and the future of soft magnetic materials'. I took this opportunity to reintroduce a European audience to J.A. Ewing, the father of magnetism in Japan and in England, and to pay tribute to Alex Hubert, a great magnetician of the current period, who died last spring at 60. Both left behind books which should be appreciated 100 years from now as much as many appreciate all that Ewing did more than 100 years ago. The visualization of magnetism in three dimensions is an obvious future extension of the work begun by Ewing [1] and so well brought up-to-date by Hubert and Schäfer [2]. I chose to simulate the reversal of magnetization in a cube of iron with 100 nm edges as an example. The simulation was continuing on my departure for Budapest, thus some of the results were still in the future. Some remain there because of a hard disk problem.

Ewing's remarkable career is well documented [3,4]. I hope someday to read his autobiography, *An Engineer's Outlook*, published by Methuen. He arrived at Edinburgh University as the first school boy from Dundee to make it there on an engineering scholarship. In a few years he became the protégé of the leading Scottish scientists. Lord Kelvin had Ewing at 19 aboard his cable-laying ship off the coast of South America. At 23 Ewing was appointed full professor at the Imperial University of Tokyo. There he built the first recording seismograph and tracked the course of some 300 earthquakes. He studied the effect of stress on thermocouple wires, rediscovering mechanical hysteresis and independently finding magnetic hysteresis. Ewing gave hysteresis its name [5].

In his famous paper, Experimental Researches in Magnetism, communicated by Sir William Thompson (Lord Kelvin), Ewing says, 'I found it convenient to have a name for this peculiar action, and accordingly called it Hysteresis (from $\nu\sigma\tau\epsilon\rho\epsilon\omega$, to lag behind)'. He footnotes this with references to Proceedings of the Royal Society, No. 216, 1881, p. 22 and No. 228, 1883, p. 123. In an adjacent footnote he says, 'The results to be described below were all obtained before I became acquainted with the recent work of Warburg on the same subject (Wied. Ann., XIII, p. 141)'.

The history of magnetism in Japan starts with Ewing and is recounted in a talk given by Chikazumi [6] at the International Conference on Magnetism in Japan in 1982 on the 100th anniversary of Ewing's discoveries. The line continues with K. Honda, who founded the Institute of Iron Steel and Other Metals at Sendai. Honda and his student S. Kaya are famous for the first measurements on single crystals of iron, cobalt and nickel. Professor Kaya went on to become the President of the University of Tokyo and a principal advisor to General MacArthur on the rebuilding of Japan. Chikazumi's paper has photographs of Ewing, Honda and Kaya. As a young man I had the good fortune to spend 10 years learning magnetism from H. Sato, who was a student of Kaya and married to Honda's granddaughter. Assuming that every

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one knows what I know, I was surprised at the conference by a slide on the history of soft magnetism in Japan which had as its first entry Pierre Weiss in 1907 but no mention of Ewing, who had mastered much of ferromagnetism some 20 years earlier.

I knew that there was a problem in Europe in maintaining the legacy of Ewing, because, for all the praise that I will put later on the book by Alex Hubert and Rudolf Schäfer, they make no mention of Ewing. But I did not expect that to be the case in Japan. The decline from dominance in ferromagnetism of Ewing's contributions was partly because there were many, including Ewing himself, who took Ewing's model too seriously. Later, he acknowledged that dipolar interactions could not quantitatively explain what we all know now as the effects of the quantum mechanical exchange interaction. Bozorth [7] in his classic *Ferromagnetism* from 1951 starts his discussion of the theory of ferromagnetism with a section on Ewing's theory, and why it is not fundamental, without sufficient emphasis on all that Ewing got right. Fortunately, Ewing is still revered in the United Kingdom where the UK Magnetics Society sponsors the annual Ewing Lecture [8] and Professor Beckley [9] still has a working Ewing magnetometer in his laboratory in Cardiff.

Ewing received renewed recognition in 1999. Ewing plays a role in *Code Breaking, A History and Exploration* by Rudolf Kippenhahn [10]. The first two capters are introductory, Chapter 4 is on Julius Caesar and Chapter 10 is on Alan Turing and the Enigma. Chapter 3 is the story of how British Naval Intelligence broke the German code in World War I and how an intercepted message brought the United States into the war against Germany. The hero of that chapter is J.A. Ewing, the head of Room 40 in the Admiralty. Ewing is introduced to the readers as one who discovered hysteresis. Though I told some of Chapter 3 in my talk, I will leave it here as a reference so as not to spoil a good story.

