Magnetostriction

Corey Anderson

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Abstract

This report presents the findings of an experimental study on the magnetostriction behaviours of nickel, iron, and copper samples using an interferometer setup. The experimental trends observed in the study were found to be in agreement with the theoretical values predicted for each material. The nickel sample exhibited consistent contraction with increasing magnetic field, while the iron sample initially expanded and then contracted. No change was observed for the copper sample due to its non-ferromagnetic nature. The contrasting behaviours were attributed to the orientation of magnetic domains relative to the magnetisation direction. Uncertainties arising from vibrations, including thermal vibrations, were identified as significant sources of measurement error. Mitigation measures, such as wearing padded shoes and allowing for solenoid cooling, were suggested to reduce these uncertainties. The experimental results provide valuable insights into magnetostriction phenomena and demonstrate the applicability of the interferometer setup in studying magnetic material behaviour.

Contents

1 Theoretical Background

1.1 Magnetostriction

Ferromagnetic substances undergo magnetic distortions, i.e. they exhibit a length change parallel to the direction of magnetisation when a external magnetic field H is applied. This phenomenon is known as magnetostriction and is caused by a magnetic field aligning the domains, resulting in a length change.

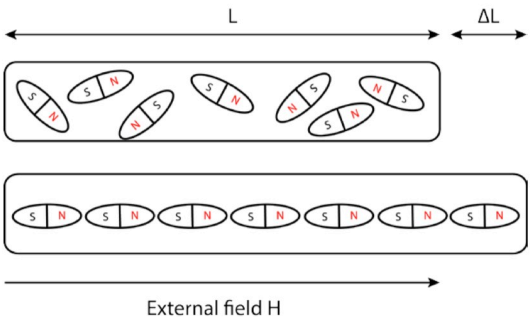


Figure 1: Upper panel shows zero magnetisation. Lower panel shows the aligning of domains under an external magnetic field H. This causes an elongation of the sample by ΔL

1.2 The Michelson interferometer

The change in length ΔL due to magnetostriction is very small. For this reason we will use an interferometer which is extremely sensitive to small variations in length. We will place one of the mirrors M_3 onto the sample and the variations in length will shift the mirror which will be detected by the interference pattern.

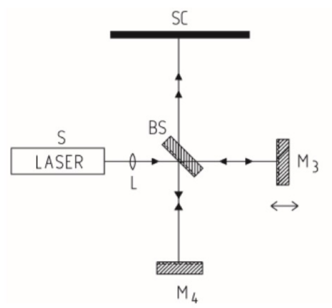


Figure 2: The Michelson Interferometer

Let the distance between BS and and M_4 to be distance a and BS to M_3 to be distance b. Then

$$OPL = 2(b-a) = \frac{n\lambda}{2} \tag{1}$$

$$b - a = \frac{n\lambda}{4} \tag{2}$$

Now let b_0 and a_0 be the initial positions which result in constructive interference. Since we are not changing a,

$$(b-b_0) - (a-a_0) \overset{\mathrm{a=a_0}}{=} b - b_0 = \Delta L = \frac{n\lambda}{4} \tag{3}$$

Which leads to:

$$\Delta L = \frac{n\lambda}{4} \rightarrow \begin{cases} n \text{ even} & \Longrightarrow \text{constructive interference} \\ n \text{ odd} & \Longrightarrow \text{destructive interference} \end{cases} \tag{4}$$

1.3 Relating current and interference fringes to sample deformation

We want to relate the sample elongation and deformation to the magnetic field strength H through the sample. Since we control the current I, we need an equation that relates I and H. From Ampere's law:

$$\oint_C \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_{enc} + \mu_0 \epsilon_0 \frac{d}{dt} \int_S \mathbf{E} \cdot d\mathbf{a} \tag{5}$$

we find the magnetic flux density induced by a solenoid to be:

$$\mathbf{B} = \frac{\mu_0 N I}{l} \hat{\boldsymbol{\phi}} \tag{6}$$

and the magnetic field intensity to be

$$\begin{aligned} \mathbf{H} &= \frac{1}{\mu_0} \mathbf{B} && (7) \\ &= \frac{NI}{l} \hat{\boldsymbol{\phi}} && (8) \\ &= 2 \times 10^4 I \hat{\boldsymbol{\phi}} \quad \text{for } N = 1200 \text{ and } l = 6\text{cm}. && (9) \end{aligned}$$

