Pearson BTEC Levels 4 and 5 Higher Nationals in Engineering (RQF)

Unit 3: Engineering Science (core)

Unit Workbook 3

in a series of 4 for this unit

Learning Outcome 3

Engineering Materials

3.1 Background

The behaviour of materials is based around Chemistry, they way they bond with each other is how the structure, strength and properties are determined. Taking these into consideration is how we develop the practical applications of the material, and the most appropriate method of manufacturing.

3.1.1 The Periodic Table of Elements

Developed by the famous Russian scientist Dmitri Mendeleev in 1869. The periodic table of elements is the system used to categorise the elements into their atomic weight and their "groups". Table.3.1 shows the current periodic table of elements.

Table.3.1: Periodic Table of Elements

Group	1	2											3	4	5	6	7	8
Period																		
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Co	27 Fe	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn						

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Key

Atomic No.	1	X	X	X	X
Symbol	H	Synthetic	Liquid	Solid	Gas

Alkali Metals	Earth Metals	Transition Metals	Other Metals	Metalloids	Other Non-Metals	Halogens	Noble Gases	Lanthanides & Actinides

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As you can see, this is a substantial table with a lot of information in it, but you will find that elements in the same group will exhibit similar properties.

3.1.2 The Atom

The atom can be split into three distinct parts, the proton, neutron and electron. The protons and neutrons form the nucleus of the atom, while the electrons fly around the outside of the nucleus. A diagram of a Helium atom can be seen in Fig.3.1.

Proton: The number of protons is shown by the Atomic number in the periodic table. This number is the defining characteristic of an element. You cannot have a Hydrogen atom with two protons, that would make it a Helium atom. Since the protons are positive, they are electronically repellent, and so to keep an atom stable, neutrons are required.

Neutron: The neutron is a constituent part of the atom that uses the "residual strong force" to overcome the repelling electronic forces and keep the nucleus together.

Electron: Electrons keep the charge of an atom at zero, but they are also very important when it comes to chemical reaction and bonding.

Table.3.2 shows some of the characteristics of the constituent parts of the atom.

Table.3.2: Constituent atomic parts

	Proton	**Neutron**	**Electron**
Mass	$1.673 \cdot 10^{-27}$kg	$1.675 \cdot 10^{-27}$kg	$9.11 \cdot 10^{31}$kg
Relative charge	$+1$	0	-1

3.1.3 The Electron

As mentioned, electrons orbit the nucleus, but not in a simple or random fashion. In fact, they orbit the nucleus in distinct groups, known as shells. Each shell can have a maximum number of electrons within it, determined by the principles of quantum physics, as follows;

