TEN MATERIALS THAT SHAPED OUR WORLD

M. Grant Norton

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1

Introduction

Possibly the first time that we looked critically at the world through our changing relationship with materials was when Danish archaeologist and Curator of the National Museum of Denmark Christian Jürgensen Thomsen examined a collection of Scandinavian antiquities and decided to arrange them, not in terms of their shape or properties or function or where they were from, but on the primary material from which they were made. Thomsen's classification produced three distinct groupings of material: stone, bronze, and iron. These became the basis for the popular Three Age system—the Stone Age, the Bronze Age, and the Iron Age—that was published by Thomsen in 1836 and is still widely used by museums today.

Over time, it became clear that there was complexity and subtlety within each of the classifications, which led to further subdivisions. In 1865 English naturalist John Lubbock distinguished the earliest Stone Age period that he called the Paleolithic characterized by flaked flint tools and the much more recent Neolithic where our ancestors worked clay into pottery. Chemically flint and clay have a number of similarities, for instance their main constituents are the elements silicon and oxygen. As materials, clay is very distinct from flint requiring a different understanding of material behavior to shape it in useful objects.

The enormity of the Paleolithic period and the technological innovations that happened over the approximately 2 million years led French prehistorian Gabriel de Mortillet to further divide it into: Lower, Middle, and Upper. Even further subdivision has been used to separate the earliest pebble and flake

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tools discovered in Africa with the appearance of the handaxe, which is associated with two extinct hominin species *Homo erectus* and *Homo heidelbergensis* [1].

The Stone Age produced four important materials technologies. The first was the ability to shape flint by removing flakes to produce tools and weapons. The second was the idea of joining different materials together to increase functionality, when a stone tip was attached to a wooden shaft to form an arrow or a spear or a sickle. Thirdly, the concept of creating an object additively rather than by subtraction—building a pot by adding layers of clay rather than chipping away flakes of flint. And fourth, the importance of fire. All the materials described in this book after flint, and many others, require heat at some stage during their synthesis and processing.

As we learned more about the evolution and spread of bronze and iron technology these metal ages have also been subdivided, although each covers much shorter time periods than the Stone Age. For metals the subdivisions focus less on the material, but more on where and when the technology was being used. Civilizations in Greece began working with bronze before 3000 BCE. In the British Isles the use of bronze began around 1900 BCE and in China even later around 1600 BCE. One of the reasons for this difference, spanning more than 1,000 years, was that for a society to enter into the Bronze Age it required a nearby source of the raw materials; copper and tin. Both are regionally abundant, but neither were widely available to our ancestors without the establishment of robust trading routes. Despite the worldwide availability of flint there is evidence that the most advanced early technologies and societies developed where the highest quality flints were available [2]. So, regional advantages possibly existed prior to the Bronze Age.

The discovery of bronze brought an end to the Stone Age (although not to the end of our use of flint). Bronze in turn gave way to iron. Then many of the applications that would have been satisfied with iron instead used the far superior and more widely useful iron alloy, steel.

Although there has been no formal extension of the Three Age system into a fourth (or more) age, an argument can be made that in terms of identifying a single material that defines our present world more than any other a case could be made that about sixty years ago we entered the Silicon Age. From the first period of human prehistory to the present day we have gone from the Stone Age characterized by flint tools that gave our ancestors an evolutionary advantage to the Silicon Age that enabled social media, artificial intelligence (AI), the Internet of Things (IoT), and has connected almost everyone on the planet.

This book begins with flint, concludes with silicon and in between looks at eight other transformative materials.

1.1 Looking at the World as a Materials Scientist

Using the Three Age system, we can see that materials have an intimate connection with our earliest history. The materials ages cover by far the longest period of our existence; millions of years rather than just the few thousand years from the end of the Iron Age to the present day. The subdivision of these ages has been used to mark important technological changes in our ability to work with the natural world—for instance by shaping flint—and to go beyond the bounds of what nature provides—by combining copper and tin to produce bronze.

Despite our long association with materials, materials science as a discipline only began in the early 1950s. The first university department including the term “materials science” in its name was at Northwestern University in Illinois. The *Journal of Materials Science* established to publish the latest research in the field was created in 1965 and recently celebrated its 1,000th issue [3]. But our study, our examination, of materials goes back to when our ancestors first looked at the sharp curved surfaces of a piece of fractured flint or obsidian and realized it could be used to cut.