The general procedure is to slowly increase the magnetic field H by increasing the current through the coil, while keeping track of the interference pattern on the detector screen (for a laser with $\lambda = 632$ nm). The interference pattern will oscillate between constructive and destructive interference and we can use Equation 4 to find the ΔL. This is done by taking $a = 0$ as the position where constructive interference occurs and then by default we can take $\Delta L = 0$ at this position (see Section 1.2).

2 Aim

To investigate the change of length of different metal rods induced by an external magnetic field using an Michelson Interferometer.

3 Methodology

1. Align the apparatus as directed in the operating instructions
2. Adjust the position of $M3$ such that constructive interference occurs when there is no current.
3. Increase the current gradually while recording the current where constructive and destructive interference occurs for nickel, iron and copper.

4 Results

$\Delta L/L$	$H\ (Am^{-1})$	$\Delta H\ (Am^{-1})$
0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
-5.3×10^{-6}	3.6×10^{3}	3.2×10^{2}
-1.1×10^{-5}	4.6×10^{3}	4.0×10^{2}
-1.6×10^{-5}	5.8×10^{3}	4.0×10^{2}
-2.1×10^{-5}	7.1×10^{3}	4.1×10^{2}
-2.6×10^{-5}	9.4×10^{3}	5.1×10^{2}
-3.2×10^{-5}	1.3×10^{4}	7.7×10^{2}
-3.7×10^{-5}	2.0×10^{4}	1.7×10^{3}
-4.2×10^{-5}	3.2×10^{4}	3.4×10^{3}
-4.7×10^{-5}	5.6×10^{4}	1.5×10^{3}

Table 1: Data obtained for Nickel

$\Delta L/L$	$H\ (Am^{-1})$	$\Delta H\ (Am^{-1})$
0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
2.6×10^{-6}	1.0×10^{4}	2.7×10^{3}
1.0×10^{-5}	1.9×10^{4}	1.6×10^{3}
2.6×10^{-6}	2.6×10^{4}	4.8×10^{3}
0.0×10^{0}	4.5×10^{4}	1.6×10^{2}

Table 2: Data obtained for Iron

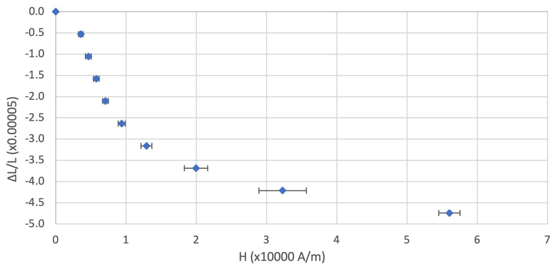


Figure 3: Plot for the Nickel Data

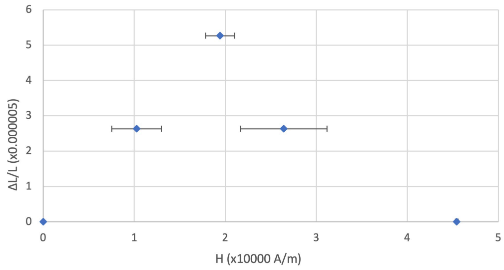


Figure 4: Plot for the Iron Data

5 Discussion

For the nickel sample, we had sinking fringes as the magnetic field increased which means the sample contracted ($\Delta L < 0$). Meanwhile, the iron sample first expanded, then contracted as shown in Figure 4. Copper is not ferromagnetic and hence the copper sample does not have any magnetic domains to align so no change was observed for copper. For nickel, $\Delta L \approx 1$ μm and for iron, $\Delta L \approx 0.1$ μm for a 6 cm rod. The limited current meant that we had limited readings for iron since it was more resistant to the magnetic field H. Having a larger range of H and having more intermediate data points could help us determine the trend of iron better. However, the non-ideal nature of the apparatus made this difficult to accomplish.

