



Historical Introduction to the Development of Material Science and Engineering as a Teaching Discipline

by Clive Ferguson

1 Introduction

Metals have long held the dominant position as the most important engineering materials; steel being by far the most significant over the past few centuries. Nevertheless, increasingly in many areas this position is being challenged by other materials such as plastics, ceramics and composites. The relatively recent development of materials science and engineering (MSE) is a merger of metallurgy with polymer science, physical and inorganic chemistry, mineralogy, glass and ceramic technology and solid state physics (Cahn, 2001) to include all structural and functional materials, thus making it one of the broadest of study disciplines.

The material science concept developed from metallurgy in the 1950's almost simultaneously in the GE research laboratories in the USA, the University of California Los Angeles (ULCA), and Northwestern University (Cahn, 2002). The COSMAT report of 1974, written to ostensibly persuade the scientific committee of the existence of MSE (Cahn, 1992), defined MSE as being 'concerned with the generation and application of knowledge relating the composition, structure and processing of materials to their properties and uses' (ibid.). Cahn observes that since 1974 the main focus of MSE has moved from structure, and especially structural defects, to the influence of processing variables.

From the dawn of human existence materials have been fundamental to the development of civilisation. Anthropologists define the historical epochs by the materials used by the different civilisations such as the Stone, Copper, Bronze and Iron ages. The different rates of progression towards more sophisticated materials between cultural groups correlated with different levels of innovation and the local availability of those materials, and led to varying standards of living.

The early lack of technological information diffusion led to significant differences in advancement between cultures at any one time. For example, in 1500BC those in Asia Minor (Turkey) were already experimenting with iron, whilst in Mesopotamia (Iraq) they were still in the Bronze Age. The Europeans, Palestinians and Egyptians were in the Copper and early Bronze Age; the Chinese had melted iron and were advanced in the development of Bronze; the Spaniards and Portuguese were still in the Chalcolithic period (an overlap of the Stone and Copper Age) whilst in North Africa there was still evidence of the late Stone Age. Those in the Americas were also still in the Chalcolithic period having not yet discovered bronze, but they made beautiful artefacts of gold, silver and copper - metals they found naturally (i.e. not combined with sulphide, oxide or other ores). The Native Americans (unfortunately) had not progressed from the Chalcolithic period three millennia later when the Europeans arrived with steel guns to conquer, colonise and settle (Ohring, 1995). Even more recently, in the late 19th century the first white settlers found Australia rich in minerals of all kinds, however there too there was no evidence that the aborigines had made practical use of these minerals in their metallic form (Raymond, 1984).

Metallurgy, defined as the science and art of processing and adapting metals (Polmear, 1972), has been around for approximately 6000 years from when Neolithic man recovered and used metals through observation and deduction (Charles, 2002).

Some significant developments took place in the pre-Roman period, e.g. cold welding; the lost wax process for bronze castings including high lead additions to improve fluidity; and the control of carbon content in iron, forging and the heat treatment of steel. Manufacturing techniques improved steadily during the Greek and Roman periods but without any major progress in alloy development. In the Post Roman period metallurgy moved into the secretive period of alchemical experimentation, with an emphasis on precious metals, amalgams and chemical properties (ibid.). Some advances were made and the emergence of chemistry as an independent discipline can be traced to the need for assaying for standards of trade (Charles, 2002). However alchemy in the form of a belief in transmutation persisted into the 17th century. Even Newton (Warden of the Royal Mint) held some faith in it (ibid.)!

In the 18th and 19th centuries developments in iron and steel issued in the machine age that led the Industrial Revolution that was to transform Britain from a mainly agrarian economy to an industrial economy. This period was also called the Metallurgic Age (Skrabec, 2006). However during the 20th century there ensued an explosive increase in the understanding of the fundamental nature of materials which has led to phenomenal advances across a wide range of materials, dwarfing those of previous ages.

In this chapter we first study the significant historical contribution of metallurgical developments to the burgeoning UK industrial economy throughout the (first) Industrial Revolution, as well as the subsequent impact of poor 18th century science and engineering education. The latter part of the Industrial Revolution also marked the start of UK scientific development, the naissance of metallurgy as a profession, and subsequently the origins of metallurgical education. We then consider the historical development of each major precursor MSE science before looking at the emergence and development of MSE as a teaching discipline.

2. *The significance of metallurgy to the Industrial Revolution*

In 1700, although most employment was still in agriculture, England was already an important industrial country. The most famous of English industries at that time was the manufacture of woollen cloth which was the chief export, with leather goods and ironware coming second and third. Sheffield had long been famous for its cutlery. Firearms, nails, hardware and metal trinkets were manufactured in districts around Birmingham.

Most of industry at that time was domestic, i.e. work carried out in the worker's own homes. Although many new iron built machines had been developed in the sixteenth and seventeenth centuries, the cost of iron forgings and the inefficient harnessing and inflexibility of sources of power¹ meant that they could not be widely used, so mass production involving iron machinery was practically impossible (Hill, 1977). Machines were only used when there was no alternative, when profits were high or where the industrial unit became of sufficient size – such as breweries, iron-foundries and mines (Thompson, 1976).

¹ At that time the only available sources of power for the continuous driving of machinery were wind, water or living muscle.

Centres for the production of pig-iron were widely scattered across the country and included Sussex, South Wales, Yorkshire, Cheshire and the Forest of Dean but the total output of these centres was small and insufficient to meet the demand of those areas that manufactured iron goods. Moreover manufacturers of quality steel goods such as the cutlers of Sheffield needed better quality raw materials which they imported from Sweden (Hill, 1977).

Typically the manufacture of iron goods took place on the coal fields as coal could be used as the fuel in this process. Britain was blessed with vast coal reserves and with the growing shortage of wood had, by the Middle Ages, become the world's largest coal consumer. However the production of pig-iron was dependent on the availability of charcoal. The shortage of timber suitable for making charcoal restricted output and made pig-iron expensive. Many of the pig-iron production centres had already exhausted their local supplies of timber and new centres were being built in parts of the country where timber was still available. The drawback of using coal to make pig-iron was the presence of sulphur, phosphorous and other contaminants which made the pig-iron impure, brittle and impossible to cast (Thompson, 1976).

A century earlier the brewers in Birmingham had switched from charcoal to coal for their furnaces but found the sulphur in the coal tainted the malt. In 1603 Sir Hugh Platt suggested the idea of charring the coal to remove the impurities – just as wood was charred to make charcoal. It was not until about 1642 that the brewers of Derbyshire achieved a method of charring the coal – which they called 'coaks' (Raymond, 1984) and were able to confirm that malt dried with coke was untainted and produced sweet pure beer (ibid.). In 1709 Abraham Darby (who served an apprenticeship associated with the brewing industry), convinced that the same volatiles that tainted the malt were also responsible for making cast iron brittle and useless, used coke to produce the first iron of moderate quality using a coal product (ibid.). Initially this process was limited to the production of pig-iron suitable only for casting. It was 1750 before Abraham Darby Junior improved his father's process to produce small quantities of bar-iron suitable for forging.

The use of coke for smelting was slow to spread. In 1740, of 59 furnaces in Britain, Darby still had the only coke furnace however thirty years later 81 out of 109 furnaces were using coke (Thompson, 1976). Nevertheless, coke produced pig-iron still carried more impurities than charcoal furnaces and manufacturers of quality iron and steel products still imported iron from Sweden.

Around 1740 Benjamin Huntsman, a clockmaker developed a process of making small quantities of impurity free cast steel which was flexible and peculiarly hard. It was suitable for articles such as watch springs and razor blades. The process involved hardening bar-iron by heating in a charcoal oven for 12 days and then melting it in small clay crucibles in a coke furnace so hot that all impurities were burned away (Hill, 1977); (Skrabec, 2006).

The Seven Years War with France (1756 – 63) placed demands for munitions that led to the opening of new ironworks and hastened the next important technical developments. John Wilkinson, who, amongst other wide business interests, owned a group of blast furnaces in the Midlands and ironworks in France, was significant in enabling the commercial development of Watt's steam engine by supplying accurate borings and castings.

Watt's first attempt had not worked because of the poor accuracy of the parts. His financial partner went bankrupt and Watt fell into debt. His later partnership with Matthew Boulton, a small metal goods manufacturer, successfully rebuilt the trial engine - the world's first really effective steam engine - with more accurate parts. This was largely due to the use of John Wilkinson's newly devised cannon lathe, which was able to bore the cylinder to the necessary accuracy (Hill, 1977).

It was Watt's steam engine (and subsequent developments) that was to enable the machinery age that characterised Industrial Revolution, and Wilkinson became the first ironmaster to use the steam engine to blow the blast of his furnaces and drive the hammer at his forge. However the cost and quality of iron and steel still remained the barrier to the machinery age. The high stresses imposed by steam power demanded the replacement of the common materials used in machinery from wood and stone to iron. It took the next major iron industry development to provide the essential breakthrough.