When a materials scientist looks at an object, for instance, a Stone Age handaxe the first consideration is its *structure*—a teardrop shape, uneven, but smooth with many conchoidal impressions. Then, its *properties*—the edges are sharp, it is hard, it will abrade wood and scratch metal. *Processing* was required to transform what was once an unassuming and unremarkable pebble into this purposed tool. This transformation was deliberate. It required intent. It required skill. Finally, what was the *performance* of the tool when it was put to its task. How well did it do its job? The field of material science is defined by the interrelationships between structure, properties, processing, and performance, which are typically represented as the four corners of a tetrahedron [4].

This book is very much written from the perspective of a materials scientist. With that context in mind I have attempted to add the why, rather than just the how, certain materials have had the impact they have. For instance, it is the fracture behavior of flint—a direct result of its microstructure, consisting of tiny quartz crystals, formed over millions of years that gave our ancestors the evolutionary advantage of being able to add meat to their diet. When Sir Francis Drake was relieving the Portuguese and Spanish of their gold, he was unaware that the material he sought held its power over Queen Elizabeth I because of the relationship between the outermost electron and the nucleus of the gold atom. But it is that relationship that made gold so desirable for its color and its inertness.

Over time our view of gold has changed. Sir Thomas More, counselor to Henry VIII, saw gold as being "in itself so useless", but it became an essential material—in the form of whisker thin wires—for the fabrication of silicon chips. It is the crystal structure of gold that allows one ounce of the metal to be drawn into a wire 50 miles long. Now 500 years after Sir Thomas, gold is the workhorse of nanotechnology with applications spanning from low emission automobile exhaust catalysts to treating cancer through the delivery of drugs directly to the site of the tumor. It is certainly not useless!

1.2 Why This Book

In this book, I have selected ten materials that have undeniably shaped our world. If these ten materials had not been discovered—or didn't exist—the world as we know it would be very different. There are several books that have been written that take a similar approach to that used here where a materials science professor describes the critical role that materials have played since our earliest ancestors first found or made an object that could be used as a tool. Maybe it happened as imagined by Cornell University professor Stephen Sass where a lump of obsidian was thrown against a rock causing it to shatter into razor-sharp shards that were found to be useful for cutting [5]. Maybe our ancestors found that certain stones were shaped in such a way that they were suited to a specific task; cutting, chopping, scraping. Eventually—slowly—the idea emerged that these stones could be deliberately and carefully shaped to produce a more useful engineered tool.

Although some of the stories associated with these ten materials have been told by others the field is evolving such that there are constantly new discoveries and developments that build on what has already been documented. This is especially true with nanomaterials. For instance, not only has nanoparticle gold challenged our view of this traditional material, but nanomaterials including carbon nanotubes and nanoparticles of silica are being combined with concrete to make it even more durable and stronger [6].

Another example of where we have to update our existing view of a material is glass. We constantly look through glass without even noticing it, unless of course it is dirty or covered in greasy fingerprints, but nanostructured forms of glass are opening up new possibilities for this ubiquitous and ancient material. For instance, tiny glass springs, called nanosprings, have been shown to be effective in trapping exosomes, tiny vesicles excreted by normal and cancerous cells that provide information about the progression of the disease and can possibility help identify the best ways to treat it [7]. This book describes some of these exciting innovations that could impact our future as stone, bronze, and iron impacted the past.

The audience for this book is primarily those that want to learn more about materials and how they affect who we are and how we live our lives. Although not a textbook, the content has been used in a general education course in the sciences taught within the Honors College at Washington State University, a summer course for engineering students at the Chien-Shiung Wu Honors College at Southeast University in Nanjing, and in lectures at Tecnológico De Monterrey at both the Querétaro and San Luis Petosí campuses.

1.3 Why These Materials

The materials described in this book have shaped our world in both large and small ways. Frequently we identify uses that have benefited society, but it is also possible to find instances where our use or quest for materials has been damaging and destructive. The selection of which ten to write about has included some personal bias, which is the prerogative of any author. But the ten do include at least one from each of the primary categories of material: metals, ceramics, polymers, and semiconductors. The materials that were left out suggest possibilities for a future edition.