Table.3.3: Atomic shells and subshells with maximum electron occupancy

Shell (known by a number)	Max. Electrons
1	2
2	8
3	18
4	32
5	50

Subshell (known by a letter)	Max. Electrons
s	2
p	6
d	10
f	14

The electrons are the determining factor between the groups, looking at Fig.3.1, it is clear that there are four electrons on the outer shell, and they are both in Group 4 in the periodic table, they also show similar properties (can conduct electricity in certain configurations, high melting points, etc.). The same applies for the other groups, all the noble gases are unreactive, while the alkali metals are very unstable.
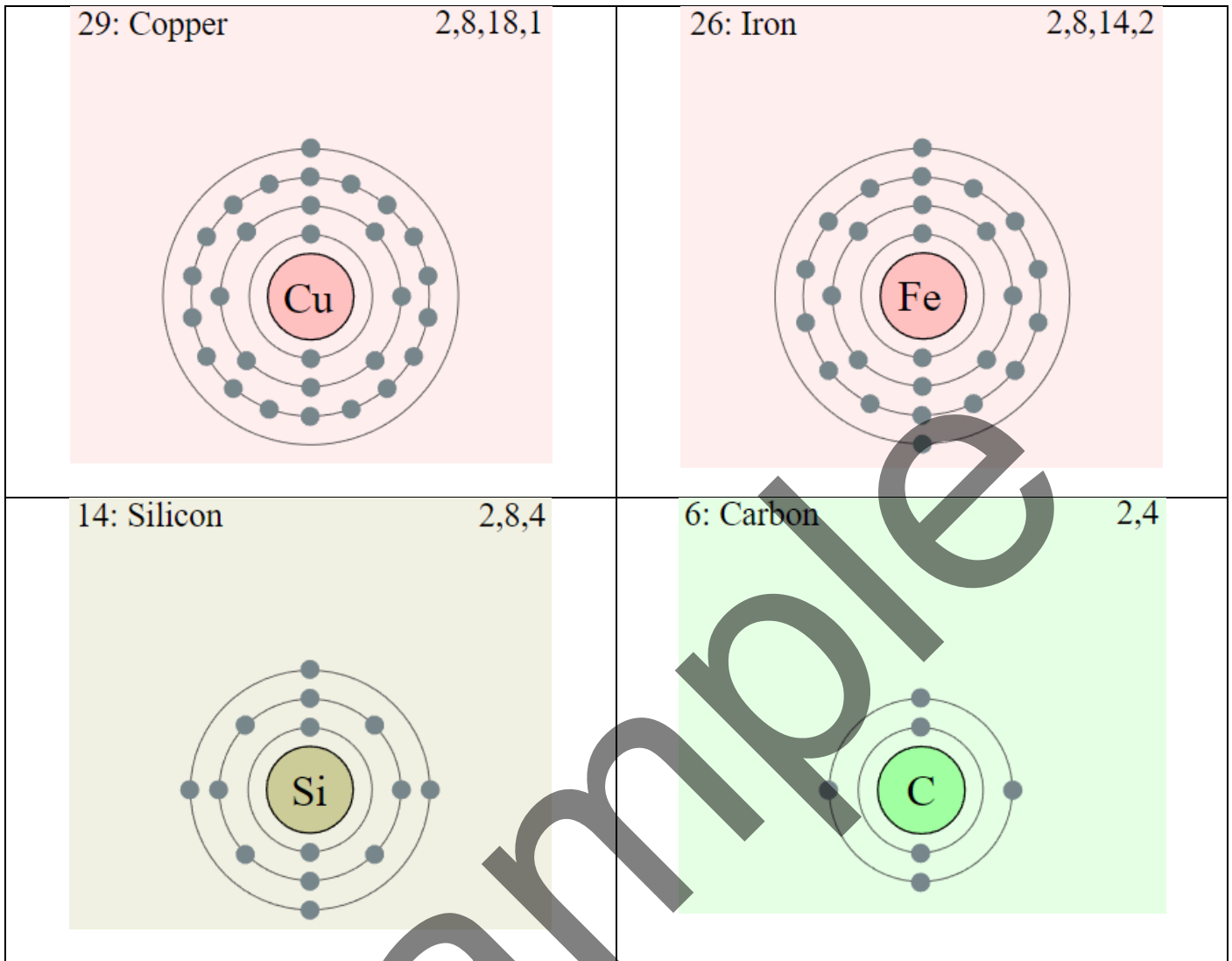
29: Copper	2,8,18,1	26: Iron	2,8,14,2

14: Silicon	2,8,4	6: Carbon	2,4

Fig.3.1: Atomic structure of some common elements

3.2 Chemical Bonding

The bonding of materials is governed through the behaviour of the electrons of the atoms. Different bonds occur with different elements, and this determines how hard it is to break down.

3.2.1 Simple Covalent Bonding

Non-metals are most likely to bond in this fashion, they are typically weak bonds and are brought about by the atoms "sharing" electrons to fill the outer shell. If we consider carbon dioxide (CO_2) we know that Carbon has four atoms on the outer shell (noted as $1s^2 2s^2 2p^2$) and Oxygen has six atoms on the outer shell ($1s^2 2s^2 2p^4$).