In 1783 Henry Cort invented the processes of puddling² and rolling to produce quality bar-iron in quantity. His puddling process was to reheat the pig-iron in a reverberatory coke fired furnace and stir or 'puddle' the molten mass with iron rods to burn away most of the carbon, and other impurities. After collecting and cooling the molten metal in 'loops' or 'blooms' the rolling process involved reheating the metal and passing it through rollers to produce bar stock, and at the same time press out the remaining dross. The resultant iron was comparable to metal produced by charcoal (Hill, 1977; Thompson, 1976).

The iron makers were now free of their dependence on wood for charcoal. The previously widely scattered iron industry began to centre on the coalfields (thus cutting transport costs). The greatly improved quality meant the cutlery and other manufacturers of high quality steel products were no longer dependent on expensive Swedish iron imports. The availability of cheap high quality iron now paved the way for the age of machinery - the 'first' Industrial Revolution³ - providing the accuracy, strength and durability essential for mechanical development. By 1800 England had a steel monopoly and controlled Europe's supply⁴ (Skrabec, 2006).

As with all major wars further immense stimulus and catalyst for technological development was created by The Great French War (1792-1815) which demanded mass mobilisation and huge orders for equipment (Thompson, 1976). This ended more than a hundred years of conflict with France from which Britain emerged more powerful than at any previous time in her history (Hill, 1977) and allowed her industries to develop at a rapid rate during the 19th century.

² In the 1970s a first century AD Chinese puddling furnace was discovered in the Henan province, leading to the conclusion that in fact Cort had **reinvented** puddling.

³ Barry Jones (1995) proposed that there were three Industrial Revolutions. The first, the most recognised Industrial Revolution, was the 'Steam' Revolution. The second Industrial Revolution (1869-1910) was the Electric Revolution and the 3rd is the Information Revolution. This chapter will show the significance of Materials Science and Engineering in each.

⁴ Breaking that monopoly became a passion of Napoleon who offered a reward to the first manufacturer on the continent who could produce cast steel of British quality. This led to the formation of the Krupp Cast Steel Factory in Germany (Skrabec, 2006). Krupp's biographer Norbert Muhlen is quoted as saying that 'Krupp used spies to help fully understand the Sheffield steel making process' (ibid.).

In the early 19th century there was a dramatic extension of engineering into new areas of industry with a rapid series of inventions and incremental innovations. The power/weight ratio of the steam engine was vastly improved and Trevithick's development of a direct-action steam engine provided the potential for self-propelling locomotion and the application to transport - principally to the railways and increasingly to ships⁵.

Essential support for these developments were the advances taking place in the iron and steel industry, including Neilson's 'hot blast' in 1825 that further improved the quality of the iron and the fluidity of the slag, enabled the use of lower quality coal rather than coke and reduced the fuel/ore ratio from 1.5:1 to 1:1. Initially the higher furnace temperatures however led to considerable problems – particularly the cracking of the cast iron pipes that comprised the blast regenerative heating stoves. Nevertheless the advantages were well worth the cost and the later invention of refractory type regenerator stoves by Cowper and Whitwell solved the problem.

In 1851 the Great Exhibition in London - with working exhibits of steam engines, pumps, textile machinery, machine tools and a multitude of products from British industry - demonstrated that Britain still had the lead in industrial development. She laid claim to the title 'the 'workshop of the world' and was virtually unchallenged in industrial supremacy, producing 40% of the world's manufacturing output (Jones, 1995). Nevertheless it was the German steel company of Alfred Krupp that won the gold medal for his cast steel cannon.

Further significant developments in steel manufacture were to come. The first in 1856 was the Bessemer/Kelly converter. The process involves pouring molten pig-iron from the Blast Furnace into a brick-lined kettle. Powerful jets of air were then blown into the bottom of the converter and the oxygen in the air jets burns out the carbon directly to produce steel. Problems with the composition, porosity and over-oxidation were eventually mostly solved by the British metallurgist Robert Mushet in 1857. However most of the world's ores contain phosphorous and it was another two British metallurgists, cousins Thomas and Gilchrist, who in 1879 developed the process of using a limestone brick in the converter lining to remove the phosphorous (Tylecote, 1992).

The second in 1865 was the Siemens-Martin process (also known as the open-hearth process) which used regenerative preheating of combustion air and gases, reusing the heat from the furnace exhaust gases to generate furnace temperatures of around 870⁰C. Impurities including carbon float out of the molten iron to form a slag on the surface which is poured off. It is controlled to ensure the correct carbon level remains to make steel.

Towards the end of the 19th century, during what Barry Jones refers to as the Electric (or 2nd) Industrial Revolution, cheap electricity from dynamos led to the development of electric furnaces. The electric induction furnace by Roechling and Rodenhauser first went into production in 1907 and led to the replacement of the Huntsman crucible process for high quality steels such as ball bearings, stainless steels, and die and tool steels.

⁵ Trevithick's initial experiments in 1801 were with 'road locomotion' - a steam powered automobile!

The first patent for the use of an electric arc furnace to produce steel was by an Italian, Stassano in 1898. However following an intense and lengthy Norwegian development of this process, it was the late 1940s before the process was first adopted to make pig-iron in Northern Norway. Later, 3-phase arc furnaces with acid or basic linings provided an economical way to make steel by melting and alloying scrap, and a more recent development using an oxygen lance has extended this method to enable pig-iron to be used (Tylecote, 1992). Electric furnaces have a higher output/capital cost ratio as well as lower maintenance costs so as the difference in cost between electricity and other fuels continues to diminish, electric furnaces become increasingly cost effective.

The next major development was the Austrian development of Basic Oxygen Steelmaking (BOS) which took place in the early 1950's. This replaces the air jets in the Bessemer converter with oxygen jets to reduce the high nitrogen content of Bessemer steel. Initially this process had to use low phosphorous pig-iron but a later development of adding lime to the oxygen jet enabled higher phosphorous pig-iron to be used. BOS now produces most of the world's mild steel (Tylecote, 1992).

A further development, hot metal dephosphorization, took place in Japan in the 1980's. In this process most of the phosphorous content is removed from the hot metal whilst in the ladle prior to charging the converter using oxidising fluxes. This method so far has not been applied outside of Japan (MATTER, 2007a).

2.1 Special Steels

In 1860 the main product of the Sheffield steelmakers was high quality carbon steel using the Huntsman crucible furnace. Focusing on the development of improved and specialised steels, they experimented with developing new steel alloys using the wide range of newly discovered metals. The most important included cobalt (1730-1737), tungsten (1783), chromium (1798), nickel (1804) magnesium (1852) and titanium (1910).

Mushet discovered his famous 'self-hardening' tungsten steels, considered the forerunner of high speed steels, through carrying out experiments involving the addition of manganese to crucible steel made from Swedish iron (Tylecote, 1992). In 1865 he astonished the Paris Exhibition with his tungsten tooling which almost doubled tool cutting speeds. Further development of Mushet's alloy over the next 30 years led to the manganese being entirely replaced by chromium (ibid.)

The next major step to high speed steels took place in the 1890s when Frederick Taylor 'The Father of Scientific Management' and Maunsel White of Bethlehem steel in the US applied Frederick Taylor's scientific experiment methods that resulted in the development of a patented high temperature heat treatment to create steel that could retain its hardness at high temperatures and capable of retaining its cutting strength in the red hot condition (Skrabec, 2006). Bethlehem Steel was awarded the gold medal for this 'tool steel' in the 1900 Paris Exhibition. The tool steel created a revolution in the machining industries which demanded new stronger machine tool designs able to take advantage of this new development.

Further development led in the early 20th century to 'high speed steels'. Modern high speed steels contain tungsten, chromium, molybdenum, vanadium and/or cobalt and

require high temperature heat treatment. They are characterised by a combined tungsten–molybdenum content of 10-11%

In 1889, James Riley made a tremendous impact on the armaments and other engineering industries through his invention of nickel steel. He found that by adding up to 4.7% nickel he was able to increase the tensile strength of steel from 460 to 1400MN/m² with an increase in toughness and only a minor decrease in ductility (ibid.) (Tylecote, 1992). This stimulated other researchers into the study of nickel-steel alloys using various additions including chromium, aluminium, vanadium and titanium. Portevin in 1905 established that steels with more than 9% Cr resisted acid attack, and Strauss of the German steelmaker Krupps, aware of the significant heat resistance of high chromium-nickel steels, in 1912-1913 patented a 20% Cr, 5% Ni steel. This steel was difficult to work and could not be hardened by normal heat treatment. It was Harry Brearley of the Firth-Brown Research Laboratories in Sheffield who is generally credited as the inventor of stainless steel. In 1914 he patented a 12-14% Cr steel which eventually became the mainstay of the cutlery industry. Later Strauss's steel was also recognised as being stainless steel (Tylecote, 1992).