Diamond—*The Material of Eternity*, which with its superlative hardness is essential for machining everything from lightweight aluminum alloys to high strength concrete and silicon. Since the 15th century diamond has symbolized commitment and although diamonds don't last forever as Shirley Bassey might suggest when she sings the theme tune to the seventh James Bond movie, we are unlikely to witness any spontaneously changing into graphite.

Other contenders might include: Uranium—*The Material of Energy*, the main fuel for nuclear reactors; Plutonium—*The Material of Fear*, one of our synthetic elements that formed the core of the atomic bomb dropped on Nagasaki, Japan; or Graphene—*The Material of Expectation*. Graphene, a sheet structure comprising just a single layer of carbon atoms, has not had an impact equaling that of the ten materials highlighted in this book, but many people think that with its incredible range of properties that it just might.[1]

Notes

1. 11 ways graphene could change the world, https://www.mnn.com/green-tech/research-innovations/stories/10-ways-graphene-could-change-the-world Downloaded January 25, 2019.

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6. Nanosilica refers to nanoparticles of silica glass. A recent paper that describes the benefits of using of nanosilica in cement is: Liu, R., Xiao, H., Liu, J., Guo, S., & Pei, Y. (2019). Improving the microstructure of ITZ and reducing the permeability of concrete with various water/cement rations using nano-silica. *Journal of Materials Science, 54,* 444–456.
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2

Flint—*The Material of Evolution*

Our information is processed and delivered by tiny silicon chips. Telephone calls and internet data pass at the speed of light under the Atlantic Ocean (and soon the Arctic Ocean) along glass optical fibers that stretch for thousands of miles [1]. We fly around the world in airplanes made of tough aluminum alloys and lightweight carbon-fiber composites, and we live on "platinum" and "gold" credit cards. But two and a half million years ago one material ruled: flint. To our ancient ancestors, flint was an invaluable material because it could be found almost anywhere and, with only a little effort and a lot of patience, a smooth pebble could be transformed into a tool with razor sharp, wear resistant edges. Up until just a few thousand years ago, stone tools made of flint were still widely used for cutting through the hides of animals and butchering their carcasses for food, working and shaping wood that was used to build shelters, and even cracking nuts, a valuable protein-rich snack.

Visiting museums such as the Natural History Museum in London or the American Museum of Natural History in New York City and looking at collections of these early stone tools through eyes acquainted with iPhones, "Dreamliners," Xbox 360s, and all the products of modern technology, they can seem somewhat modest, unimpressive, and certainly primitive, but their importance in our evolutionary process cannot be overestimated. Simply, we probably owe our very existence to the brittleness of flint and the complex way in which it breaks. We are here right now because our ancestors discovered how to transform a piece of flint into a useful tool. As we learned to shape flint, so flint, in turn, has shaped us.

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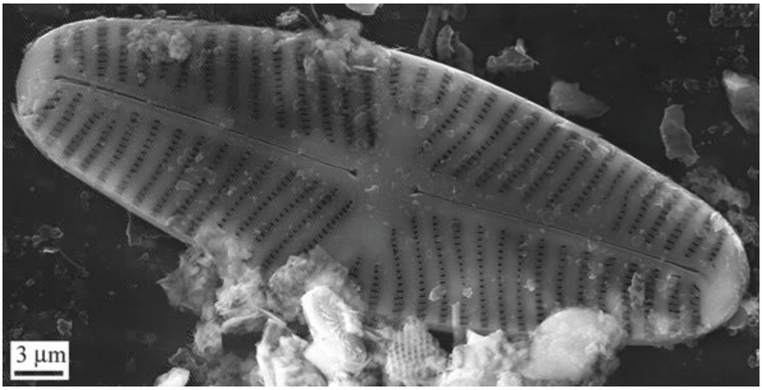

Fig. 2.1 Scanning electron microscope image of a diatom structure. There are a great many variations in these structures, which can only be seen using powerful microscopes. (The image was recorded by J.L. Riesterer and C.B. Carter and originally published in C.B. Carter and M.G. Norton, Ceramic Materials: Science and Engineering, 2nd edition (New York: Springer, 2013),p. 405. Republished here under Springer Copyright Transfer Statement.)