The most favourable position for any atom is a complete outer shell, this is the most stable state for the atom (noble gases have filled outer shells and are unreactive and very stable). Fig.3.2 shows the bonding of CO_2. The electrons shared fill all the atoms' outer shells and they resist attempts to split the bonds.
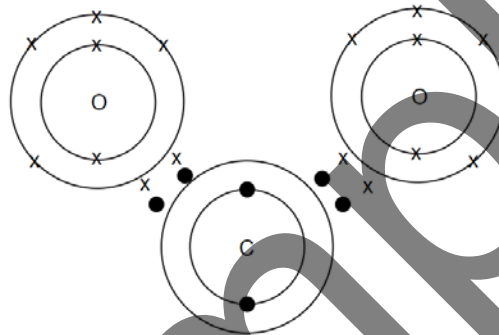

Fig.3.2: Covalent bonding of Carbon Dioxide

3.2.2 Giant Covalent Structure

This follows the same principle as the simple covalent bonds, but on a much bigger scale. The best example of a giant covalent structure would be diamond, which is simply carbon that has formed in a specific fashion (high pressures and heat).

Giant covalent structures exhibit very high melting points and are extremely hard but are not particularly tough (diamonds can be used to cut through nearly all materials but will shatter if hit with a hammer).

3.2.3 Ionic Bonds

Ionic bonding occurs between alkali metals and halogens, an example is sodium chloride (NaCl), also commonly known as table salt.

Alkali metals have one electron in the s subshell and have one too many to be stable, while halogens need one electron to have a complete shell and be stable. The solution is therefore simple, the alkali metal donates the extra electron to the halogen. The following chemical equations explain what happens.

$$Na \rightarrow Na^+ + e^-$$

$$Cl + e^- \rightarrow Cl^-$$

$$Na + Cl \rightarrow NaCl$$
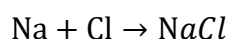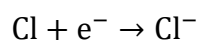
The attraction between the positive and negative "ions" (charged atoms) creates the attraction that creates the bond, and forms a strong lattice, shown in Fig.3.3.
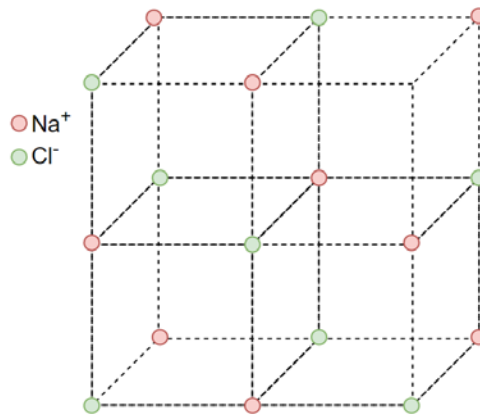

Fig.3.3: Ionic Lattice of NaCl

3.2.4 Metallic Bonding

Metals are bonded by sharing the electrons on the outer shell in a similar way to ionic bonds. The metal atoms let their electrons run free through the structure, this creates bonds that are strong, much like the ionic bonding. The delocalised electrons however, are not constrained in the same way as the ionic bonds, and this means that metals can conduct electricity. Fig.3.4 shows metallic bonding.
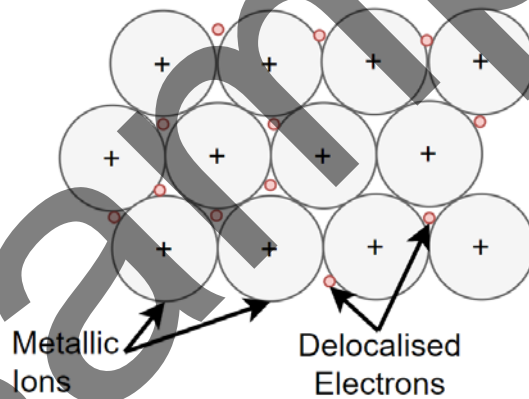

Fig.3.4: Metallic Bonding

3.2.5 Bonding Properties

Table 3.3 compares the general properties of different bonds.

Table.3.3: Comparison of Material Properties

	Simple Covalent	Giant Covalent	Ionic	Metallic
Melting Point	Low	Very High	Very High	Very High
Electrical Conductivity	Negligible	Negligible	Yes, when dissolved or melted	Yes
Heat Conductivity	Low	Low	Low	Good
Hardness (resistance to scratching)	Low	Very High	High	Varies
Toughness (resistance to bending)	Low	Low	High	Varies

There will be some exceptions, for example Mercury has a very low melting point and is liquid at room temperature, and this is why thermometers use mercury; Gallium is a solid metal at room temperature but will melt in your hand as it heats up to $30°C$, to name but a couple.

