Examining the Causes of Ferromagnetism through the Microstructure of Iron

Qingyuan Wu

April 27, 2021

Figure 1: Pure iron

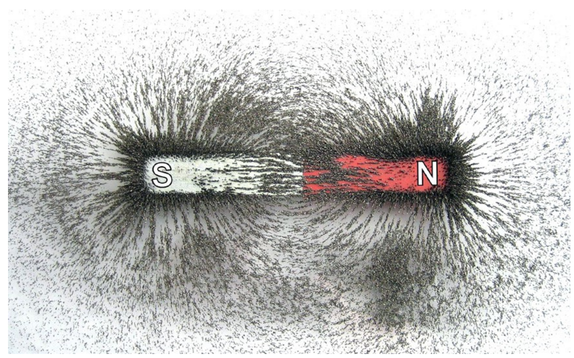

Figure 2: A bar magnet with iron scattered around it, displaying the characteristic magnetic field lines

1 Introduction

Iron, element symbol Fe, is the 26th element on the periodic table. It is the most common element on Earth, making up 32.1% of the Earth's total mass [1]. Its most common application is in the manufacturing of steel, an indispensable material in construction and civil engineering. Steel is an iron-carbon alloy composed of 98%-99% iron [2]. Iron also has an uncommon property known as ferromagnetism. This property causes iron to be attracted to an external magnetic field [3]. This report will detail the ferromagnetic properties of iron and attempt to explain these properties from the perspective of iron's microstructure.

2 What is Ferromagnetism?

Ferromagnetism is a fundamental property of some materials, including cobalt, nickel, and iron, that makes them attracted to an external magnetic field. These materials can become permanently magnetized. Ferromagnetism has been observed for thousands of years by the ancient Greeks, the Chinese, and the Islamic world. Around 2000 years ago, the Chinese invented the compass after observing that lodestone, a naturally magnetized iron-oxide, will always face the same direction when allowed to freely rotate [4]. Despite its early discovery, scientists did not gain a good understanding of ferromagnetism until the development of quantum mechanics in the 19th century. This is because ferromagnetism is a purely quantum phenomenon and cannot be explained by classical mechanics [3][5].

3 Basic Properties of Pure Iron

At low temperatures, iron takes on the Body-Centered Cubic (BCC) crystal structure As shown in Figure 3, iron's structure is characterized by one atom in the centre of each unit cell, surrounded by eight atoms above and below this central atom, 1/8th of each is in the unit cell. Therefore, there are $1 + 8 * 1/8 = 2$ atoms in each unit cell. The BCC structure has coordination number 8, meaning each iron atom is surrounded by eight neighbouring atoms. Iron only takes on the BCC structure at low temperatures. After it is heated to 912°C, pure iron experiences a phase change and takes on the Face Centered Cubic (FCC) crystal structure instead [6]. Another critical temperature for iron is the Curie temperature, $T_C = 770°C$. When heated above T_C, iron loses its ferromagnetic properties [7]. As shown in Figure 4, the electron configuration of iron is $[Ar]3d^6 4s^2$. Iron has six electrons in its $3d$ orbital, four of which are unpaired. This fact becomes significant when examining the cause of iron's magnetic properties.

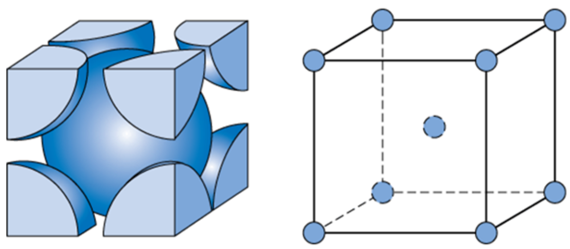

Figure 3: A unit cell of the BCC crystal structure

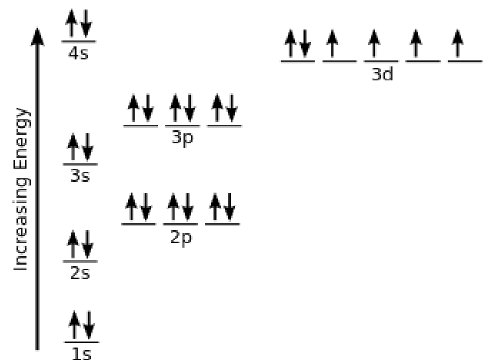

Figure 4: The electron configuration of iron. Note the four unpaired electrons in its $3d$ orbital

4 Why are some Materials Ferromagnetic?

There are many different scales of magnetism. First, magnetic properties exist within the subatomic level, as each electron behaves like a tiny magnet. Second, some atoms may be overall magnetic due the presence of unpaired electrons. Third, millions of atoms must align in microscopic domains to produce an overall magnetic moment. Finally, a permanent magnet is characterized by all its domains aligning in the same direction [8][9].