Following WWI, steady improvement of the major steel types took place through continuous research and development across many countries using additional elements such as aluminium, niobium, molybdenum, titanium and cobalt.

2.2 Aluminium

Aluminium is the most abundant metallic element in the earth's crust. The salts of aluminium had been used by the Greeks and Romans for dyeing and as a wound dressing but it was not until 1808 that Humphrey Davy⁶ identified the metal base. Wohler is credited in 1827 as being the first to isolate aluminium as a metal. Nevertheless the Danish physicist Orsted, whilst studying the process of electrolysis had already published widely read papers that demonstrated that two years earlier he had produced aluminium as a by-product of his experiments. Both had used chemical reactions between aluminium chloride and potassium to produce grains no bigger than a pinhead and the cost of production of aluminium by this method was \$US545 per pound! The French chemist Deville in 1854 brought down the price to \$US16 per pound using a complex sodium reduction process and provided a starting point for the Hall-Heroult process (Skrabec, 2006). It's pricing still placed aluminium as a semi-precious metal rather than a practical engineering metal.

However in 1886 Hall in the US and Heroult in France simultaneously and independently developed an electrolytic process for the freeing of aluminium from its ore (aluminium oxide) using the addition of a new solvent fused cryolite Na₃AlF₆. (Bowden, 2005 (web edition)) As aluminium oxide is one of the earths most stable compounds the freeing of aluminium from its ore was a complex metallurgical problem.

However the process not only requires many intermediate steps but also vast quantities of electrical power. The production of aluminium in commercial quantities was dependent on the Electric Industrial Revolution. Success rested on the availability

⁶ Humphrey Davy discovered over 20 new metals and because of this is sometimes referred to as the 'father of metallurgy' (Skrabec 2006).

of powerful electric dynamos. For Hall who commenced production in 1888 this was supplied by two Westinghouse Dynamos rated at 1,200 amps and 25 volts. By 1892 his company (later to become Alcoa) was producing 138,307 pounds per year at \$US0.65 per pound. (Skrabec, 2006) It had become truly competitive as an engineering material. The Hall-Heroult process is still the only commercial process to produce aluminium.

As the cost of the electricity supply forms most of the cost of aluminium, aluminium refineries are placed close to low cost electrical energy supplies. The most modern smelters consume 25 000kW.h/t (Tylecote, 1992). Using recycled aluminium creates considerable energy savings in the production of aluminium as recycled aluminium uses only about 5% of the energy (MATTER, 2007b).

As an engineering material it has numerous advantages such as good strength, light weight, corrosion resistance, good electrical and heat conduction, easy to cast, and is 100% recyclable. It is also a useful additive to steel as a deoxidizer which improves the casting of steel and initially this made the steel industry the biggest customer for aluminium. Even today aluminium additives are critical in continuously cast steel (MATTER, 2007b) (Skrabec, 2006).

2.3 Traditional metals

As well as discovering many new metals scientists of the 18th and 19th centuries made significant advances in the ore extraction and the isolation of a number of traditional metals from their ores. These included copper (in great demand from the new and expanding electrical industries), platinum (it's great acid resistance gave it an initial use in chemical apparatus and crucibles), lead, and the precious metals gold and silver.

3. Science and engineering education.

3.1 Reasons for the erosion of Britain's lead in the first Industrial Revolution.

Jones (Jones, 1995) suggests that Britain's industrial lead eroded in the second half of the 19th century was largely due to a sudden switch in government economic policy from a long period of 'large government' economic policy (i.e. large spending on infrastructure, facilities and services) to 'small government' economics at a time when her competitors (US and Germany) were increasing infrastructure spending. For example Bessemer steel had enormous impact on the US economy initially in their development of railways and by 1895 Bessemer steel production in the US amounted to 60% of its gross national product! (Robert Hessen cited (Skrabec, 2006).

However Pullin (Pullin, 1997) states 'some historians argue that the lack of scientific foundation in British engineering may have been a factor'. Engineering Heritage: Highlights from the History of Mechanical Engineering (1963,) supports this viewpoint. It argues that most engineering achievements up to around the 1860s showed a lack of theoretical foundation and there was little evidence that these early engineers were conscious of the scientific discoveries of Newton, Hooke, Boyle and others. 'For a century or more they got on very nicely without much theoretical framework and when science began to catch up with engineering, they - or their successors - were slow to realise that times had changed; that further progress had to be based on physics and

chemistry' (ibid.). The process of invention was described by Jones (1995) as mainly 'amateurs' responding to deficiencies in existing industries.

Burstall (Burstall, 1965) cites Sir William Fairbairn's report of the Paris Exhibition of 1855:

The French and Germans are in advance of us in theoretical knowledge of the principles of the higher branches of industrial art; and I think this arises from the greater facilities afforded by the institutions of those countries for instruction in chemical and mechanical science.....we have perseveringly advanced the quantity, while other nations.....have been studying with much more care than ourselves.....and are in advance of us in quality.

The blame can be laid squarely on the total inadequacy of the prevailing system of education in England. Most English and Welsh children of the 18th century either did not go to school at all or at best went for a very short time. Scottish children were better off as parish schools existed over most of Scotland since mid 17th century (Hill 1977). In England in the early part of the 18th century, children of the poor who received any education received it from Charity Schools which gave elementary instruction in reading, writing and arithmetic. Children of the wealthy middle classes often went to the Grammar Schools which provided slightly less elementary education but had an overly narrow focus on the classics and did not meet the needs of the industrial age. Both types of school fell into decline in the second half of the 18th century. The sons of the nobility either had private tutors at home or were sent to board at the very small group of elite 'Public Schools'. The English government made no grant of public money to education until 1833, and had no universal system of elementary education until 1870. In 1880 compulsory education to the age of 10 was introduced but it was not until 1891 that this elementary education became free (ibid.).

3.2 British (and Continental European) Higher Education

Prior to 1828 there were only the universities of Oxford and Cambridge. They drew their entrants primarily from the prestigious Public Schools attended by children of the nobility and the wealthier upper and upper-middle classes. Hill (Hill, 1977) paints an appalling picture of the educational standards of these two universities in the period to 1800. Oxford professors rarely lectured, its 'examinations both for entrance and degrees were farcical' and 'Cambridge was a little less bad'. Hill indicates that it was close to 1900 before they became healthy and efficient, and 1930 before the enrolment of non Public School educated students approached 25% (ibid.).

Classics and arts were the traditional university studies in England and in the conservative atmosphere of the universities were considered 'higher forms of academic life' than science, the newcomer. Engineering, the latecomer, was considered, particularly by those at Oxford, as hardly a fit subject for university study (Gerstl, 1966).

Drucker (Drucker, 1993) provides interesting background to this. He describes a radical change in the meaning of knowledge that took place in the West around 1700 from a core of learning akin to 'liberal education' as we understand it today, towards 'utility' (i.e. vocationally related skills and knowledge). Although contempt for 'skill' was significant in the East through the Confucian, Taoist and Zen beliefs, in the West this contempt was unknown until the English gentlemen of the 18th Century adopted it as 'a

last ditch' defence against being replaced as society's ruling class by capitalists and technologists (ibid.).

In contrast Scotland's three universities and two colleges were notably progressive and more democratic than the English. The parish school system provided opportunities for all. Most Scottish university students came from the working class and were determined to make the most of their education. The universities thrived particularly in medicine and science and attracted many able students from England and elsewhere. Billington (Billington, 1996) describes Scotland at that time as 'the intellectual centre of Great Britain'.

At the start of the 19th century the traditional university system in Central Europe went through a major reformation. (Fallon, 1980) describes most of the universities of German speaking Europe at the end of the 18th century as 'sites of rote disputation inhabited largely by pedants'. They taught 'usually by reading aloud from old texts' (ibid.). They were held in low regard and between 1792 and 1818 most ceased to exist. This changed when Wilhelm von Humboldt, Privy Councillor for Culture and Public Instruction (1809-1810) in the Prussian Interior Ministry developed a comprehensive system of public state-controlled education from elementary through to university level. He created the University of Berlin as a widely admired new university model based on three principles:

1. The unity of research and teaching.
2. Protection of academic freedom; the freedom to learn (for students to pursue any curriculum) and the freedom to teach (the right to free inquiry).
3. The central importance of the Arts and Sciences⁷ which led to and gave significance to the concept of pure research in universities. (Fallon, 1980) ibid.)

He persuaded some of the most respected German scholars to accept appointment to the professorial positions in the university and instigated a strong relationship between secondary schools and the university that included university entrance exams on graduation from secondary school, and mandatory state (university) certification of secondary teachers. He also upheld that the state had a natural responsibility to fund universities and their research (ibid.).

