MATERIALS SCIENCE AND ENGINEERING

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Summary

Materials science and engineering is concerned with the development and selection of the best possible material for a particular engineering task and the determination of the most effective method of producing the materials and the component. In this article the history of materials is traced and the concept of structure (atomic structure, microstructure and defect structure) and its relationship to properties developed. The complexity of modern processing and the need for efficient production and use of materials are discussed and illustrated by examples from current practice. Properties are determined by structure, which in turn depends on the processing route. The later sections of the article demonstrate the correlation between structure, properties and processing.

1. Introduction

The first materials used by man were natural materials such as stone, bone and fur. These materials were utilized because they were readily available and exhibited the properties required to manufacture articles essential to life, i.e., the implements to assist in obtaining food, for protection and for warmth. Stone, wood and bone were employed for applications that exploited their mechanical properties, i.e., the properties that determine a material's response to an applied force. For example, the hardness of stone, coupled in some cases with a fracture mode that gives sharp edges, such as those found with flint, made it suitable for cutting tools and weapons, whereas advantage was taken

of the strength and toughness of wood and bone to construct spears and arrows. Fur was used for clothes, bedding and shelter, and for these applications functional properties, such as good insulation associated with its low thermal conductivity, were paramount.

So important has been the role of materials in the development of civilization that eras have been designated according to the dominant material. Thus, the period of time, when man was using stone and other natural materials, is known as the Stone Age. As the term defines a state of civilization, the Stone Age occurred at different dates throughout the World, and in Europe ended in about 1200 BC. Primitive man soon learned to construct implements with a combination of materials in such a way that the merits of the component materials were fully exploited. For example, an axe might have a stone head and a bone or wooden handle and a shelter a wooden frame clad with fur. This principle of maximizing the performance of an article by careful selection of materials with the appropriate properties for the different components of the article is as relevant today as it was in the Stone Age.

Stone and wood have of course, been widely used since the Stone Age—the sturdy Roman aqueduct in France, Pont du Gard, and the magnificent white marble Taj Mahal exemplify the human ability to construct in stone. The first piped water into London, at the beginning of the seventeenth century, was through wooden pipes. Indeed, today stone and wood are still prized for their mechanical and aesthetic qualities.

The first synthetic material produced by man was pottery. Clay, the raw material for pottery, is plentiful throughout the world and is characterized by being readily shaped when wet. It will then retain its shape as it dries in the sun to give a solid that may be handled, but has limited strength. In this condition, the clay is said to be in the "green state." To improve its strength, the shaped clay is fired, that is heated to an elevated temperature, to create, what is known as, pottery.

The earliest examples of fired clay are figures dating from about 22 000 BC. Pottery vessels appeared later, probably around 15 000–10 000 BC. The early pots were made by coiling and stacking lengths of rolled clay to build up the vessel. Later, the potter's wheel was developed. A wheel dated 5000 BC was found in Mesopotamia, and must be one of the earliest examples of mechanization in the materials industry.

The technical skill to make defect free pottery is considerable. An appropriate amount of water has to be added to give the clay the correct consistency for shaping. The shaped clay has to be carefully dried and the firing temperature and the heating rate to, and the cooling rate from, the firing temperature are critical if cracking is to be prevented. As well as their successes, potters until recent times must also have had many failures, indeed one of the gates of Jerusalem was called the "Gate of Potsherds" (a sherd is a scrap or broken piece of pottery).

Pottery belongs to the class of materials known as ceramics. Early ceramics were made from raw materials such as clay that, other than some cleaning, received little attention before being shaped and fired. Ceramics are still produced via that route, but in addition, many modern ceramics, sometimes termed high-tech, special or engineering ceramics, are produced from raw materials which have been processed to give high

purity, fine-grained size products. Examples of the latter class of ceramics are the oxides of aluminum (Al_2O_3, alumina) and zirconium (ZrO_2, zirconia).

Glass is found naturally, and was used by Stone Age man. Obsidian is a high silica content mineral with a chemical composition that does not differ greatly from that of ordinary window glass (73.0 wt% SiO_2–13.0 wt% Na_2O–9.5 wt% CaO–3.0 wt% MgO–1.5 wt% Al_2O_3). It naturally occurs as a greyish-brown, translucent glass, formed by rapid cooling of molten rock, and was used for knives, spear- and arrowheads. It is possibly better known in its froth-like form, called pumice.

Nowadays we are familiar with the beautiful colored glazes on pottery, and other ceramics, such as porcelain and stoneware, and with colored coatings, known as enamels, on metals. Both glazes and enamels are glasses and were the first man-made glasses. Much ancient pottery is not glazed, but there is sufficient evidence from glazed articles to indicate that glazes were in use by about 12 000 BC, well before man had the ability to produce articles, such as vessels, from glass. The earliest glass articles date from about 7000 BC and a glass industry, capable of producing transparent glass, was in place by 1500 BC. In contrast, enameling was not established until much later—probably in Egypt and Cyprus during the second century BC.