Flint is a naturally occurring sedimentary rock consisting of densely packed quartz crystals that are so small they can only be seen using a microscope. Although it is uncertain how flint was formed, the chemical constituents of flint—silicon and oxygen—are usually accepted to be biogenic, originating from the skeletons of marine organisms such as radiolara and diatoms, which form a silica gel. Figure 2.1 is an electron microscope image of just one variety of the many thousands of species of diatoms. The silica skeleton is an example of a naturally occurring glass, a topic we will meet again in Chap. 6.

Over time as the moist gel dried it began to crystallize forming small quartz crystals. Whilst flint is usually black, changes in the chemical conditions, such as the inclusion of colorful metal sulfides and metal oxides during drying, produced a variety of different colors. The semiprecious gemstones onyx and tigereye are very similar to flint. It is the presence of impurities such as the mineral crocidolite (a blue form of asbestos) and dark brownish red iron oxide that give rise to the colored bands in these pretty stones.

Flint is one of a relatively few types of rock that when broken form sharp hardwearing edges. When flint is chipped the propagating crack twists and turns to follow the boundaries between the densely packed quartz crystals. We describe the fracture as being conchoidal, or shell-like, because the resulting fracture surface resembles the concave shape of a bivalve shell such as a mussel. It is flint's proclivity for conchoidal fracture and its hardness that made it the perfect material for making tools.

Many of the other naturally occurring minerals that were widely available to our ancient ancestors do not undergo conchoidal fracture. Clay and mica, two very abundant silicate minerals, break along well-defined planes of atoms in the crystal structure. These planes are called cleavage planes and coincide with certain crystal faces. In clay and mica, which both have layered structures cleavage occurs between the layers where the atoms are only weakly bonded. It is easiest for a crack to pass *between* adjacent layers rather than propagating *through* a layer where the bonding between the atoms is strong. The familiar soft soapy feel produced when clay is mixed with water is due to cleavage of the clay particles. And, although clay is very useful as we shall see in Chap. 3, it does not have the properties necessary for producing hard-wearing tools for cutting and chopping and would not have provided the evolutionary advantage of flint.

In addition to the way it fractures the other property of flint that makes it particularly suitable for producing cutting and chopping tools is its hardness. At the molecular level the hardness of a material is directly related to the strength of the bonds between constituent atoms. In quartz these atoms are silicon and oxygen. The silicon-oxygen bond is very strong. Flint is a hard mineral because of the hardness of its constituent quartz crystals.

On the hardness scale developed by German mineralogist Fredrich Mohs in 1822, flint has a hardness of 7. To put this number into context, the hardest of all known materials is diamond with hardness on the Mohs' scale of 10. The carbon–carbon bonds in diamond are extremely strong and inflexible. The softest mineral on the scale is talc, which has a hardness of only 1. The basic idea of the Mohs' scale is that a mineral higher on the scale will be able to scratch or abrade one below it. A tool must be harder than the work piece in order to act on it—the harder the material the tool is made out of, the more materials it can work on. So, in addition to preparing food and building shelter, flint tools were used to shape bone (Mohs' hardness 5) into needles to make clothing, and shell (Mohs' hardness 3) into hooks for catching fish.

Shakespeare alludes to the persistence of flint in *Romeo and Juliet*: "Here comes the lady: O! so light a foot will ne'er wear out the everlasting flint." When *Romeo and Juliet* was written—between 1591 and 1595—flint was widely used in both simple and elaborate architectural constructions from cathedrals to farmsteads. Flint buildings define the landscape of many towns and villages in England. It was the material of choice for churches in Norfolk, walls in Hertfordshire, houses in Wiltshire, and barns in Sussex. The Romans built with flint extensively in parts of England where there were abundant supplies that were easy to collect. Flint's hardness and resistance to wind and rain made it an ideal material for fortifications such as castles and city walls. As a young child I would spend the summers with my grandparents in Great Yarmouth. A regular day trip was to visit the Roman fort at Burgh Castle, built in the late third century with flint and brick walls. It is one of the best-preserved Roman monuments in the country.