4.1 The Electron

Scientists have experimentally determined that electrons possess an intrinsic magnetic moment, also called an electron magnetic dipole [10]. This magnetic dipole is produced by two types of electron movements: (1) the electron's rotation along its own axis, called the spin magnetic dipole moment, and (2) the electron's revolution around the nucleus of the atom, called the orbital dipole moment. The electron carries a fundamental charge of $1.602 * 10^{-19} C$. According to Ampere's Law, moving electric charges produce a magnetic field. Therefore, all electrons in an atom produce tiny magnetic dipoles. Due to the two possible spin orientations of the electron, designated "spin up" and "spin down", the electron's magnetic field can be aligned in one of two directions. This is determined by an electron's spin quantum number, m_s [10][11].

4.2 Individual Iron Atoms

All atoms have electrons, but clearly not all atoms are magnetic. This is because most of the electrons in an atom exist in pairs - they reside in the same sub-orbital and have opposite spin quantum numbers, $+1/2$ and $-1/2$, as guaranteed by the Pauli Exclusion Principle [10]. Due to the cancelling effect of the opposite spins, electrons in filled orbitals have no overall magnetic dipole moment, leaving a net zero magnetic effect. Individual iron atoms are magnetic due to the unpaired electrons in their half-filled shells. As discussed, the electron configuration of iron is $[Ar]3d^6 4s^2$. Four of the six electrons in iron's $3d$ orbital are unpaired (see Figure 4). These unpaired electrons have the same spin and therefore their magnetic properties add up instead of cancelling out. As a result, each individual iron atom produces an overall magnetic moment [9][11]. However, individual ferromagnetic atoms does not guarantee the overall ferromagnetism of the material.

4.3 Domains of Irons

Many elements have unpaired electrons, like aluminum, carbon, or copper. However, these elements are not ferromagnetic. This is because collections of atoms of these elements do not align their individual magnetic fields, so they have no net dipole moment [9]. The alignment of individual atoms in the direction of their magnetic field is known as domains, and is responsible for the ferromagnetic properties of a material [12]. In iron, the atoms align in domains, each of which acts as a tiny magnet. Domains, as shown in Figure 5, are in the microscopic range, between $10^{-6}m$ and $10^{-3}m$. The small size of these domains is due materials favouring the lowest energy state. Within a small enough scale, magnetic moments aligning in the same direction is favourable. If all atoms spontaneously aligned in one large domain, however, there would be too much magnetostatic energy. This energy is minimized by the material splitting into multiple small domains in opposite directions. Domains are separated by domain walls, which are usually hundreds of atoms thick. They are characterized by the gradual realignment of the magnetic moment of these interface atoms [12]. Naturally occurring iron is often unmagnetized because their domains align in different directions. Therefore, the net magnetic moment of an ordinary piece of iron is zero. This is why two pieces of iron ore do not attract each other [9].

4.4 Remanence and Creating a Permanent Magnet

Remanence is the magnetization of a ferromagnetic material using an external magnetic field [13]. There are multiple means of creating a permanent magnet, but all of them involves making individual domains align in the same direction to produce an overall magnetic dipole moment. One method is heating the iron above its Curie temperature, which causes the disassembly of its magnetic domains. Then the iron is hammered as it cools to force the domains to realign in the same direction. Iron may also become a permanent magnet upon exposure to a strong enough external magnetic field.