Today glass is not only used for its aesthetic qualities but also for its technologically important properties in applications such as optical fibers. However, its major contribution to our everyday life is as a transparent material for windows. For centuries, the only way to manufacture sheet glass was through the expensive procedures of grinding and polishing, but in 1959 the then revolutionary float process was introduced. In the float process, molten glass leaves the furnace in a continuous ribbon up to 4 m wide, and floats on the surface of a bath of tin. With careful control of temperature, it is possible to produce glass of constant thickness and a good surface finish, at reasonable cost.

The first useful objects, such as beads, pins and awls, to be manufactured from metal were made from native metals, that is materials that exist in nature in the metallic state and have not been produced by man by smelting ores. Native copper, gold, iron and platinum are present in reasonable quantities on the earth's surface, but there are no records of native platinum having been used in antiquity, although gold objects with high platinum content have been found. Large nuggets of native metal have been reported and have received much publicity; the largest gold nugget found in the US was in 1799, in Northern Carolina, and weighed nearly 13 kg. Native copper, in particular, is commonplace. Most copper ores contain a significant amount of native copper, and it has been estimated that about 15% of the world's copper production at the beginning of the twentieth century came from native copper deposits that were situated mainly in North America. The main source of native iron is particularly interesting being meteors that reached earth and which usually contain around 10% and occasionally as much as 25% nickel. The hardness of native copper and meteoric iron depends on their composition and microstructure but are about 50 and 200 $kg\,mm^{-2}$, respectively, however the deformation that took place during the fabrication of an artifact would have increased the hardness significantly. The increase in hardness with deformation (strain) is known as strain or work hardening.

Greater quantities of metal were available to man once he had mastered the smelting of metals from natural minerals, termed ores. In the Copper Age, which commenced in about 4000 BC in the Middle East, a variety of tools (e.g., axes, spearheads, chisels, awls, spatulas) were produced predominantly from copper-arsenic alloys. Although there is a slight improvement in hardness on alloying copper with arsenic, the main benefit is in the increased rate of strain hardening that enabled hardnesses approaching 250 kg mm^{-2} to be achieved in cold worked material, e.g., a material that has been hammered into shape at ambient temperature (Figure 1). It is thought that the copper-arsenic alloys of the Copper Age were produced by chance because of the composition of the ores used. In contrast in the following era, the Bronze Age, the copper-tin alloys with tin contents that sometimes exceeded 10% must have been deliberately produced, probably by heating a mixture of copper and a tin ore. In the late Bronze Age, some of the bronzes had additions of lead. Lead improves fluidity of molten bronze and hence aids accurate casting of artifacts with fine details. It is clear that, by this stage, man was controlling, albeit crudely, the composition of the alloys by intermixing ores to obtain specific properties. Humankind was also becoming more expert at shaping metals into a variety of forms, even into wire. Wires were made by twisting a thin strip of metal into a fine hollow tube, rather like an extremely thin old-fashioned paper drinking straw or by block-twisting, whereby a rod of small square-section was twisted then rolled and beaten until the cross section was approximately circular (Figure 2). It was not until medieval times that wires were fabricated in a similar method to that employed today, namely wire drawing (see chapter Materials Processing and Manufacturing Technologies).
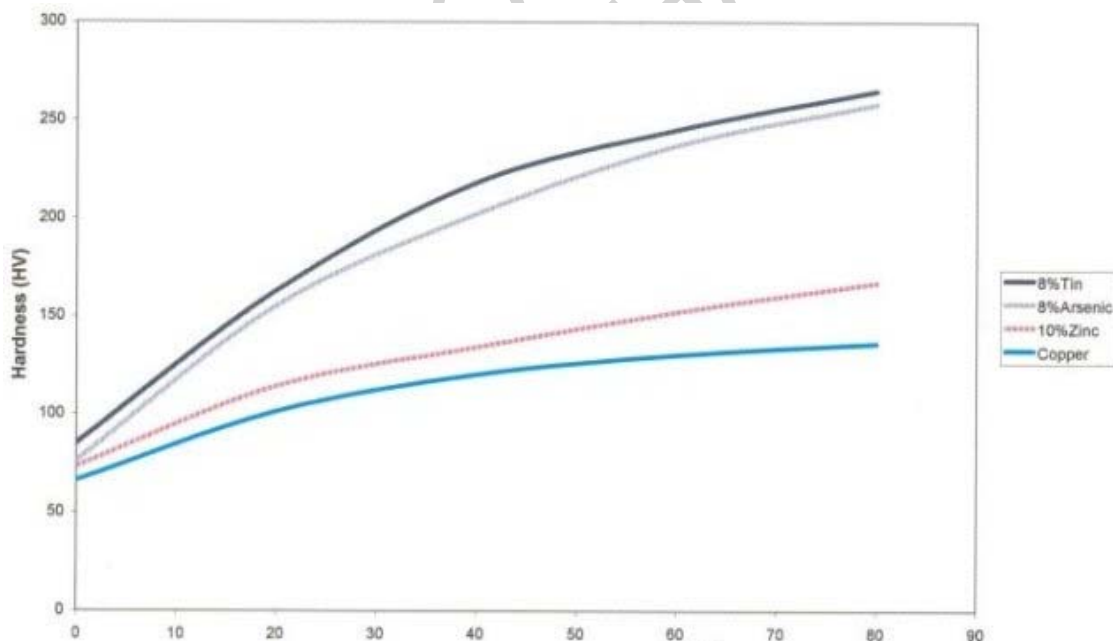