When Ewing returned to Scotland from Japan after five years, he started engineering and physics at the University of Dundee. He was honored there by the Ewing Building [11]. It was opened in 1954, and was the first major new building for the University of Dundee since the first world war. An excellent picture of Ewing as a young man can be found on the web pages of the university archives at Dundee [12]. It was in his chair of engineering at Cambridge that he had the most profound influence on technical education in the United Kingdom. He is credited with making engineering respectable at Cambridge and Oxford. Just after the turn of the century, when the British Navy decided that it could no longer rely on the sea to educate its officers, the Admiralty turned to Ewing to create an educational program for naval officiers. Later it was Ewing's chance remark to a friendly admiral that he enjoyed doing cryptograms that led to his becoming the head of naval cryptology at the age of 59 just before the Great War started. From near the end of the war to the early 1930s Ewing took over the reins of the University of Edinburgh and has been widely praised for bringing it to the forefront of education in the UK.

In April 1929, Sir James Alfred Ewing, KCB was given the Freedom of the City of Edinburgh: 'As a mark of the high esteem in which he is held by the citizens of Edinburgh, in testimony of his valuable services to the city, and in recognition of his brilliant and distinguished career as Principal of the University of Edinburgh during a period marked by exceptional difficulty on account of the war and also by unprecedented development and the expansion of the University'. This citation was found at http://www.efr.hw.ac.uk/hisc/digest/ewin1.html. This site also quotes from a speech he gave to the Institution of Civil Engineers in 1928 in which he said:

'There are people who talk glibly of the next great war. I wonder if they know how near, in the last Great War, the world came to destruction through misapplying the endowment which it owes to the engineer. Do they realise that with added experience and further malignant ingenuity, the weapons of a future war will be more than ever deadly, more than ever indiscriminate, and the peril to civilization will be indefinitely increased?'

I told the audience that I want a new generation to read Ewing's book, *Magnetic Induction*, to see for themselves how much he learned and understood about magnetism more than a century ago. I claimed that if he were to have attended the present conference he would have understood much of the discussion. And if he had spent the weekend before the conference reading Hubert's and Schäfer's book, Magnetic Domains [2], he would have understood almost all the rest. (Their book discusses more than 1500 references.) One thing that surely would have puzzled him would have been the papers on vector Preisach diagrams (which Hubert and Schäfer mention on the last page of their book). In 1885 he predicted that rotational hysteresis should disappear when the magnetization closely follows the magnetic field at high fields. This was confirmed a year later. As far as I know, one cannot extract that simple result from current vector Preisach models.

How did Ewing know as much as he knew without knowledge of exchange or anisotropy? The answer is that he made many experiments with his recording hysteresographs showing all the minor loops, including the effects of stress and temperature. He knew about many things that I rediscovered years later when I defined the ideally soft magnetic material as one in which the anisotropy is negligible and all the magnetic charge goes to the surfaces (see Ref. [13]; see also Ref. [14]). He fully understood demagnetizing fields and why magnetostatic interactions are dominant in iron and other soft magnetic materials. His expertise in magnetic measurements would surpass that of most any student of magnetism today.

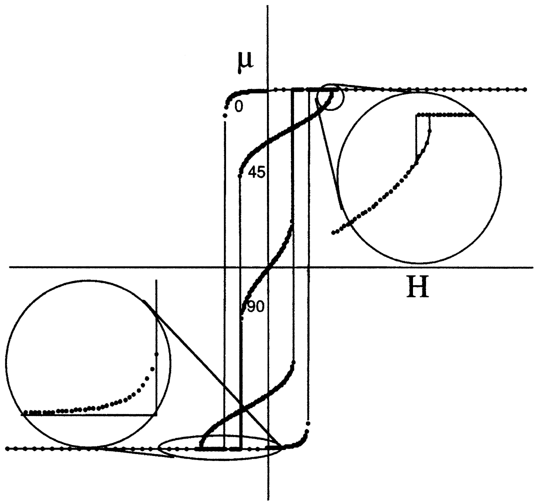

Fig. 1. Calculation of the component along the applied field direction of the magnetic moment of four extended dipoles at the corners of a square. The curve labeled 0 is for starting the four dipoles aligned in the direction of the field parallel to one edge of the square. The inset at the lower left shows the approach to saturation. The curve labeled 90 starts with the dipoles aligned perpendicular to the field. It illustrates an initial reversible susceptibility followed by a rapid magnetization almost to saturation, after which the loop is the same as the curve labeled 0. The curve labeled 45 is for the field along the diagonal of the square. The inset in the upper right shows a small amount of hysteresis near saturation.