The reason for the two ferromagnetic materials exhibiting different magnetostriction behaviours is due to the shape of the magnetic domains relative to the magnetisation direction $\hat{\mathbf{M}}$. If $\hat{\mathbf{M}}$ points in the direction of the domain's longer side, then the material will have positive magnetostriction (expansion) and if $\hat{\mathbf{M}}$ points in the direction of the domain's shorter side, then we have negative magnetostriction (compression) as illustrated in Figure 5 and Figure 6 below.

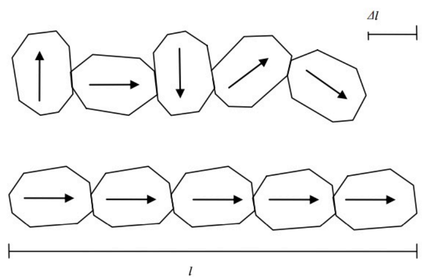


Figure 5: Positive Magnetostriction

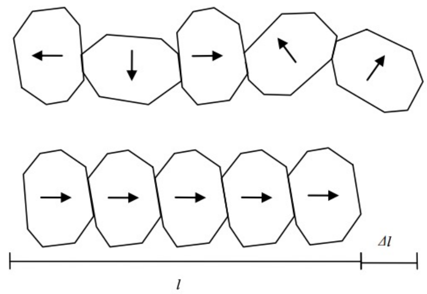


Figure 6: Negative Magnetostriction

From this, we can deduce that the nickel rod must have domains similar to Figure 6. The iron rod on the other hand, expanded and then contracted. Hence I hypothesise that the iron rod domains must have a magnetisation direction similar to Figure 5. However, when the magnetic field is increased, a state of alignment saturation is reached and any further increase can cause changes in the actual shape of the domains (which contract to minimise stress). It is certain that the contraction of nickel is not due to this effect since the sample started contracting even for small $\mathbf{H}$ magnitudes.

The uncertainties were obtained by running three trials for each sample and finding half the range of the trials, then we used the propagation of uncertainties to relate this to other quantities. We did not account for the equipment rounding uncertainties because this is negligible due to the fluctuating interference pattern. The fluctuating interference pattern was the most significant uncertainty and it was due to vibrations from footsteps and thermal vibrations generated by the solenoid. The thermal vibrations are evident in Figure 3 as the uncertainties increased for larger $\mathbf{H}$ magnitudes and hence larger current magnitudes (remember $|\mathbf{H}| \propto I$). To reduce these sources of uncertainty, padded shoes could be worn and we could wait for the solenoid to cool down fully before taking each measurement, or isolate the solenoid in a cold environment. Another area of improvement is to take more than three trials so we can calculate the average value and the uncertainty of the current more reliably.

6 Conclusion

In conclusion, our experiment revealed contrasting magnetostriction behaviours in nickel and iron. Nickel contracted consistently with increasing magnetic field, while iron initially expanded and then contracted. Copper, lacking ferromagnetic properties, showed no change. The differences can be attributed to the orientation of magnetic domains relative to the magnetisation direction. Uncertainties arising from vibrations were significant, but wearing padded shoes and allowing solenoid cooling improved measurements. Further investigations with a wider range of magnetic field values for iron would enhance our understanding.

7 Appendix

7.1 Bibliography

1. McHugh, M.W. (no date) 'Properties of Nickel as a Magnetostrictive Material for Ultrasonic Conditions'. Available at: https://sear.unisq.edu.au/22562/1/McHugh_2011.pdf

2. Magnetostriction (2016) Engineering LibreTexts. Available at: https://eng.libretexts.org/Bookshelves/Materials_Science/Supplemental_Modules_(Materials_Science)/Magnetic_Properties/Magnetostriction (Accessed: 6 July 2023).