Drucker (Drucker, 1993) describes this as the birth of the modern university. Higher education institutions throughout central Europe soon followed the 'German university' model. Humboldt's model also had the most profound influence on American higher education - particularly the graduate school. This was because at this time there were no higher degree places in the US and in the aftermath of the American War of Independence higher degree places for US citizens in the UK were 'limited', so most US citizens who wished to take higher degrees studied in Germany. The German university model also stimulated university development in Great Britain (Fallon, 1980).

The first engineering courses in continental Europe were established almost a century earlier than those in the UK and most were in new separate technical universities under state or royal patronage. Amongst the earliest were St. Petersburg, Prague and Berlin.

⁷ The practice in Europe previously was that all students had to study arts and sciences before studying in the 'higher faculties' such as theology, law, or medicine. Thus the arts and sciences had lower status.

In France the *École des Ponts et Chaussées* was established in 1747 to train civil engineers for government service. Others quickly followed setting high standards in mathematics and engineering science. However it was the instruction in engineering science at the *École Polytechnique* in Paris (founded in 1795) that set the standard in continental Europe throughout the 19th century. It began with a two-year course in mechanics, physics, chemistry, and mathematics, followed by courses by practising engineers in design, construction and operation (Burstall, 1965). They established the concept of a high-level professional school.

German polytechnics followed a similar plan to the *École Polytechnique*, but they educated technical people at all levels and established research institutes at the top. By 1830 polytechnics were established in seven major German cities (ibid, p.202) and both the German and French polytechnics/polytechniques flourished as independent technical universities.

World-wide, by the end of the 19th century Australia, South Africa, Canada and even less developed countries such as Japan (at that time) had established university engineering courses. But in the United States of America the rate of establishment of higher technical education (and the rate of industrial growth) began to out pace the rest of the world.

By 1900 the standard of engineering teaching at many American universities was comparable with any in the 'Old World' and a greater proportion of the population was being taught (ibid.). In contrast, at this time Britain 'had fewer universities in proportion to our population than any other civilised country in Europe with the exception of Turkey' (Bowden cited (Gerstl, 1966).

4. *Developments in the Formation of Metallurgists*

Public acceptance of metallurgy as a profession in its own right dates back less than 150 years. Its predecessors were the alchemists and blacksmiths who practiced their arts of armoury, shaping, treating and using metals (Polmear, 1972) without any awareness of the science involved.

The genesis of chemistry and metallurgy is deeply embedded in mining. Courses in metallurgy first started in chemistry departments towards the end of the 19th century, mainly focused on chemical analysis of minerals and assaying for precious metals (Polmear, 1972). Polmear describes them as 'wayward chemists who became involved in assaying and the quantitative analysis of minerals' (ibid.).

The early development of mainly metallurgical scientific study to the production of iron and steel led to the formation of the Iron and Steel Institute – a proto-professional organisation (Lundgreen, 1990) - in 1869. Twenty years later (1889) this was supplemented by the Institution of Mining Engineers. However as with the other engineering institutions of the time, education played no part in membership criteria. Practical training and either years of experience in a position of responsibility or eminence in the profession formed the early membership requirements.

Within the Empire the origins of the educational formation of metallurgists began in London in the Government School of Mines and Sciences Applied to the Arts established in 1851 which was developed from the Museum of Economic Geology

which opened 10 years earlier. In 1853 it merged with the Royal College of Chemistry and in 1863 became the Royal School of Mines; subsequently (in 1907) becoming a constituent college of the Imperial College of Science and Technology.

Records of the second School of Mines within the British Empire – the School of Mines, Ballarat (SMB) – depict the course content of these early metallurgy courses. SMB was established on the goldfields of Victoria, Australia in 1869 by the University of Melbourne. A Certificate course in Inorganic Chemistry and Metallurgy supported by an ‘Analytical Laboratory’ and a ‘Metallurgy Laboratory’ began in 1871. The program began with a group study of chemistry of metals in the first term, and in the second term they undertook practical exercises in assaying for silver and gold (Polmear, 1972)⁸.

By the 1880’s the syllabi for Ballarat and comparable institutions in Australia and overseas comprised assaying, chemical analysis and the new topic of electro-metallurgy⁹. In 1890 the qualification was upgraded to an Associate of the School of Mines; a three year course covering physics, chemistry, metallurgy, geology, mineralogy, petrology and applied electricity (ibid.). It was not until 1914 that limited coverage of secondary metallurgy topics such as alloying behaviour were included but soon the handbooks referred to career opportunities for secondary metallurgists with the principle attraction being the opportunity to live a conventional city based life (ibid.).

Internationally a sudden increase in courses and departments of metallurgy emerged in the early 1920’s. Notable examples included the establishment in 1923 of a Faculty of Metallurgy at the University of Sheffield; a course in Metallurgy at the University of Cambridge; a Department of Metallurgy at Tohoku University¹⁰ in Japan and in 1924 a School of Metallurgy at the University of Melbourne¹¹ (ibid.). Nevertheless, other major universities commenced Metallurgy courses much later. For example, at the very conservative University of Oxford, Metallurgy only occurred in the early 1950s as an option in the Chemistry degree. It was 1960 before the first intake into a Metallurgy course and this was still heavily based on Chemistry.

In the late 1960s, Professor Richardson of Imperial College depicted schematically the contemporary ideas of the structure of the profession of metallurgy. He depicted metallurgy as having three components:

1. Extractive metallurgy extending from ore-pre-treatment through to refining and solidification.
2. Mechanical metallurgy comprising casting, shaping and metal treatments.
3. Design based on knowledge of the behaviour of industrial alloys and related materials such as refractories.

Richardson proposed that these were in essence based on chemical metallurgy, process science and physical metallurgy: metallurgy being based predominantly on process science and chemical metallurgy; mechanical metallurgy being based on

⁸ By the 3rd term the number of students in the course had dropped from an initial student intake of 5 to only 2.

⁹ The Hall and Heroult electrolytic process for the extraction of aluminium was developed at that time.

¹⁰ It is interesting to note that a year earlier the university had renamed its before By the early 1970s Tohulu University had the world’s largest undergraduate metallurgy course.

¹¹ The other Australian states did not have university courses in metallurgy until after WWII.

physical metallurgy and process science; and design based predominantly on chemical and physical metallurgy (Martin, 1969).

The more traditional depiction was that metallurgy comprised both primary and secondary metallurgy. Primary metallurgy was essentially concerned with mineral dressing, metal extraction and refining whilst secondary metallurgy was essentially mechanical and physical metallurgy and the economic application of metals (Polmear, 1972).

5. The development of the precursor sciences

5.1 Metallurgy and Metallography

In 1722 Reaumur became the first to investigate the internal structure of steel using the light microscope, enabling him to develop a schema for the internal structure of steel. By the end of the century Clouet and deMorreau discovered that iron gains its hardness through the presence of carbon, and the first systematic studies on crystallisation and fusibility of alloys were started by Rodberg in 1831 (Dobrzanski, 2006).

Henry Sorby in 1863 was the first to use microscopy techniques on etched steel to discover its microstructure and witness the Widmanstätten structure (Smith, 1963). Later he developed the process of photomicroscopy to produce a permanent record (Tylecote, 1992). Photomicrographs became a basic tool of metallography and the developed understanding of microstructures has enabled metallurgy to gain most of its eminence as a science and much of its ability to control industrial products (ibid.).

From 1885 a number of notable scientists and engineers contributed to the development in 1901 of the nearly correct Roberts-Austen iron-carbon equilibrium diagram based on the phase rule and accepted thermodynamic principles of chemistry. At about the same time the use of crystallography changed previous misconceptions of the nature of quenched steel to one of crystallinity and the deduction that gamma iron is cubic.

Further developments in metallurgy and in materials science have been dependent on the availability and expertise in the use of increasingly advanced instrumentation. Controversy reined over the allotropy of iron and its relationship to the hardening of steel until 1912 when the availability of X-ray diffraction became a new tool in the armoury of metallurgists (ibid.). The following year Braggs used X-ray diffraction to determine the lattice parameters and in 1922 it was used to study alloy constitution and the structures of alpha, beta, gamma and delta iron were finally resolved.

The continuing accumulation of alloy constitution data gained through X-ray diffraction techniques enabled continuing studies into fields such as the properties of grain boundaries, the effects of impurities, the symptoms of diffusion in the solid state and the effects of mechanical deformation on the crystal structure. Early studies into age hardening of aluminium alloys led to the development of 'Duralumin' with an increase in strength of a factor of two compared to commercial purity aluminium. One of the first applications of Duralumin was for the airframes of the Zeppelins in WW1. The phenomenon of age hardness was better understood with the use of X-ray diffraction over the use of the microscope but it was the availability of the electron microscope, designed by Knoll and Ruska in 1931 (Dobrzanski, 2006), that enabled these theories

to be fully confirmed in the 1950's. These theories have since led to a remarkable range of high strength alloys and more are still being developed.