Ewing's understanding came from a simple model that has the major ingredients of micromagnetics. His interacting extended dipoles give hysteresis, a low initial susceptibility, a high permeability during irreversible switching, and an approach to saturation very much like $1/H^2$. He had a threshold and an upper limit to rotational hysteresis. He made two-dimensional arrays of 24 extended dipoles and measured what happens in a uniform applied field. He saw domains. The extended dipoles have anisotropy depending on the arrangements of the dipoles. There are both short-range interactions, from the north pole of one magnet interacting strongly with the south pole of its neighbor, and long-range interactions, from the far dipoles in the arrays. He had a clear vision that explained the many experiments he made with real magnetic materials. Ewing's experiments on four extended dipoles is simulated, as shown in Fig. 1, using a simple program for the interaction of the eight charges on the ends of four rigid rods.

I showed many examples from Ewing's book and from his 1885 classic paper. (I have an original off print with his autograph.) These include the phenomena that Neél would describe later and name *reptation*. I talked about Hubert's and Schäfer's book and how much we know and understand about domains from their work. Most of this is visual and can be enjoyed by any student of physics, engineering or art. I strongly recommended it as required reading for students of magnetism and to anyone interested in the power of a strong interaction between experiment and theory; something that Ewing knew very well.

In talking about our present understanding, I noted that we are still in the stage initiated by Ewing. We have two-dimensional views of magnetic structure, because most of our images come from studies at surfaces. In the future we should have better access to three-dimensional pictures. I pointed out that some of that future was already here in the poster presented by Schäfer [15], using a metallurgical trick by which the domain structure gets written into the grain structure. Then he was able to slice the body without changing the image of the domain structure.

In the spirit of Ewing I showed a modern calculation of a soft magnetic material in the form of a single-crystal cube of iron $100 \times 100 \times 100\,\mathrm{nm}^3$. I explained why it was necessary to use a grid size not exceeding $2 \times 2 \times 2\,\mathrm{nm}^3$ by showing configurations during the reversal of that cube in which $2 \times 2 \times 2\,\mathrm{nm}^3$ borders on having a too rapid change in magnetization from one grid point to the next. I used this example to represent both the present and future of soft magnetic materials because the dynamic demagnetizing process that I was following was only partially complete when I left to attend the conference. The future would be the result that was waiting for me when I returned. It remains the future as I write this because of the size of the file that contains the full dynamics of what happens to the cube when a magnetizing field $\mu_0 H = 1.6\,\mathrm{T}$ is removed quickly, where quickly means less than a picosecond. The file is 2.6 GBytes. The program I am using is Prof. Michael Scheinfein's LLG micromagnetic simulator, which is commercially available. It can take a big file like that and play back movies of the dynamic response but only in pieces smaller than the active memory, which in my machine is only $\frac{3}{4}$ GBit. LLG takes the big file and splits it in half as many times as necessary, but it requires that the disk drive have a capacity twice the size of the file. As my largest disk drive is 4.1 GBytes, I can only see the first half of the file.

I do have the last time frame of the whole file. So I know what happens then, but not how the magnetization changes from the end of the first half of the file to the last time frame of the whole file. When I got back from Hungary and realized that I was in trouble because of the size of the file, I captured what was happening before I stopped the calculation. After 600 ps the spins were still precessing but about a configuration that is very close to an equilibrium state in zero field.

Scheinfein's LLG micromagnetic simulator presents three-dimensional images by allowing the viewer to move through the images and to rotate them. Coordination of the visual field with hand movements on the mouse or keyboard adds much to the grasp of the complex

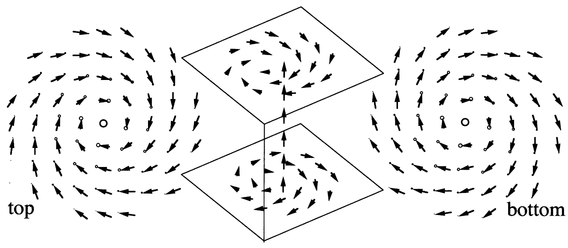

Fig. 2. Part of an equilibrium magnetization pattern for an iron cube with 100 nm sides showing that the two ends of a vortex of magnetization are not equivalent because the minimization of the divergence of M is different if the magnetization points away from the singularity, as it does on the bottom surface, and into the singularity, as it does on the top surface, see Eq. (2).

patterns. That cannot be translated to current methods of publication of scientific results, but this is soon to change through the use of the internet and personal websites. I hope to create a site where anyone can manipulate the LLG files to view any aspect of the results of the calculation with all the ease that one has at the terminal on the machine that created them. A safe prediction for the future is that this sort of publication will become common place.

It is a challenge to convey on paper just two visualizations from that calculation. One is the breaking of symmetry in an equilibrium configuration that has axial symmetry. The patterns on two opposite faces perpendicular to that axis differ as shown in Fig. 2. The cause of this difference is in the nature of a divergence in three dimensions. The other visualization requires frames from the movie that shows the dynamical reversal of the magnetization along that axis. The reversal occurs because there can be an extremely large concentration of exchange torques to create a pair of point singularities in three dimensions.