Flint's hardness and durability, its resistance to weathering, are two of the reasons that stone artifacts have survived over so many years and provide a rich evidence of the prehistoric period. We can compare the abundance of stone tools dating back tens of thousands of years with the comparative lack of Iron Age artifacts lost because of rusting that were just a few thousand years old.

The very earliest flint tools were found in the early 1920s in the Olduvai Gorge in northern Tanzania by Louis and Mary Leakey. The Olduvai Gorge is forty kilometers long and cuts deep into the Serengeti Plain. It is here that anthropologists find the world's best examples of early Stone Age artifacts that are over 2 million years old. The discovery of this archeological site established the great antiquity of human tool making and suggested that Africa (not Asia as some scientists believed at the time) was the cradle of humanity. The current thinking remains that we all descend from African ancestors that migrated out of the continent sometime after 100,000 years ago: Africa is in every one of our DNA [2]. This position on the origin of human evolution was in agreement with that of Charles Darwin, who in 1859 had published the groundbreaking book *On the Origin of Species*. What was also significant about the Leakeys's discoveries was that they pushed back by almost two million years the known dates for the existence of hominin species.

Sir David Attenborough, the famous naturalist and broadcaster, describes his feelings on holding one of the stones brought back from Olduvai Gorge:

> Holding this, I can feel what it was like to be out on the African savannahs, needing to cut flesh, for example, to cut into a carcass, in order to get a meal. Picking it up, your first reaction is it's very heavy, and if it's heavy of course it gives power behind your blow. The second is that it fits without any compromise into the palm of the hand, and in a position where there is a sharp edge running from my forefinger to my wrist. So I have in my hand now a sharp knife. And what is more, it's got a bulge on it so I can get a firm grip on the edge, which has been chipped specially and is sharp . . . I could perfectly effectively cut meat with this. That's the sensation I have that links me with the man who actually laboriously chipped it once, twice, three times, four times, five times on one side and three times on the other . . . so eight specific actions by him, knocking it with another stone to take off a flake, and to leave this almost straight line, which is a sharp edge [3].

In most cases, these examples of what was the most advanced technology of their time lay strewn, unrecognizable, among other rocks and pebbles. Chopping tools from Olduvai Gorge have a smooth, rounded base and an irregular, undulating work face, where a few crude flakes have been removed, maybe by simply throwing the stone at a large rock. What made these tools stand out as examples of Stone Age technology to the Leakeys was that they were often found clustered together in groups or lying alongside fragments of bones from animals such as giraffes, antelopes, and elephants. There also is something deliberate about their shape. It does not have the randomness that would be expected from natural processes of weathering and abrasion or having been modified by repeated use. They were manufactured with a clear purpose.

Over time, as our ancestors developed more complex brains and became increasingly dexterous, they created more elaborate flint tools, such as handaxes. With its very distinctive chiseled teardrop shape, the handaxe is regarded as the hallmark of *Homo erectus* ("upright man"), the ancestor of the first *Homo sapiens*. These tools are very different from, and more recognizable to the modern eye, than the earliest artifacts found at Olduvai Gorge. Handaxes are shaped by a process called percussion flaking, which involves chipping away small flakes from one large stone (called the core) by striking it with another stone (called the hammer). Cracks, which form from the impact of the hammer hitting the core, travel at speeds up to 1,000 m per second. That is about three times the velocity of a bullet fired from a 9-mm handgun. The resultant crack edges that form on both the flake and the core are very sharp.

As more and more flakes were removed from the core, the shape of the tools evolved displaying a stronger sense of symmetry. They became increasingly refined demonstrating a greater technological finesse. Mousterian flake tools, named after an archeological site in the Dordogne region of France, are very long and narrow and were made about 50,000 years ago. These flake tools, with their well developed, almost intricate, retouched edges and sharp points, are the technology of the Neanderthal. Mousterian-style tools are found all over Europe, from France to Greece and from England to Hungary, and represent the pinnacle of flint technology.