Tylecote suggests metallurgy's greatest contribution to science has been the discovery of dislocations in metals, This discovery led to significant contributions to the whole of solid state physics (Tylecote, 1992).

It had become clear from work by Roberts-Austen on diffusion in both molten and solid metals presented in his 1896 Bakerian lecture, that defects were present in metallic materials. However physicists preferred to believe in idealised models and ignore structure related properties of matter. It was an engineer C.E. Inglis who in 1913 first proposed that inherent defects in solid materials would (under tensile stress) propagate as cracks. This was investigated by A.A. Griffith who propounded the Griffith crack theory, originally for non-crystalline material, in 1920.

However it was clear that large cracks were not present in wrought metals and that another mechanism was needed. Gradually the concept of line defect dislocations in the form of additional lines of atoms normal to and terminating at the slip plane was born. W.L. Bragg developed a model of the lattice structure using a layer of soap bubbles leading to the development of a comprehensive theory. However it was not until 1951 that the invention of Muller's field microscope enabled discrete point defects to be seen, and 1956 before developments to the electron microscope by Hirsch and others enabled the dislocations moving through metals to be seen and filmed (ibid.).

5.2 Solid state physics and solid state chemistry

5.2.1 Solid state physics

Solid state physics and chemistry are crucial to the development of modern materials science. The bulk of solid state physics theory and research has been focused on crystals. Nonetheless solid state physics also embraces the fields of electronic structures and electronic transport (e.g. electron hole, exciton, magnetoresistance and superconductivity), mechanical and optical properties (e.g. specific heat, elasticity, lattice vibrations and crystal optics) as well as amorphous solids.

The focus on crystals is largely because the periodic structure of atoms in a crystal enables mathematical modelling, but also because they often have mechanical, optical, magnetic or electrical properties that can be exploited. Thus knowledge of crystal structures are indispensable, but that knowledge only emerged after the advent of X-ray diffraction from crystals in 1912 (Cahn, 2001). At that time many of the pre-war physicists held physics of the solid state in near contempt (Cahn, 2002) and in 1930 when Wilson proposed the first quantum theorem of semiconductor function, he was warned that by concerning himself with such useless dirty substances he risked professional suicide (ibid.)!

However in the 1930s, various books on the topic as well as the Bragg/Williams papers on the statistical mechanics of ordered alloys paved the way for recognition of solid state physics and Seitz's 1940 textbook 'The modern theory of solids' marked the turning point.

After WWII Seitz published two classic papers on the interpretation of colour centres in

ionic crystals which led eventually to superionic conductors, modern storage batteries and fuel cells. At the same time physicists such as Nabarro and Mott produced the first quantitative analyses of the dynamic properties of dislocations (ibid.). This led in 1949-1950 to a number of metallurgists, most notably Cottrell of the University of Birmingham, developing strictly quantitative theories of dislocation behaviour and alloy equilibria which could be experimentally verified. Cahn proposed that this led to the 'quantitative revolution' that 'forever changed physical metallurgy'.

5.2.2 Solid state chemistry

Solid state chemistry and its modern derivative materials chemistry, are post WWII developments of 'crystal chemistry': systematic research into chemical and physical features that control the structures in which chemical families crystallise (Cahn, 2001). From the 1930s many books were published on this topic. The most important developments of solid state chemistry over crystal chemistry were the investigations into crystal defects. The solid state chemists' first major contributions were through a classic book on the linkage of crystal defects to non-stoichiometry by Kroeger in 1974, and another on disorder in crystals by Parsonage and Staveley in 1979.

Solid state chemistry through its direct relevance to commerce has been strongly driven by advanced technology and its 20th century application focused discoveries have included platinum and zeolite-based catalysts for petroleum production in the 1950s, high purity silicon for microelectronic devices in the 1960s, and high temperature superconductors in the 1980s.

Solid state chemistry entered materials science as 'materials chemistry' much later than solid state physics. By 1990 crystal defects, phase transitions and novel methods of processing were just beginning to define materials chemistry. However, at that time, following a report from their Committee on MSE calling for increased emphasis on material synthesis and processing for chemists in the materials field, the US National Research Foundation issued a formal call for research proposals in that area, thus directly influencing the direction of this sub-field of materials science and engineering.

5.3 Inorganic and Physical chemistry

In mid 19th century there were only inorganic chemistry (the French call it mineral chemistry) and the burgeoning discipline of organic chemistry. Inorganic chemistry is defined as 'the study of chemical elements and their compound other than compounds of carbon, however the oxides and sulphides of carbon and the metallic carbides are generally included in organic chemistry'(Walker, 1991). It is primarily concerned with acids bases and salts. Organic chemistry is the study of compounds of carbon.

This was a significant period in the discovery and isolation of a wide range of chemical elements including tartaric acid, chlorine, sodium, potassium, boron, iodine, selenium, thorium, silicon, titanium and zirconium.

Amongst the major events that had taken place in inorganic chemistry at that time:

- Lavoiser, ‘the father of chemistry’ had proposed a theory of acids which had been corrected by Berthollet. Together they had devised a chemical nomenclature; the basis of the modern system of naming chemical compounds.
- Avogadro had proposed his Hypothesis that equal volumes of air contained the same number of molecules.
- Berthollet¹² had contributed to the development of stoichiometry through analysing the combining of weights of atoms.
- In 1811 Davy had laid the foundations of electrochemistry, studied electrolysis of salts in water. Gay-Lusac¹³ discovered litmus acid-base indicators.
- Berzelius had classified minerals according to their chemical properties.
- Thomas had studied membrane diffusion of solutions and established the foundation of colloid chemistry.

Nevertheless at that time chemists of both disciplines were mainly focused on methods of synthesis and the establishment of the quantity of the different atoms in each newly synthesised compound. As a science chemistry was at a descriptive stage that simply recorded the process outcomes to result in masses of accumulated data. However physics had progressed beyond that stage to the stage of determining the general governing laws for the appropriate phenomena (Cahn, 2001).

The German chemist Wilhelm Ostwald considered chemists were focusing too narrowly on the composition, structure and properties of the chemical elements involved in the chemical processes leaving unanswered questions relating to the rate, direction and yield of chemical reactions (ibid.). He felt chemists needed to study the conditions under which compounds formed and decomposed and also to study the problems of chemical affinity and equilibrium, reaction velocity and mass action (ibid.). He was given the opportunity to make an impact when, in approximately 1887, aged only thirty four, he was offered a chair in chemistry at the University of Leipzig – a major research university. Considered one of the three founders of physical chemistry his founding work was on mass action. Nevertheless Ostwald’s Nobel Prize for Chemistry awarded in 1909 was for his work in catalysis. The two other founders of physical chemistry were Jacobus van’t Hoff and Svante Arrhenius (ibid.).

Van’t Hoff, originally an organic chemist who had already published a pamphlet giving rise to stereochemistry (see below), carried out physical chemistry research into reaction dynamics, osmotic research in solutions and on polymorphism. He was awarded the inaugural Nobel Prize for Chemistry in 1901 (ibid.).

Svante Arrhenius recognised and proved the concept that constituent atoms of salt when dissolved in water dissociated into charged forms, now called ‘ions’. This was based on a lengthy systematic study of electrical conductivity of progressively diluted solutions. He also noted that no current was needed to promote ionic dissociations (ibid.). He received the Nobel Prize for Chemistry in 1903.

Walther Nernst was another notable scientist who in 1887 was invited to join Ostwald. His research was on the theory of electrochemistry.

In the US physical chemistry grew from the influence of Ostwald’s forty four American research students. One, Willis Whitney, founded America’s first industrial research

¹² Berthollet also discovered the bleaching capacity of chlorine.

¹³ Gay-Lusac also developed an improved method of making sulphuric acid.

laboratory for General Electric which employed Nobel Prize winner metallurgist Irving Langmuir who undertook research into the physical chemistry of gases and surfaces. This enabled considerable industrial innovation particularly in incandescent lamps.

Noyes, another of Oswald's students, tried unsuccessfully to establish a graduate school of physical chemistry at MIT but was eventually successful in Throop College of Technology, Pasadena, California (now Caltech). He founded the science of physical chemistry in the US and by the early 1920s physical chemistry was well established in European as well as US universities.

5.4 Polymer science

In the early 19th century Berzelius proposed that 'substances of equal composition but different properties be called *isomers*'. The following year he proposed the name '*polymeric*' for the larger of two compounds with the same relative composition but different absolute numbers of molecules in each molecule. The term '*polymer*' was slow to be adopted and initially misunderstood.