3.3 Transition Metals

Transition metals are the metals in the middle of the periodic table, they do not belong to a specific group, but are defined as metals with an incomplete d subshell, with some exceptions such as Copper. Metals can be arranged into three arrangements. Face-Centred Cubic (FCC), Body-Centred Cubic (BCC) and Hexagonal Crystal Packing (HCP). This helps define certain properties of the metals.

3.3.1 FCC

Face Centred Cubic is mostly associated with ductile metals such as with copper, a unit cell of a copper can be seen in Fig.3.5. They are typically weaker than the other arrangements, and will have a slow, noticeable failure. The lines in Fig.3.5 between the atoms signify the sharing of electrons.
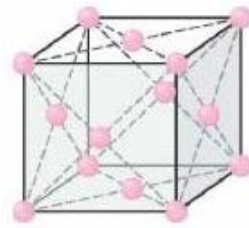

Fig.3.5: FCC unit cell

3.3.2 BCC

Body Centred Cubic is associated with brittle materials, such as iron, the unit cell of iron can be seen in Fig.3.6. Brittle metals will have a sudden, catastrophic failure.

Fig.3.6: BCC unit cell

3.3.3 HCP

HCP are densely packed systems, roughly the same spacing as a FCC material, but they have a very wide range of strength, for example, magnesium is a very brittle metal, while titanium and zinc are quite ductile. Fig.3.7 shows a HCP unit cell.
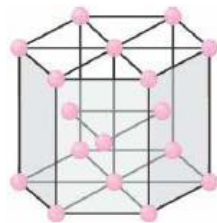

Fig.3.7: HCP unit cell

3.3.5 Alloys

No metal is perfect, in fact most pure metals are quite weak, so engineers develop alloys. Alloys are a mix of elements, but with a predominant base of metal, such as steel (base iron). Alloys are categorised into two categories, interstitial and substitutional.

Interstitial alloys are alloys that have additional elements with much smaller atoms than the base atom, examples of this are carbon atoms in steel, or oxygen in titanium oxide. The interstitial atoms lie in the gaps between the metal atoms and will stop the atoms slipping across each other.
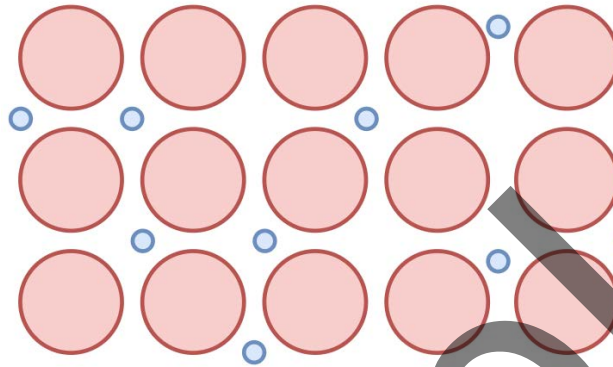

Fig.3.8: Interstitial alloy arrangement

Substitutional alloys will have elements that will be of a similar size of the base atom (±12% in size). This is another method of making sure the atoms stop slipping across each other, examples of substitutional alloys include bronze (copper and tin) or stainless steel (Iron, Chromium and Nickel)
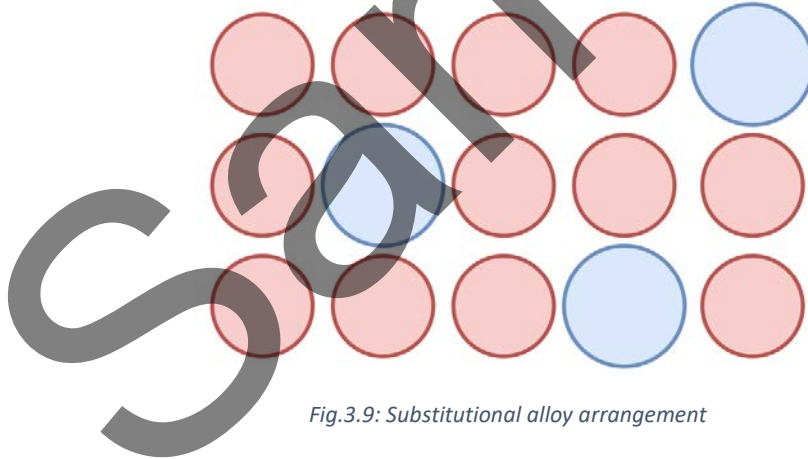