3. 'Magnetostriction' (2023) Wikipedia. Available at: https://en.wikipedia.org/w/index.php?title=Magnetostriction&oldid=1149050686 (Accessed: 6 July 2023).

4. Magnetostriction (no date). Available at: http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/magstrict.html (Accessed: 6 July 2023).

7.2 Prework

1. *Briefly describe the basic working principle of a laser in general. Name at least two different kinds of lasers. What kind of laser are you going to use? How does it work?*

   When a medium is pumped with energy from electric discharge or flash lamps, some of the electrons transition energy levels which emit photons. These photons get sent through the optical resonator which consists of two mirrors placed at opposite ends of the medium. One mirror is partially reflective, allowing some light to escape, while the other mirror is highly reflective, causing the light to bounce backwards and forth through the resonator. This creates a feedback mechanism that builds up the intensity of the light.

   Two types of lasers are Solid-State Lasers (uses a solid medium) and Gas Lasers (uses a gas medium).

2. *What is the difference between a red light emitting diode with an emission spectrum centered around 632nm and our laser source? Could you use the LED for the purpose of our measurement?*

   A laser produces a monochromatic wavelength while the red LED produces a narrow range of wavelengths centered around 632nm. An LED cannot be used for this experiment because for a sharp diffraction pattern, we require a singular wavelength.

3. *What is the condition on the optical path difference for two waves to obtain constructive/destructive interference? A drawing might be helpful.*

$$\Delta L = \frac{n\lambda}{4} \rightarrow \begin{cases} n \text{ even} & \Longrightarrow \text{constructive interference} \\ n \text{ odd} & \Longrightarrow \text{destructive interference} \end{cases} \tag{10}$$

4. *Make sure you've understood the purpose of all the optical components we are going to use. In particular, why do we use the beam-splitter and the lens?*

   The beam splitter is used to separate the laser into the reference and sample beams so they can interfere with each other. The lens is to focus and collimate the beam.

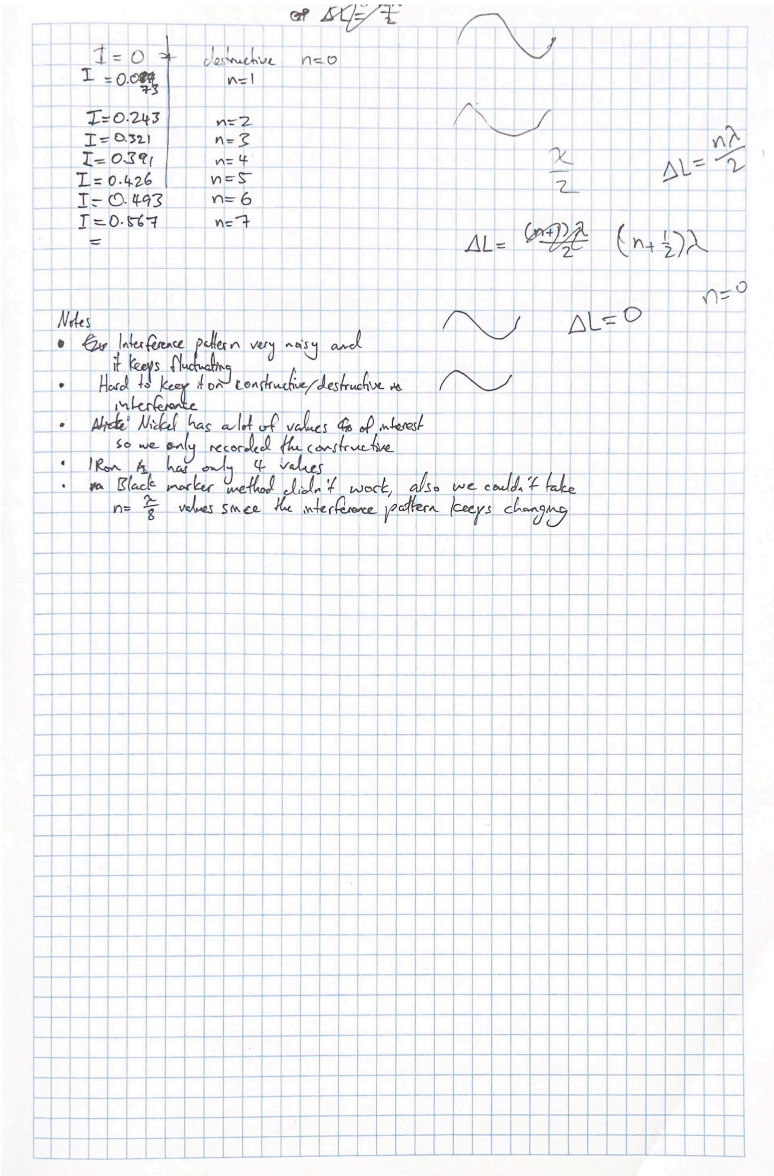
5. *What is the typical behaviour of the magnetisation M of a ferromagnet in an external field H. How do you call those diagrams?*