Figure 1. Graph of the Hardness of Copper, Copper–8% Arsenic; Copper–8% Tin (Bronze), and
Copper–10% Zinc (Brass) as a Function of the Amount of Cold Work Showing the Higher
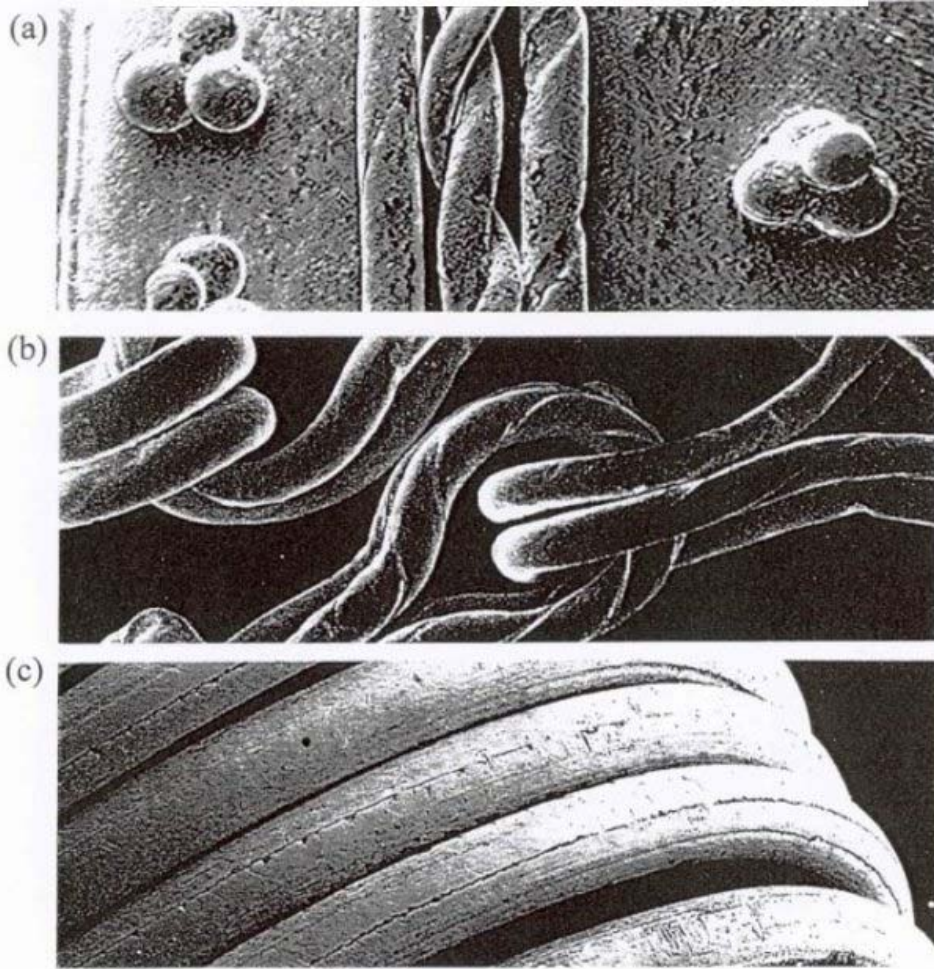Strain Hardening Rates of the Alloys, Particularly Cu-As and Cu-Sn

Figure 2. Wires Produced by (a) twisting a thin sheet, (b) block-twisting and
(c) wire drawing (Source: Jones M. (ed.) (1990). *Fake? The Art of Deception*,
London: British Museum Publications Ltd.)

The iron age is thought to have started in Asia Minor in about 2000 BC, and over the next 2000 years spread widely across parts of Europe, Asia and North Africa, reaching Sudan in 200 BC. Copper melts at 1083 °C, and a temperature in excess must have been achieved in early furnaces for man to have produced molten copper. The melting point of pure iron is much higher, 1540 °C, and early furnaces were not capable of reaching such temperatures. Thus, during the iron age, iron was produced by a chemical reaction, known as reduction, at around 1200 °C, between the ores and charcoal, to give solid iron. It was not until the AD nineteenth century, that furnaces could reach the temperatures required for the melting and casting of iron.