During the 19th century chemists studying the global compositions of compounds developed the concepts of stereochemistry and its consequence; optical isomerism.

In 1874 van't Hoff proposed that a carbon atom carries 4 valencies (already recognised by August Kekule in 1858) directed towards the vertices of a regular tetrahedron. Louis Pasteur in 1850 had noted an optical activity in tartrates in that when they were dissolved in a liquid they would rotate the plane of polarisation of plane polarised light. It was van't Hoff who in 1874 recognised the causal linkage between optical rotation and molecular structure and showed that particular forms of tartrates were stereoisomers (Cahn, 2001). This led eventually to the central concept in polymer science; the recognition of stereoisomerism in polymers.

Once stereochemistry had become accepted, research into monomers, oligomers and polymers slowly began to take off. Although the first industrial plastics like rayon and celluloid were produced towards the end of the century, these were based on natural products rather than the result of detailed chemical understanding (ibid.).

Early polymer research put considerable effort into understanding the structure of rubber by breaking down the constituents and attempting to re-polymerise isoprene. This led to in 1887 to the development of the technique of photopolymerisation that enabled successful re-polymerisation. Copolymers (such as synthetic rubbers) were foreshadowed by Engler in 1897 who stated 'one need not assume that only similar molecules assemble' (cited ibid.).

The concept that rubber was one of many naturally occurring macromolecules with long molecular chains with varying molecular weights led to conflict with the organic chemists, who strongly resisted this notion. It was hard to counter that scepticism.

Then in 1886 Zinoffsky determined the empirical formula for haemoglobin which showed that the smallest possible molecular weight was 16,700 and thus molecular weights of several thousand do exist in the natural form (ibid.). Nevertheless those that were active in colloidal science proposed that polymers were in fact colloids – made up of groups of particles each consisting of groups of molecules with each particle held together by van der Waals forces and this became the orthodox view.

It was 1917 before the German chemist Herman Staudinger was able to demonstrate the property that demonstrated the difference between colloids and polymers. In contrast to colloids, polymers exhibited 'colloidal properties in all solvent in which they dissolve'. That is, they had large stable molecules. However it was 1930 before a meeting of the Colloid Company Registered Association - formed in 1922 in Leipzig as a branch of physical chemistry - eventually conceded that 'this fruitless battle, between proponents of long-chained molecules and those that insisted that polymers were simply colloidal aggregates, delayed the arrival of large scale synthetic polymers by a decade or more' (cited *ibid.*)

The two main families of synthetic polymers comprise: addition methods, in which monomers simply become attached to the long chain; and condensation reactions in which this is accompanied by the generation of a by-product molecule (e.g. water).

Wallace Carothers of Du Pont started the first sustained program of research to find new macromolecules in 1929. It was mainly focused on condensation reactions and resulted in the discovery of nylon just before WWII. Due to its wartime application (parachutes) it was not made public until after the war.

Similarly ICI began the first program in making addition polymers in 1933. They found that under large hydrostatic pressures in the presence of traces of oxygen that ethylene would polymerise to become polyethylene. The process was eventually successfully scaled up to a production level on the day Germany invaded Poland. Nothing was announced until after the war. The material was ideal as an insulator for radar circuits, and thus gave the allied forces an advantage. Nevertheless the ICI process was expensive and after the war was found to be commercially unviable.

In 1953 the German chemist Karl Ziegler discovered a 'stereoactive' polymerisation catalyst able to yield high density polyethylene. This material was very much cheaper than the previous low density form and its properties and physical form could be tailored to the customer's requirements. This development was followed shortly by the Italian chemist Giulio Natta who used a similar catalyst to produce stereoregular crystalline polypropylene and in the US the use of a similar catalyst to produce stereoregular polyisoprene (synthetic rubber). Polyethylene, polypropylene, and polyisoprene transformed the market for polymers and were quickly taken up by industry round the world.

From the 1930's onwards the field changed from the exclusive domain of the experimental chemists to include theoretical chemists and a growing contribution from physicists who, in particular, studied the thermodynamics of long-chain molecular assemblies and investigated rubber elasticity.

5.5 Mineralogy

Traditionally mineralogy is linked with crystallography. For centuries it focused almost entirely on the systematic collection of data. Modern science only touched on mineralogy with the creation of crystal chemistry and yet as the physicists were considered the guardians of X-ray diffraction (and the physicists considered mineral crystallography the domain of the mineralogists) there was considerable delay in applying X-ray diffraction to minerals.

Mineralogy in the modern sense (mineral physics) did not start until the 1970s (Poirier cited *ibid.*) and almost immediately it merged with modern geophysics. Typical of the work of the modern geophysicist/mineralogist is the interpretation of heat flow, material transport and phase transformations of materials deep in the earth through knowledge of physical and mechanical properties of rocks and metals under extreme pressure. Skills and tools needed include sophisticated seismology, X-ray diffraction, and computer simulations and many of the scientists who have introduced these methods were trained materials scientists or solid-state physicists who have also introduced other modern materials science skills such as transmission electron microscopy and crystal mechanics.

Computational mineralogy - the application of computer simulations to minerals – has delivered some impressive advances. Examples include the calculation of MgO ionic diffusion at high temperatures and pressures; the melting behaviour of iron at the earth's core; and an estimate of the transport properties of solid and molten iron under pressures representative of those at the earth's core.

5.6 Glass and ceramic technology

5.6.1 Ceramics

The term 'ceramic', derived from the Greek word for pottery, describes a broad range of materials that include glass, chinaware, porcelain, pottery, brick, cement, concrete, and enamel. The use of ceramics - as fired clay - goes back to around 6000BC, the late stone age, when they formed clay bowls and baked them in the campfires (Purdue University, 2004).

Modern ceramic science evolved from the 1700's from the European development of porcelain. Chinese porcelain first created in 600AD had reached superb standards by the mid 13th century. Western demand for this material was insatiable and Europeans tried assiduously to reproduce it. The two major problems were that the high temperatures needed (at least 1350^oC) could not be reached in the primitive European kilns, and that the Chinese were adept at keeping details of the ingredients secret.

At the beginning of the 18th century in Saxony, Bottger and Tschirnhaus developed a furnace to reach the appropriate temperature and then after years of experimentation, in January 1708, Bottger was able to produce high quality porcelain through a mix of white kaolin and alabaster. When Saxon porcelain was sent to France the chemist Reaumur analysed it to enable Sevres pottery to make porcelain – reverse engineering!

A little later in England Josiah Wedgwood developed revolutionary ceramic materials, notably basalt, a hard black stone like material, and jasperware, a durable unglazed porcelain. He used chemical methods to better control the raw material in his manufacturing processes and in 1782 developed the first high temperature pyrometer for kiln temperature control. Chemical analysis and control of the raw materials, glazes and bodies had become accepted practice by the end of the century.

In the 1870's refractory materials able to withstand extremely high temperatures were developed using materials made from lime and magnesium oxide (or magnesia). This was a key enabler for the future development of industries dependent on high

temperature processes - such as iron and steel¹⁴, glass, nonferrous metals, the production of lime and cement, and...ceramics.

In 1887 Thomas Edison directed what was arguably the first example of advanced ceramic research. He directed the testing of a broad range of ceramic materials for resistivity for use in his latest invention, the carbon microphone.

'The long process of moving ceramics from a craft to a science based technology conducted under the direction of engineers was underway in the 1800s and has continued to the present day' (Wachtman cited (Cahn, 2001). Since then ceramics have been developed for an immense range of advanced applications where materials are required that can resist thermal shock, provide high temperature and electrical insulation, act as abrasives, have a better (compressive) strength weight ratio. More recent breakthroughs have included:

- In 1965, the development of photovoltaic cells which convert light into electricity (solar cells);
- In 1987, the discovery of a superconducting ceramic oxide with a 60°C higher critical temperature than metallic superconductors with potential use in integrated circuits in high speed computers; and,
- In the early 1990s the development of a range of ceramic materials called 'smart' materials that sense and react to variable surface conditions. An example of use is in the triggering of airbags.

The range of ceramics developed to exploit their special properties to meet a wide range of demanding engineering applications is vast. It now includes:

Electrical ceramics:

- Phosphors for cathode ray tube screens which have been used until recently for computer, TV, radar and oscilloscope screens, computer monitor;
 - Piezoelectric (used in sonar and ultrasonics), pyroelectric, electro-optic and magnetic ceramics
 - Ceramic conductors (e.g. the varistor), superionic conductors, superconducting ceramics.
 - Ceramic capacitors
- Magnetic ceramics
 - Ferrite as the ceramic core of the 1948 giant synchrotron (replacing the metallic core).
 - Computer memory
 - Telecommunications.
- Thermal insulation and refractory materials
 - Refractory materials
 - Ceramic tiles for thermal insulation against high re-entry temperatures of the space shuttle
 - Alumina ceramics for missile and rocket nose cones
 - Silicon carbide and molybdenum disilicide for rocket nozzles
- Nuclear power
 - Fuel elements as a ceramic compound
 - Control rod elements in ceramic form.