   The magnetisation M of a ferromagnet in an external field H is represented by a hysteresis loop. As H increases, M also increases until it saturates. When H is decreased, M retains residual magnetisation. Reversing H requires a coercive field to switch the magnetisation. Hysteresis loops show this behaviour in a graph.

6. *The length of the coil is shorter than the length of the rods. Which length should you use in the analysis? How does this influence the analysis?*

   The length of the coil should be used since l in Ampere's law is the length of the N turns. This would result in a smaller l than using the rod length.

7.3 Logbook



$I = 0$ → destructive $n=0$

$I = 0.073$ | $n=1$

$I = 0.243$ | $n=2$

$I = 0.321$ | $n=3$

$I = 0.391$ | $n=4$

$I = 0.426$ | $n=5$

$I = 0.493$ | $n=6$

$I = 0.567$ | $n=7$

$\frac{\lambda}{2}$

$\Delta L = \frac{n\lambda}{2}$

$\Delta L = \frac{(n+1)\lambda}{2}$ $(n+\frac{1}{2})\lambda$

$n=0$

$\Delta L = 0$

Notes
- Interference pattern very noisy and it keeps fluctuating
- Hard to keep it on constructive/destructive interference
- Note: Nickel has a lot of values of interest so we only recorded the constructive
- IRon has only 4 values
- Black marker method didn't work, also we couldn't take $n=\frac{\lambda}{8}$ values since the interference pattern keeps changing

Figure 7: Experimental Logbook (most data was directly inserted into excel)

7.4 Excel Document

Nickel

n	I_{t1} ± 0.1 A	I_{t2} ± 0.1 A	I_{t3} ± 0.1 A	Iavg	dI	ΔL (m)	dL/L (m)	H	dH
0	0	0	0	0	0	0.00E+00	0.0E+00	0.0E+00	0.00E+00
-2	0.196	0.178	0.164	0.179333333	0.016	-3.16E-07	-5.3E-06	3.6E+03	3.20E+02
-4	0.232	0.252	0.212	0.232	0.02	-6.32E-07	-1.1E-05	4.6E+03	4.00E+02
-6	0.286	0.31	0.27	0.288666667	0.02	-9.48E-07	-1.6E-05	5.8E+03	4.00E+02
-8	0.354	0.374	0.333	0.353666667	0.0205	-1.26E-06	-2.1E-05	7.1E+03	4.10E+02
-10	0.477	0.491	0.44	0.469333333	0.0255	-1.58E-06	-2.6E-05	9.4E+03	5.10E+02
-12	0.642	0.686	0.609	0.645666667	0.0385	-1.90E-06	-3.2E-05	1.3E+04	7.70E+02
-14	1.068	1.023	0.902	0.997666667	0.083	-2.21E-06	-3.7E-05	2.0E+04	1.66E+03
-16	1.793	1.597	1.455	1.615	0.169	-2.53E-06	-4.2E-05	3.2E+04	3.38E+03
-18	2.85	2.853	2.702	2.801666667	0.0755	-2.84E-06	-4.7E-05	5.6E+04	1.51E+03