Fig.3.9: Substitutional alloy arrangement

3.3.6 Magnets

Certain metals can also exhibit magnetism. Atoms in magnetic materials have an aligned magnetic field (or flux). When a material that is capable of magnetism is not magnetic, then each atom's individual magnetic flux does not line up to create a strong magnetic flux. When considering a magnet, however, the atom's magnetic flux all align with one another. A visual representation of the magnetic alignment is shown in Fig.3.10. **Not all metals are magnetic.**
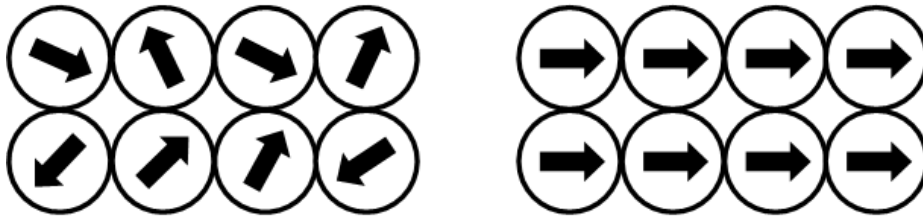
Fig.3.10: Magnetic alignment in a demagnetised metal (left) and a magnetised metal (right)

All of the individual atoms will be creating a very small magnetic flux around themselves. Once all of the magnetic fields are aligned, the fields add up and create the overall magnetic flux of the system, moving from the magnetic north pole to the magnetic south, demonstrated by Fig.3.11. A stronger magnet will have a more magnetic flux (creates a denser magnetic field).
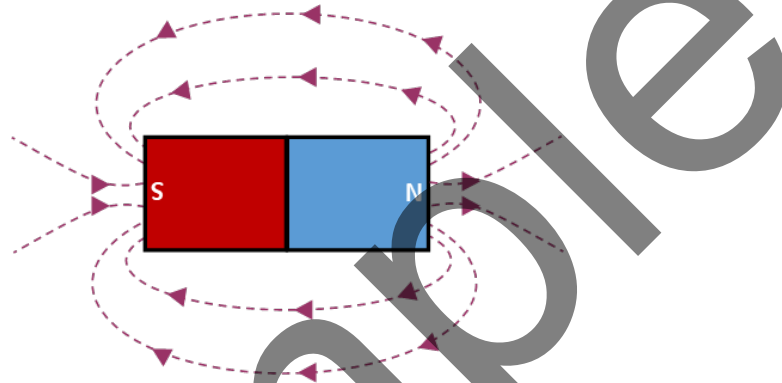

Fig.3.11: Magnetic flux flowing from the North Pole (N) to the South (S)

When a magnet comes into contact with a demagnetised metal. The flux from a magnet flows through the metal and forces the atoms to align, this alignment and magnetic field flow generates the magnetic force that attracts the metal to the magnet, shown in Fig.3.12. If you think about water or current flow, the magnetic flux will follow the "path of least resistance". In this case, the magnetic field will flow through the metal and bring it closer to reduce the distance the field has to travel to return to the South pole.
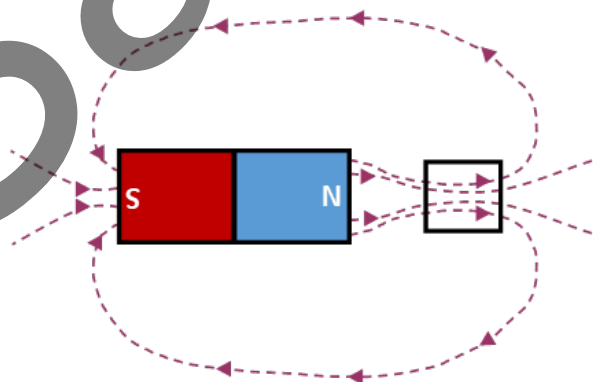