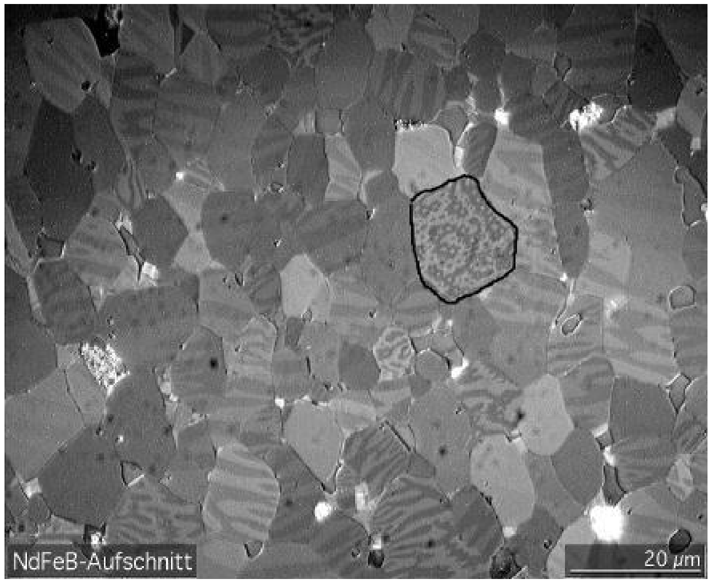

Figure 5: The domains of an iron compound made visible by a special telescope. Note the domains, which are the stripes within each grain, are smaller than the grains of the compound

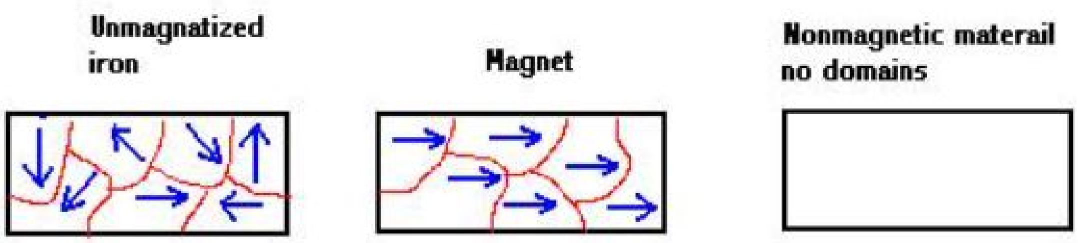

Figure 6: An illustration distinguishing the domains of an unmagnetized iron, a permanent magnet, and a material with no ferromagnetic properties

5 Applications of Iron's Magnetic Properties

As mentioned, iron's magnetic properties have been observed and used for over 2000 years. Some of its most prominent applications include compasses and magnetic cores.

5.1 Compass

The ancient Chinese discovered between 2nd century BC and 1st century AD that lodestone, a naturally-occurring iron ore, will experience an external force which caused it to align in a constant direction when allowed to freely rotate. This led to the invention of the compass, which became widely used for navigation [4]. Scientists now understand that the cause of this alignment is due to the attraction between the south magnetic pole of the ferromagnetic material and the north magnetic pole of the Earth [14].

5.2 Magnetic Core

A more recent application of ferromagnetism is using magnetic cores in generators, electric motors, and other devices that generate energy through a magnetic field. The main mechanism of magnetic cores involves placing a piece of iron or its alloy inside a coil (solenoid) through which current flows. This adds to the magnetic field generated by the current by up to hundreds of times [15][16]. The magnification is due to the core concentrating the magnetic flux of the solenoid [17]. Also, iron has a very high magnetic permeability compared to air: $\mu_{Fe} = 2.5 * 10^{-1} H/m$ vs. $\mu_0 = 1.257 * 10^{-6} H/m$. This causes the magnetic field generated by the solenoid to be concentrated in the core material instead of freely expanding [18].

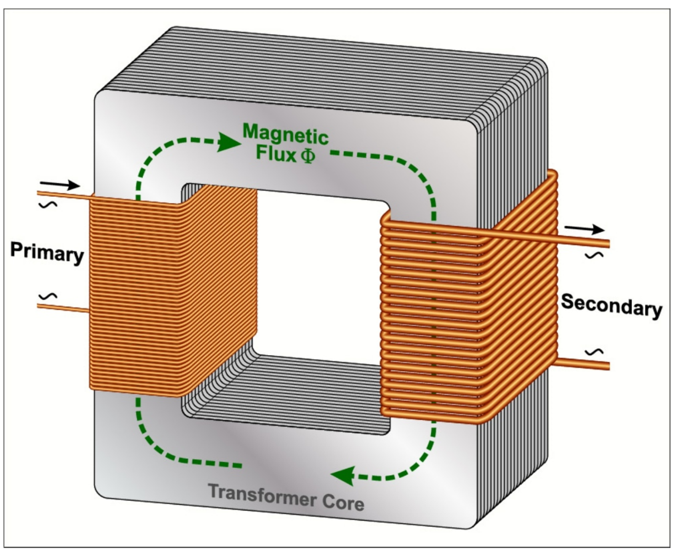

Figure 7: A standard steel magnetic core of a transformer

6 Conclusion

Iron's fascinating ferromagnetic property is caused by the existence of domains within its grains. The practical uses of iron's ferromagnetic properties range from compass needles for navigation and magnetic cores to concentrate the magnetic fields of modern power devices.