A divergentless point singularity exists just outside the center of the upper and lower ends of the symmetry axis along the z direction of the cube [16,17]. A divergentless point singularity is generated by a single component of a simple vector potential in polar coordinates

$$A_\phi \pm (r/2)\sin\theta\cos\theta \tag{1}$$

from which the magnetization is given by

$$M_r(r,\theta) = (M_s/r\sin\theta)\partial A_\phi \sin\theta/\partial r$$
$$= \pm M_s(3\cos^2\theta - 1)/2, \tag{2}$$
$$M_\theta(r,\theta) = -(M_s/r)\partial r A_\phi/\partial r = \mp M_s \sin\theta\cos\theta \tag{3}$$

and the $M_\phi(r,\theta)$ component is found from knowing that the length of the magnetization vector is M_s. The center of the spherical coordinate system is at the bottom of the vortex at one end, and there is another singularity centered at the top of the vortex. The sign of the vector

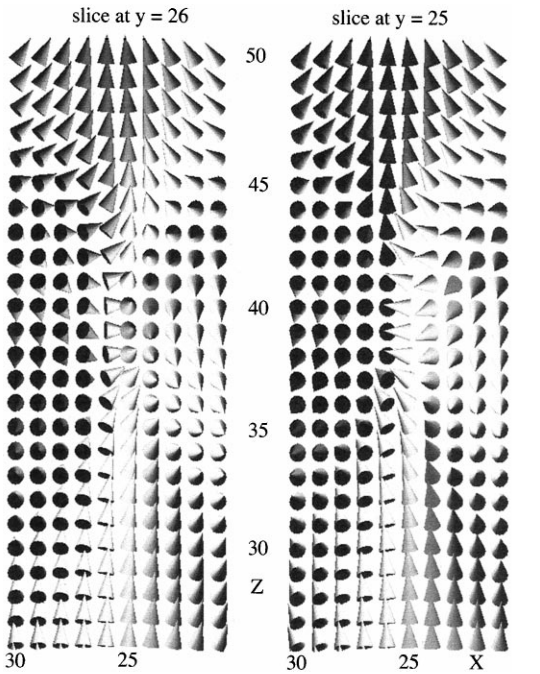

Fig. 3. The creation of a pair of singularities along the central axis during the dynamical approach to a low-energy state after a large field, 1.6 T, is suddenly removed. The $100\times100\times100\,\mathrm{nm}^3$ cube of iron is divided into 125 000 cells. The central axis along z is between slices 25 and 26 in y and between columns 25 and 26 in x. The cells at $z = 39$ about the central axis are about to reverse under the strong torque provided by the exchange as the surrounding moments precess in the demagnetizing fields of their neighbors. After a few picoseconds later the reversal begins to propagate up and down the z-axis. A similar, but not identical pair creation takes place slightly later on the lower half of the axis (not shown). A full treatment of the core of the reversal is beyond the limitations of classical micromagnetics.

potential changes from top to bottom. M_r will be into the singularity at the top and out of the singularity at the bottom. At $\theta = 0 M_r$ is along the z-axis. At $\theta = \pi/2$ the magnetization lies in the plane of the top or bottom surface with $M_r = -M_s/2$ at the top surface and $M_r = +M_s/2$ at the bottom surface. For a lower energy it is desirable to have the M_ϕ components in the same direction with magnitude $\sqrt{3}\,M_s/2$. This is illustrated in Fig. 2.

When the cube is almost saturated in the z direction, the flower state persists with the magnetization in the four upper corners pointing slightly towards the outward-going body diagonals and the magnetization in the four lower corners pointing slightly towards the inward-going body diagonals. When the external field is removed, in a time short compared to the precession frequency of the corner moments in the remaining demagnetizing fields, the corner moments precess about fields that are along the $\{1\,1\,0\}$ directions and outward on the top surface while inward on the bottom surface. This starts the relaxation process with the curling pattern along the edges on the top surface counter clockwise, while it is clockwise on the bottom surface (when both are viewed from the top). As it is lower energy to have the rotations in the same sense, the magnetization has a problem to solve dynamically.

Part of that solution starts with the formation of a line of upward pointing moments along the z-axis of the cube, followed by the reversal of the magnetization along that axis by the formation of pairs of point singularities in two places on the axes. The pair formation process is a delight to behold in three-dimensional movies. In the future this will be made available through a web page along with a mathematical representation of the process. For the present just a small part of the process is illustrated in Fig. 3.

My presentation ended with a tribute to Alex Hubert showing how his insight made it possible for me to achieve quantitative agreement between experiment and theory for the critical field and critical axial current at which a small term from magnetostriction dominates the magnetization process in an iron whisker with five do mains [18]. My final words reflected the thoughts of many, ‘Thank you, Alex’.

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