In line with other advanced materials the recent change in focus from a micro to a

¹⁴ See section 2 of this chapter.

nano-structured approach has resulted in engineering ceramics with high temperature super-plasticity; better mechanical strength (fracture behaviour approaching quasi-ductility, strength comparable to single crystals, improved reliability and improved high temperature properties and a range of new functional properties such as high electrical conductivity and elevated thermal conductivity (Sajgalik, 2004).

5.6.2 Glass

5.6.2.1 Early developments

Whilst the scientific exploitation of glass is relatively young, primitive man-made glass objects, mainly coloured glass beads, found in Eastern Mesopotamia and Egypt are believed to date back to around 3500BC. Examples found had silicate glaze coatings – an early application of ceramic coatings still commonly used for items ranging from tailpipes of jet aircraft to showers.

Two major breakthroughs took place around the time of Christ. One was the art of glass blowing attributed to the Syrians between 27BC and AD14. The other was the introduction of manganese oxide to create clear glass by the Romans who began using it for cast glass windows (with poor optical qualities) around AD100. These skills spread throughout the Roman Empire.

It was the 11th century before the first sheet glass processes were developed. There were several methods but here we will briefly describe the two most common. The first was to blow a hollow glass sphere and swing it vertically so it formed a cylindrical pod up to 3 metres long and 450mm diameter. While still hot the ends were cut off, the cylinder was then slit vertically and laid flat. The other most common type was crown glass (or bullion glass). This also started with a hollow glass sphere which was then opened out at the end opposite the blow pipe. The semi molten glass was then spun to flatten and increase in diameter.

The next major step was an improved process for making plate glass. It was developed in France in 1688 mainly for making mirrors. In this the molten glass was poured onto a table and rolled flat. After cooling it was ground with fine abrasive sands and polished. By 1691 the process had been greatly improved and produced thick flat glass up to approximately 2 metres long with good optical properties (Douglas, 1972). It was approximately 1918 before a Belgian engineer Emil Bicheroux made the next significant development in plate glass manufacture - a process in which the molten glass was poured between two rollers. This resulted in glass with a more even thickness and reduced the grinding and polishing necessary. Further improvements on the Belgian process were subsequently developed in the US.

In 1856 Friedrich Siemens invented 'an improved arrangement of furnaces which improvements are applicable in all cases where great heat is required'. It was effectively a regenerative furnace. The principle was also applied to the re-heating of iron and steel the following year.

A major development introduced in the 1880s was the improvement in glass annealing by using a tunnel-like annealing furnace (or '*lehr*') in which the temperature is varied and controlled along its length so that the glass items are cool gradually as they pass through.

5.6.2.2 *Mass production methods*

At the turn of the century Michael Owens in the US developed an automatic bottle blowing machine. The parison feeder - the basis of most automatic glass container production today – sucked up a measured molten glass charge (a 'gob') from a furnace into a two part mould by the withdrawal of a piston rod, and then transferred it to the finishing mould where its final shape was blown by pushing in the piston rod. It ensured a rapid supply of consistently sized gobs for bottle production (ibid.).

The first design to produce flat sheets of glass by drawing the molten glass vertically upward from the furnace was patented by Clark of Pittsburgh in 1857. The process failed: the vertical edges of the emerging molten glass drew together as it flowed upwards. Over the next 50 years a number of people made unsuccessful attempts to draw direct from the furnace however in the early 20th century there were three successful inventions.

The invention of Emile Fourcault of Belgium avoided narrowing by forcing the molten glass to rise under hydrostatic pressure through a slit under the surface of the molten glass. The glass was solidified by two water cooled tubes at the sides of the slit and the glass was annealed as it rose through the drawing chamber guided by asbestos rollers. After many technical setbacks the machine began to operate commercially in 1913 (ibid.).

In Toledo at about the same time Irving Colburn with the help of Libbey and Owen eventually operated a machine which after the glass had emerged approximately half a metre from the furnace bent the glass sheet over a roller so that it flowed horizontally. Some years later the Pittsburgh Plate glass company developed a machine that combined the advantages of the Fourcault and Colburn processes to overcome their disadvantages. By the mid 1950s all three processes were still in use with about 72% of world production being manufactured on Fourcault machines (ibid.).

In 1923 in the UK Pilkington brothers had successfully initiated the first continuous plate glass process. It was effectively a development of a process patented by Bessemer in 1846 that had technical difficulties which Bessemer was unable to address. However the float process developed by Pilkington's just after WWII and introduced in 1959 was the most significant innovation in flat glass making. In this the molten glass was poured across the surface of a bath of molten tin before being drawn in a continuous ribbon through the annealing ovens. 90% of flat glass is now made using this process.

5.6.2.3 *Glass Research*

It was not until the late 19th century that significant scientific research took place into the composition of the glass and the resulting physical qualities. The fathers of modern glass research are the three partners Otto Schott, Professor Ernst Abbe (a joint owner of Carl Zeiss) and Carl Zeiss who studied the effects of numerous chemical elements to make significant improvements in the optical qualities of glass optical lenses (Vogel, 1994). Their new microscopes with high quality corrected lenses provided a significant impulse to science in general.

Schott is also responsible for nearly all of the early developments in 'technical glass'. Almost all originate from his investigations into the chemistry of optical glass and glass

forming systems to improve the resolution of optical instruments (ibid.). They are all developments of his discovery of borosilicate glass and included the development of a thermally resistant cylinder glass necessary for the new gas lighting systems of the time; thermally and chemically resistant glasses for laboratory apparatus; and thermometer glass (previous thermometer glass expanded with heating and did not return to its original state on cooling). Pyrex, the brand name for the well known borosilicate glass introduced by Corning Glass Works in 1915, originated from Schott's 'Jena Apparatus Glass 20' (Ibid.).

There are many modern research tools used in contemporary studies of the structure of glasses. Electron microscopy and nuclear magnetic resonance can be considered complimentary. Siemens produced the first commercial electron microscope in 1939 providing a significant boost to glass research. Modern electron microscopes can magnify up to 2 million times. This tool is no longer a specialist tool. It is an integral part of many laboratories and an invaluable tool for solid state chemists (as this is effectively a branch of solid state chemistry). Electron microscopy has provided insights into large structural units and their influence on various material properties.

Nuclear magnetic resonance spectroscopy has been used to observe glass spectra since 1951. This has enabled closer insight into atomic interaction and the co-ordination of ions. Nuclear magnetic resonance provides clear information on the smallest regions, particularly the co-ordination and bond type of individual constituents.

5.6.2.4 Recent developments

5.6.2.4.1 Fibreglass and fibreglass composites

The first modern production method for fibreglass was patented by Dubus-Bonnel of France in 1836. In 1870 John Player developed a steam jet process to mass produce fibreglass – which he called mineral wool – as an insulation material. In 1936 Corning Glass in partnership with Owens-Illinois produced further developed the product and commenced production. In 1941 they produced fibreglass cloth. Carlton Ellis had patented polyester resin for Du Pont in 1936 and this was found suitable for making fibreglass composites.

Fibreglass is now in most family homes either as an insulation material or in composite form as items such as baths, shower cubicles, and wash basins. They are also often used for the hulls of leisure boats and for car bodies.

5.6.2.4.2 Donald Stookey's discoveries

A number of significant discoveries were made by Donald Stookey of Corning Glass. In 1948 he developed the photochemically machinable glass, 'FOTOFORM'. This was glass that when exposed to light through a patterned mask and subsequently to a particular solvent, the parts of the glass that had been exposed to light dissolved completely.

In the late 1950's when carrying out further studies on 'FOTOFORM' involving heat treatment the temperature controller malfunctioned and heated the glass to 900°C. Although the melting point of the glass was below 700°C he found a solid plate. He dropped it unintentionally and it did not break. He recognised that with further heat treatment it would turn into a strong ceramic. This became FOTOCERAM. He had

discovered glass-ceramics. Properties of glass-ceramics include high resistance to thermal shock, stronger at high temperature than glass, and slightly better heat conductivity than conventional glass. A number of glass-ceramics have now been developed with particular properties enhanced: spark plug insulators are made from glass-ceramic material developed for high mechanical strength at high temperatures; cookware and rocket nose cones are made from glass-ceramic material with high resistance to thermal shock; and building materials are made from glass-ceramic material with high wear resistance.

In 1959 he discovered photochromic glass – a material which would reversibly darken when light fell on it and become clear when it did not. This material is widely used for sunglasses.