The lumps of the reduced iron, called blooms, were heated in a fire and welded into larger pieces by hammering. The compositions of the blooms and finished products were variable; carbon could be present as a trace amount up to 3.5 wt%, but it seems that only in China were high carbon content alloys (cast irons) regularly produced. The hardness and toughness of low and intermediate carbon content material was soon recognized, and by 1000 °C iron weapons were produced on quite a large scale. The

relative merits of the early metals are epitomized in the poem by Rudyard Kipling, *Cold Iron*:

"Gold is for the mistress—silver for the maid—
Copper for the craftsman cunning at his trade."
"Good!" said the Baron, sitting in his hall,
"But Iron—Cold Iron—is master of them all."

In the twenty-first century, tens of metals, which may be combined with each other and with non-metals to gives thousands of alloys, are readily available. This large number of metals and alloys results in a great variety of properties, enabling metallic materials to be used for applications ranging from large constructions, such as oil rigs and bridges, where mechanical performance is paramount, to components in electrical devices, where electrical and/or magnetic properties determine selection.

Some of the natural materials exploited by man, such as wood, bone, plant and animal fibers, and fur, are polymeric-based materials. Rubber trees are native of the Gulf of Mexico and, not surprisingly, it was from this part of the world that we found the first evidence of the exploitation of rubber, not for an essential of life, but for sport. There are records from as early as 400–200 BC, and extending over a period of more than 1000 years, of a ball game played with a large rubber ball. In some versions of the game, the hands were used, whereas in others, the ball players wore heavy padding and hit the ball with upper arms, thighs and waist (Figure 3).

Figure 3: Player with Rubber Ball (courtesy of the Mint Museum of Art, Charlotte, US)

It was not until the AD nineteenth century, that synthetic polymers appeared. The first step forward were modifications to natural rubber; Hancock (1820) discovered that rubber was easier to blend and mould if masticated (i.e., subjected to repeated high shear forces) and Goodyear (1839) patented the addition of sulfur to rubber which reduced tackiness and improved stiffness. The first structural synthetic polymer was made from a mixture of cellulose nitrate (the explosive) and castor oil, and was known as Parkensine after the inventor Parks. In 1870, the replacement of castor oil by camphor resulted in the introduction of a more easily processed material, celluloid, which was a commercial success and dominated the market for many years.

As early as 8000 BC, rope and netting were being fabricated from plant fibers. Later spinning and weaving enabled plant and animal fibers to be used for the production of textiles. Synthetic polymeric fibers became available on the commercial market several years after the development of bulk polymers, e.g., viscose rayon fibers in 1905 and nylon fibers in 1939 (see chapter Fiber Production).

The key role of the materials scientist/engineer is to develop and select the best possible material for a particular engineering task and to find the most effective method of producing the materials and the component. Were these early workers materials scientists/engineers? Certainly their technology was of a good level; they could achieve high (1200 °C) temperatures, use controlled environments (e.g., a reducing atmosphere) and to a limited extent, control composition. Even so, there was also much superstition associated with materials production. In Babylon, the making of glass required the use of human embryos and the ancient Greeks sought the aid of the Gods before firing clay. For the materials scientist/engineer to fully achieve his/her objectives there must be an understanding of the reasons for the consequences of an action—it is not sufficient to know that hammering hardens a metal, one must know how the hardening process takes place in the metal. This detailed understanding of materials, which provides a sound basis for predicting properties and selecting materials, was not possible without knowledge of the structure of materials.

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Biographical Sketch

Rees Rawlings obtained a BSc (Eng) in Metallurgy at Imperial College, London, and stayed on in the Department of Materials to study for a PhD. He joined the staff in 1966, was awarded his PhD in 1967, and was made Professor of Materials Science in 1993. His research field is the correlation of microstructure and properties, mainly mechanical properties, but in some cases functional properties such as electrical and magnetic. Early work was mainly on brittle metals and intermetallic compounds but an interest in ceramics, including glasses and glass-ceramics, also soon developed. This work has recently been extended to composites and functionally graded materials based on metals and ceramics. He has published about 200 research papers and is the co-author of two textbooks.

He is a Fellow of the Institute of Materials, was awarded a DSc in 1989 and the Pfeil Medal of the Institute of Materials in 1990. He was Head of the Department of Earth Resources Engineering (1997–1998), Dean of the Royal School of Mines (1995–1998), is Chairman of the Steering Committee of the Center for Composite Materials, Editor of the *Journal of Materials Science* and *Journal of Materials Science Letters*, and Pro Rector (Educational Quality) at Imperial College, London.