Through the Stone Age from the earliest tools found at Olduvai Gorge to the Mousterian flake tools there is increasing efficiency in the creation of the cutting edge. Douglas Price, emeritus professor of archeology at the University of Wisconsin-Madison, and Gary Feinman, archeologist at the Field Museum in Chicago, provide an interesting illustration of this increased efficiency: From a 0.5 kg flint a pebble tool would yield 8 cm of cutting

Fig. 2.2 A "high-tech" flint tool. This particular example was found in the state of Washington and donated by the Museum of Archeology at Washington State University. From the fineness of the features it can be determined that the final shape was made by pressure flaking. (Originally published in C.B. Carter and M.G. Norton, Ceramic Materials: Science and Engineering, 2nd edition (New York: Springer, 2013), p. 18. Republished here under Springer Copyright Transfer Statement.)

edge. From a same size flint *Homo erectus* could fashion a handaxe that had a cutting edge of about 30 cm, whereas a flake tool provided about 90 cm of cutting edge, more than ten times that of a pebble tool [4].

There is evidence in the archeological record that some of these refined flake tools were shaped specifically so that they could be attached to handles or shafts. This innovation led to a new generation of more advanced tools and weapons such as handled axes and spears. As early as 200,000 years ago hunters in Africa, the Middle East, and Europe had begun hafting stone points onto the ends of their spears [5]. This was a very important technological step. It was the first time that hominins—our ancestors—had shifted from forming tools by chipping away at rocks to creating tools by joining two different materials into a single tool.

Figure 2.2 shows an example of a flint tool found in the state of Washington in the United States, not far from where I am writing. Although the exact provenance and age of this tool are not known, the basic shape was formed by percussion flaking and then retouched with extra precision using pressure flaking to create the final object. Pressure flaking involves pressing on the core with something sharp, rather than striking it with a stone as in percussion flaking. Moose or deer antler tines and bones were commonly used as instruments for pressure flaking. A skilled flintknapper could precisely control the direction and amount of force that had to be applied to remove very small flakes and produce tools that were sharper and even more intricate that those made simply by percussion flaking alone.

Anthropologists have assigned many applications to flint tools based on their size, shape, and the characteristics of the surface finish. Although it can be difficult to find direct evidence for many of these uses—it is actually pretty much impossible—indirect evidence has come by studying the technologies used by more modern hunter-gatherers such as the !Kung San of the Kalahari Desert, the Pygmies of the Congo basin, and the Aboriginal tribes of Australia. As recently as the 1950s, !Kung San living in an area close to the border between Namibia and Botswana were hunting large game using poisoned-tipped arrows and gathering food in the way that goes back thousands of years. Over the following two decades the traditional hunting grounds made way for game and nature reserves and the !Kung lost large swathes of their traditional hunting lands leaving them little left to hunt and gather.

One of the most important, possibly the defining evolutionary use, of flint tools was hunting for meat and processing the animal carcasses. These tools were a developed advantage that allowed our ancestors to kill and butcher animals despite their comparative lack of physical traits compared with predators in nature. The sharp edges produced by percussion flaking could cut through thick tough animal skins providing access to the protein-rich muscle tissue. Flint tools would have speeded up the time necessary to butcher an animal carcass. The heavy bones and skin could be discarded leaving just the valuable nutritious meat, which could easily be transported. Anthropology professor Kathy Schick, codirector of the Stone Age Institute at Indiana University, has demonstrated how very simple flake tools could cut through the one-inch-thick hide of an African elephant. There is a picture of this procedure in the excellent book by Kathy and her co-author Nicholas Toth, *Making Silent Stones Speak: Human Evolution and the Dawn of Technology* [6].

Many studies have found correlations between meat intake, fertility, intelligence, good health, and longevity [7, 8]. According to University of California-Berkeley anthropologist Katharine Milton, a new nutrient-rich meat diet enabled by stone tools provided the catalyst for human evolution, particularly the growth of the brain. "I have come to believe that the incorporation of animal matter into the diet played an absolutely essential role in human evolution" [9]. Eating meat, which supplies essential amino acids, at a young age would have helped children's brains to grow and develop more quickly. By including meat in their diet our human ancestors became smarter, bigger, and stronger, which ultimately led to their evolutionary success particularly as they spread out across Africa and into Asia.

Stone tools not only enabled an evolutionary change they also laid the foundations for human civilization. The sharp edges could be used to prepare