5.6.4.3.1.1.1 Fibre optics

In 1960, following the discovery of the laser and the observation that light will travel along a glass fibre, the new field of fibre optics was born. A fibre optic cable uses rapid light pulses to transmit huge amounts of data with negligible energy loss. A 3000km fibre optic transatlantic telephone cable first went into operation in 1988. It was designed to handle a mix of information and its installation was preceded by extensive underwater trials. However in 1991 the new field of photonic crystals led to the development of the photonic crystal fibre which can be designed to carry more power than a conventional fibre. They became commercially available in 1996.

6. *The emergence of Materials Science and Engineering*

As Cahn is quoted as saying, a modern industrial economy is no better than its best materials (Loftas, 1966).

By the late 1950s new and sophisticated experimental techniques had provided detailed knowledge of the solid state which was enabling the design of materials for specific applications. This ability was most highly developed for metals but there had been a rapid and continuing range of engineering materials in the non-metals field. It was recognised that the ever-increasing demands for improved materials properties were best delivered from an interdisciplinary approach (Polmear, 1972). It can be seen from the preceding sections that many of the historic materials discoveries and developments have been from those who have applied knowledge and skills developed in other materials specialisms, other sciences or engineering.

Political pressure to establish MSE came in response to the successful Soviet launch of the Sputnik in October 1957 which led to national concern that their Cold War opponent appeared to be ahead in the space race. This led to concern that there was a lack of materials science development to meet demands particularly for the new and hostile space environment but also the defence and nuclear energy industries (ibid.).

In response, the US government set up the Interagency Co-ordinating Committee on Materials Research and Development whose first report recommended the establishment of Interdisciplinary Laboratories to promote graduate materials research on selected campuses. Responsibility for the materials programme was assigned to the Advanced Research Projects Agency (ibid.).

This provided a honeymoon period for materials science. In the first year 34 universities submitted proposals seeking a total of \$150 million and in the second year a further 42 universities sought \$154 million. Twelve leading universities¹⁵ were selected and the contract given to all included the requirement to 'establish an interdisciplinary research program' with the necessary personnel and facilities to 'conduct research in the science of materials'. They were to cover fields such 'as metallurgy, ceramic science, solid-state physics, chemistry, solid-state mechanics, surface phenomena and polymer sciences.....as well as other research investigations which may be mutually agreed upon' (cited *ibid.*). Funding continued at a more modest level through the sixties with (for example) \$18 million being the allocation for 1966 (*ibid.*).

The concept spread world wide. Outside of the US new courses in materials spread more quickly in the less tradition bound newer universities: the first in the UK being Sussex, Loughborough, Bradford, Bath and the Open University (*ibid.*). In Australia the first was in materials engineering at the then new Monash University with Polmear as the foundation professor.

Much of the core topics were common in these and other universities in the 1970s. Effectively they had removed the primary metallurgy from the metallurgy course and replaced it with 'secondary aspects of other materials' (Polmear, 1972)

The more traditional universities were cautious. Developments at the University of Oxford demonstrate the changes due to the gradual acceptance of materials science and engineering and also developments in response to other key government higher education initiatives in the 1970s and 1980s.

A second degree program Metallurgy, Economics and Management was introduced in the mid 1970s to address the recommendations of the government's Dainton report, which was aimed at increasing management studies at UK universities. This program was later renamed Materials, Economics and Management (MEM). A third degree, Engineering and Materials (EMS) was introduced in the late 1980s to address another government initiative, in this case designed to enhance technology teaching at UK universities. EMS is effectively an option within Engineering, sharing a common intake and common first year teaching with the three other Engineering degrees available at Oxford.

Materials science and engineering is now taught through a wide range of academic departments and programs. At the undergraduate level they are not only taught in departments with purely materials titles (e.g. Materials Science and Engineering or Metallurgy and Materials Science) but also in schools where materials is combined with another discipline (e.g. Materials and Chemical Engineering) and also in departments within other disciplines such as Mechanical Engineering (Flemings, 1999).

References

¹⁵This included Northwestern University which became the first university to adopt materials science as part of a department title, even though the dean reported that he had been warned by various senior US metallurgists that they may fail to attract students by not having metallurgy in the title CAHN, R. W. (2001) *The Coming of Materials Science*, Oxford, Pergamon..

- (1963) *Engineering Heritage: Highlights from the History of Mechanical Engineering* London, Heinemann on behalf of The Institution of Mechanical Engineers.
- BILLINGTON, D. P. (1996) *The Innovators: The Engineering Pioneers Who Made America Modern*, New York, John Wiley and Sons, Inc.
- BOWDEN, M. A. (2005 (web edition)) *Chemical Achievers: The Human Face of the Chemical Sciences*, Chemical Heritage Foundation.
- BURSTALL, A. F. (1965) *A History of Mechanical Engineering*, London, Faber and Faber.
- CAHN, R. W. (1992) *Artifice and Artifacts*, Bristol, IOP Publishing.
- CAHN, R. W. (2001) *The Coming of Materials Science*, Oxford, Pergamon.
- CAHN, R. W. (2002) Transition from Metallurgy to Materials Science. IN MCLEAN, M. (Ed.) *Materials Science and Engineering Its Nucleation and Growth*. 1 ed. London, Maney Publishing for The Institute of Materials.
- CHARLES, J. A. (2002) The Origins of Metallurgy and the RSM. IN MCLEAN, M. (Ed.) *Materials Science and Engineering: Its Nucleation and Growth*. London, Maney for the Institution of Materials.
- DOBRZANSKI, L. A. (2006) Significance of materials science for the future development of societies. *Journal of Materials Processing Technology*, 175, 133-148.
- DOUGLAS, R. W. A. F., S (1972) *A History of Glassmaking*, Henley-on-Thames, Oxfordshire, G.T.Foulis & Co. Ltd.
- DRUCKER, P. F. (1993) *Post-Capitalist Society*, New York, HarperCollins Publishers.
- FALLON, D. (1980) *The German University: A Heroic Ideal in Conflict with the Modern World*, Boulder, Colorado Colorado Associated University Press.
- FLEMINGS, M. C. (1999) What next for departments of materials science and engineering? *Annual Review of Materials Science*, 29, 1-23.
- GERSTL, J. E., AND HUTTON, S.P. (1966) *Engineers: The Anatomy of a Profession-A Study of Mechanical Engineering in Britain*, London, Tavistock Publications.
- HILL, C. P. (1977) *British Economic and Social History*, London, Edward Arnold.
- JONES, B. (1995) *Sleeper Wake! Technology & the Future of Work*, Melbourne, Oxford University Press.
- LOFTAS, A. A. G., P. (EDS.) (1966) *Advances in Materials Science*, London, University of London Press.
- LUNDGREEN, P. (1990) Engineering Education in Europe and the USA, 1750-1930. *Annals of Science*, 47, 33-75.
- MARTIN, J. W. (1969) *Elementary Science of Metals*, London and Winchester, Wykeham Publications.
- MATTER (2007a) History of Steel Making. steeluniversity.org. Liverpool, UK Centre for Materials Education.
- MATTER (2007b) Materials Science and Engineering. UK Centre for Materials Education.
- OHRING, M. (1995) *Engineering Materials Science*, San Diego, California, Academic Press, Inc.
- POLMEAR, I. J. (1972) Metallurgy or Materials Science: Evolution or Revolution. *The Journal of the Australian Institute of Metals*, 17, 129 - 141.
- PULLIN, J. (1997) *Progress through Mechanical Engineering: The first 150 years of the Institution of Mechanical Engineers*, London, Quiller Press.
- PURDUE UNIVERSITY, C. E. D. (2004) Glass and Other Ceramics.
- RAYMOND, R. (1984) *Out of the Fiery Furnace: The impact of Metals on the History of Mankind*, Melbourne, The Macmillan Company of Australia.
- SAJGALIK, P. R., R. (2004) Preface: Workshop on Engineering Ceramics. *Journal of the European Ceramic Society*, 24, 3285.
- SKRABEC, Q. R. J. (2006) *The Metallurgic Age: The Victorian Flowering of Invention and Industrial Science*, Jefferson, North Carolina, McFarland & Co. Inc.
- SMITH, C. S. (1963) Preface IN SMITH, C. S. (Ed.) *The Sorby Centennial Symposium on the History of Metallurgy*. Cleveland, Ohio, Gordon and Breach Science Publishers.

- THOMPSON, H. (1976) *Engineers and Engineering*, London, B.T. Batsford Ltd.
- TYLECOTE, R. F. (1992) *A History of Metallurgy* London, The Institute of Materials.
- VOGEL, W. (1994) *Glass Chemistry*, Heidelberg, Germany, Springer-Verlag.
- WALKER, M. B. (1991) *Chambers Science and Technology Dictionary*, Edinburgh, W & R Chambers.