Iron

n	I_{t1} ± 0.1 A	I_{t2} ± 0.1 A	I_{t3} ± 0.1 A	I_{avg} ± 0.03 A	dI	ΔL (m)	dL/L (m)	H Am^{-1}	dH
0	0	0	0	0	0	0	0.00E+00	0.00E+00	0.00E+00
1	0.553	0.629	0.356	0.512666667	0.1365	1.58E-07	2.63E-06	1.03E+04	2.73E+03
2	0.961	1.056	0.897	0.971333333	0.0795	3.16E-07	5.27E-06	1.94E+04	1.59E+03
1	1.004	1.48	1.479	1.321	0.238	1.58E-07	2.63E-06	2.64E+04	4.76E+03
0	2.27	2.264	2.28	2.271333333	0.008	0	0.00E+00	4.54E+04	1.60E+02

Figure 8: Data collected and analysed in Excel

7.5 Siuuu

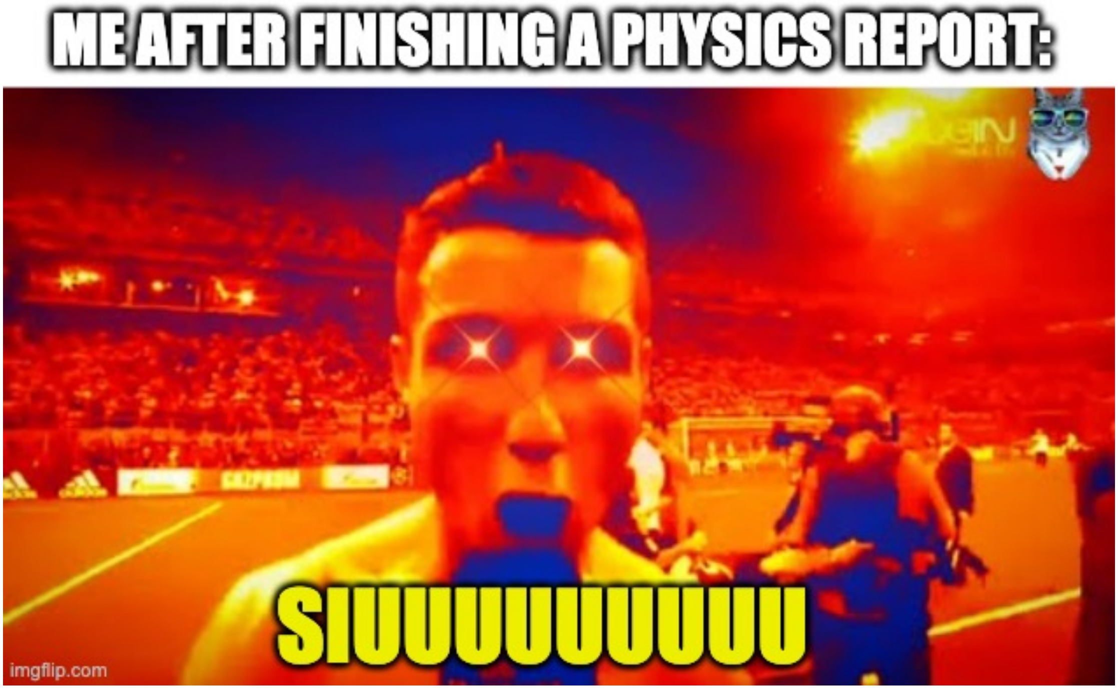


Figure 9: Footage of Corey finishing his report