Image Sources

Figure 1: https://www.globalspec.com/ImageRepository/LearnMore/20163/Powder_steel93239b16233a46278fb05b55fb927be8.png
Figure 2: https://www.etcourse.com/sites/default/files/inline-images/Magnet_Iron_Filings.jpg
Figure 3: https://www.e-education.psu.edu/matse81/sites/www.e-education.psu.edu.matse81/files/images/lesson05/BCC.png
Figure 4: https://useruploads.socratic.org/4H9OMxDSnSeqRjUtjDDy_350px-Electron_configuration_iron.svg.png
Figure 5: https://upload.wikimedia.org/wikipedia/commons/b/b4/NdFeB-Domains.jpg
Figure 6: https://www.utm.edu/staff/cerkal/magnetic_files/image006.jpg
Figure 7: https://i2.wp.com/nicoreindia.com/wp-content/uploads/2020/09/A-Standard-Transformer-Core.jpg?w=1000&ssl=1

References

[1] J. W. Morgan and E. Anders, *Chemical composition of earth, venus, and mercury*, Dec. 1980. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC350422/.

[2] *Steel*. [Online]. Available: https://www.britannica.com/technology/steel.

[3] *Ferromagnetism*. [Online]. Available: https://www.britannica.com/science/ferromagnetism.

[4] *Invention of the compass*. [Online]. Available: http://www.historyofcompass.com/compass-history/invention-of-the-compass/.

[5] J. Clark and R. Spinney, *Magnetic properties*, Feb. 2021. [Online]. Available: https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Physical_Properties_of_Matter/Atomic_and_Molecular_Properties/Magnetic_Properties.

[6] W. Pepperhoff and M. Acet, "The structure of iron," in *Constitution and Magnetism of Iron and its Alloys*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2001, pp. 1–13, ISBN: 978-3-662-04345-5. DOI: 10.1007/978-3-662-04345-5_1. [Online]. Available: https://doi.org/10.1007/978-3-662-04345-5_1.

[7] F. Lau and H. Lai, *Curie temperature of iron*, G. Elert, Ed., 2002. [Online]. Available: https://hypertextbook.com/facts/2002/FeliciaLau.shtml.

[8] J. J. Wyslocki, "Magnetic properties, microstructure and magnetic domain structure in anisotropic fealc permanent magnet," *physica status solidi (a)*, vol. 151, no. 2, pp. 421–433, 1995. DOI: https://doi.org/10.1002/pssa.2211510221. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/pssa.2211510221. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/pssa.2211510221.

[9] minutephysics, Sep. 2013. [Online]. Available: https://www.youtube.com/watch?v=hFAOXdXZ5TM&t=310s.

[10] R. F. Bader, *4.3: The magnetic properties of the electron*, Aug. 2020. [Online]. Available: https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Book%3A_An_Introduction_to_the_Electronic_Structure_of_Atoms_and_Molecules_(Bader)/04%3A_Many-Electron_Atoms/4.03%3A_The_Magnetic_Properties_of_the_Electron.

[11] M. A. Gottlieb and R. Pfeiffer. [Online]. Available: https://www.feynmanlectures.caltech.edu/II_37.html.

[12] S. L. Halgedahl, "Magnetic domainsmagnetic domains," in *Geophysics*. Boston, MA: Springer US, 1990, pp. 706–721, ISBN: 978-0-387-30752-7. DOI: 10.1007/0-387-30752-4_88. [Online]. Available: https://doi.org/10.1007/0-387-30752-4_88.

[13] S. Chikazumi, C. D. Graham, and S. Chikazumi, *Physics of ferromagnetism*. Oxford University Press, 1997.

[14] [Online]. Available: https://web.ua.es/docivis/magnet/earths_magnetic_field2.html.

[15] *Magnetic core*, Apr. 2021. [Online]. Available: https://en.wikipedia.org/wiki/Magnetic_core.

[16] *Magnetic core characteristics*, 2001. [Online]. Available: https://www.ti.com/lit/ml/slup124/slup124.pdf.

[17] *Magnetic core*, Apr. 2021. [Online]. Available: https://en.wikipedia.org/wiki/Magnetic_core.

[18] *Magnetic susceptibilities of paramagnetic and diamagnetic materials at 20°c*. [Online]. Available: http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/magprop.html#c2.