Fig.3.12: Magnetic fields flowing through a demagnetised piece of metal

We also need to consider the interactions of two magnets together. When two magnets are placed close enough to each other, the magnetic flux can either complement or interfere with each other. When two magnets are placed next to each other with the same poles facing each other (i.e., North facing North or

South facing South) then the magnetic flux will interfere with each other, this creates a resisting force and will push the magnets away (repel). Shown by Fig.3.13.
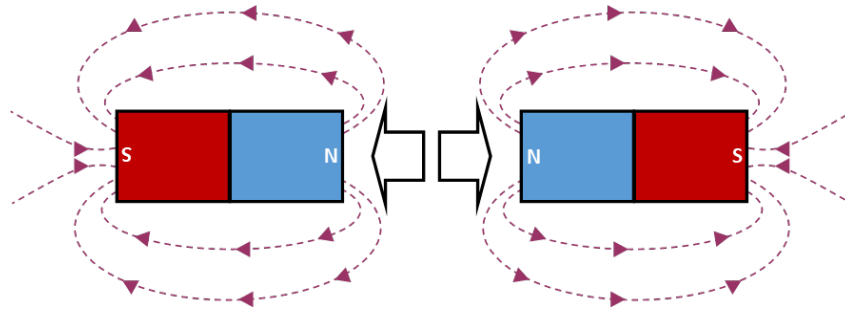

Fig.3.13: Two like poles repelling one another

When opposite poles are facing each other (North facing South) then the magnetic flux will flow in the same direction, and merge together. The North's magnetic field will flow into the South, and bring them together (attract), shown in Fig.3.14.
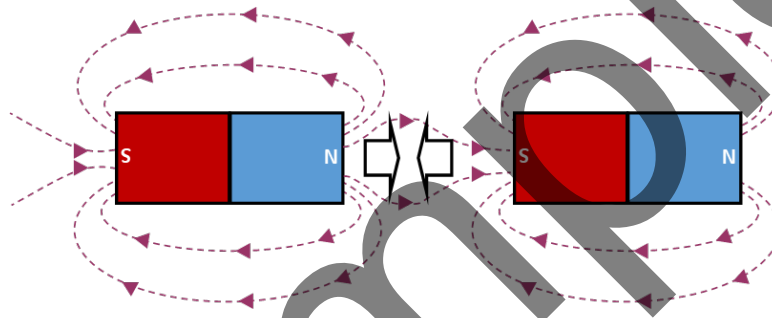

Fig.3.14: Magnets attracting each other

3.7.8 Magnetic Hysteresis

There are certain materials that will experience "hysteresis", typically elastomers, magnetic materials and quartz. Hysteresis is the phenomenon in which a physical property lags behind the change in effect causing it. Magnetic Hysteresis is shown in Fig.3.15 and can affect transformers and motors. The steps shown in the figure are as follows:
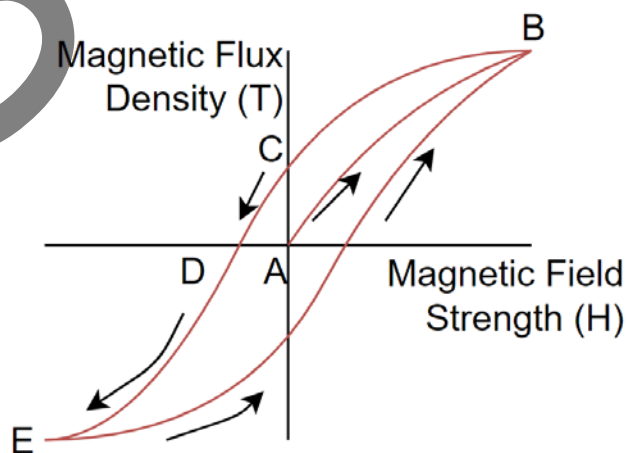

Fig.3.15: Magnetic Field strength and the resultant flux density of a magnet

The Magnetic flux density of the magnet is zero at A. As a magnetic field is induced into the material (current is fed through the coil). The magnetic flux density in the magnet will also increase, until it reaches its saturation point at B. (Typically $1.5T$). The saturation point is when the magnetic field of every metal atom is aligned, shown in Fig.3.16.
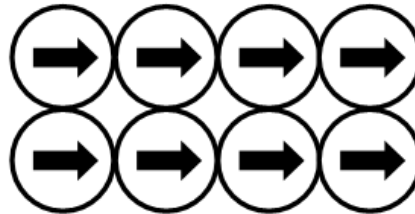

Fig.3.16: Magnetic alignment at the positive saturation point

When the field strength is reduced the atoms lose their magnetic alignment, but there is still some resistance to this movement, and at point C (from Fig.3.15), there is no current flowing through the coil, meaning there is no magnetic field strength. There is still however some magnetic flux in the system. This point is known as the remanence point.

The point when the magnetic field strength is zero is shown by D in Fig.3.15, it also states that a negative current is to be fed through the coil to reach this point. This is known as the coercivity point.

At point E the magnet has reached the maximum saturation point again, but in the opposite direction. Shown by Fig.3.17.
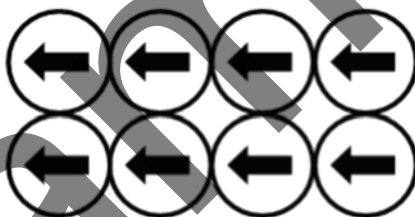

Fig.3.17: Magnetic alignment at the negative saturation point

The same occurs in the opposite direction (moving from negative saturation point to positive). Remanence and coercivity still occur as the magnetic field strength begins to increase. Table.3.4 shows the magnetic coercivity and remanence of several magnetic materials.

Table.3.4: Coercivity and Remanence values of different magnetic materials

Material	Coercivity (H)	Remanence (T)
$BaFe_{12}O_{19}$	0.36	0.36
Alnico IV	0.07	10.3
Alnico V	0.07	1.35
Alcomax I	0.05	1.2
MnBi	0.37	0.48
$Ce(CuCo)_5$	0.45	0.7
$SmCo_5$	1.0	0.83
Sm_2Co_{17}	0.6	1.15
$Nd_2Fe_{14}B$	1.2	1.2

Materials with high values of coercivity and remanence are used as permanent magnets, as they are "magnetically hard". Permanent magnets are most commonly seen in motors, as they have a lot of magnetic driving force even with no coil inductance.

"Magnetically soft" materials have low coercivity and remanence and are most commonly used in transformers to minimise losses of the transmitted electricity. Fig.3.18 shows the difference between a magnetically hard material and a magnetically soft material.
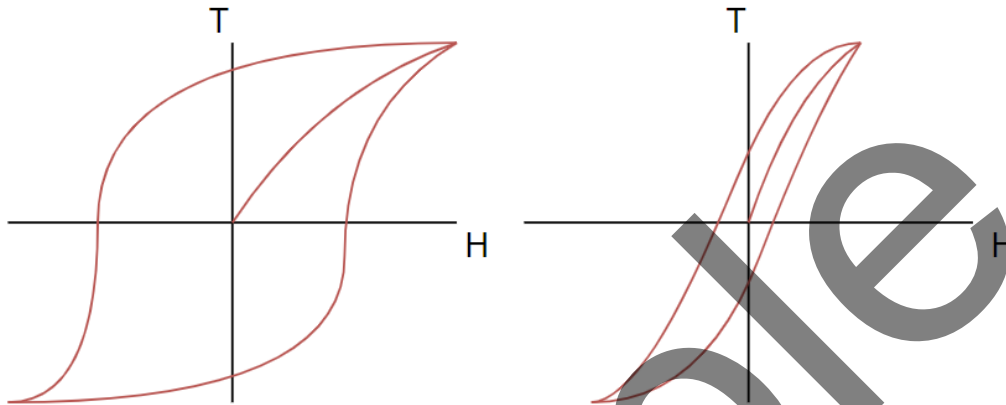

Fig.3.18: Magnetically hard hysteresis curve (left) and a magnetically soft hysteresis curve (right)