1

INTRODUCTION

Hic mortui vivunt et muti loquuntur.
—Latin inscription on the Library building of the Lvivska Politechnika National University; it means: here the dead are alive and the mute speak.

1.1 HISTORY OF MATERIALS SCIENCE AND ENGINEERING (MSE)

Unlike many other branches of science and engineering—such as mathematics, chemistry, physics, or civil engineering and architecture—MSE has not been formally recognized for a very long period of time. Mathematics has been growing for some thousands of years. Contemporary chemistry is based on alchemy developed by Chinese, Indians, Egyptians, Greeks, Romans, and Arabs. Compared with these, MSE did not even exist in the middle of the 20th century. It was only in 1959 that von Hippel and Landshoff [1] started to talk about molecular engineering as a way to create materials to order. Some historians of science claim that this was the birth of MSE. Others claim just the opposite: MSE is thousands of years old! This is because one of the constituents of MSE is metallurgy—which indeed is several thousand years old. Likewise ceramics as pottery and stoneware have been used for millennia. Presently, MSE absorbs almost instantly new and useful elements, for instance, from solid state physics or physical chemistry, created in the 21st century. Thus, in MSE we have a blend of very old and brand new.

Materials: Introduction and Applications, First Edition. Witold Brostow and Haley E. Hagg Lobland.

1.2 ROLE OF MSE IN SOCIETY

Materials surround us, comprising the clothes we wear, the tools we operate, the luxuries we enjoy, and the toys with which we entertain ourselves. Even food has now been recognized by the Materials Research Society (MRS) as a class of materials akin to commonly categorized metals, ceramics, and plastics [2]. Historians divide the history of humanity into ages: Stone Age, Bronze Age, Iron Age. Some historians have declared that we now live in the Plastics Age. The way people live and function is determined by how they utilize the available materials. From the Stone Age onwards, some people have been industrious with the materials available: maximizing their uses, inventing new uses, and sometimes discovering or developing new materials better than the old ones. Thus, moving from the Stone Age to the Bronze Age meant a dramatic improvement; people were able to furnish a desired shape more easily to bronze (alloys based on copper) objects. After—strictly speaking—the Bronze Age was over, people continued to make intricate objects from bronze. For instance, in the British Museum in London there is bronze statue of Nataraja, the lord of the dance, created ca. 1100 BC during the Chola Dynasty in Tamil Nadu, India.

In the same way, materials are constantly evolving, improving in processing and performance, finding their way into or even driving new applications. The adaptation of existing materials for new uses is driven mostly by economic factors: what manufacturers and consumers want or need. An early bicycle builder, for instance, wanted a material that was tough like iron but would dampen the shock of rocks and ruts in the road. Consequently, the process of creating fiber-reinforced materials was invented and pneumatic tires were designed, greatly improving the bicyclist's experience.

In the present as in all of history, materials are limiting. Imagine that suddenly everything made from polymeric materials disappeared. Cars would not be able to move because instead of every tire there would be a heap of carbon black dust (a tire consists of some 70% rubber which is a polymer and of 30% carbon black). Little girls would be crying because of disappearance of their plastic dolls. These are just two examples…

Alternatively, consider the future in light of the role of polymeric materials: civil engineers are accustomed to working with mineral concretes based on cement, but more and more polymer concretes and/or polymeric fiber composites are used instead [3]. Many car components that have long been made from metals are now being fabricated from polymers and/or composites (whose lower density than metals results in lower car weight, thus more miles per gallon or kilometers per liter). We now have all-composite airplanes and are not completely reliant on the aluminum fuselage. The 787 Dreamliner first rolled out by Boeing in Summer 2007 is the first large commercial airplane with fuselage, windows, wing boxes, control surfaces, tail, and stabilizers all made from carbon-fiber containing composites.

Above we said that MSE absorbs (steals?) elements of other disciplines such as physical chemistry or solid state physics, using them for its own purposes. However, this is not all one-sided. To give just one example, synthetic organic chemists create new polymers because they know that MSE people will find applications for their polymerization products. Materials Science and Engineering thus also stimulates the growth of other disciplines. Moreover, the development of novel materials and applications often enables fabrication of new equipment and techniques that serve to advance other fields. To state the obvious: the fact that materials determine the way people live is not a self-serving declaration by materials scientists and materials engineers—we did not bribe the historians. The activities of everyday life involve humans interacting with materials.

1.3 TEACHING MSE

Now a skeptic can ask the question: if MSE is so important, why do we have in high school boring classes—of chemistry, for instance—with much memorization but MSE is not taught? There are at least two answers to this. First, educational systems are slow. Because in the middle of the 20th century MSE did not yet formally exist, educational authorities such as the Ministries of Education in various countries have not yet figured out that it should be taught. A more discomfiting fact is that at the university level, one can often still get a degree in Physics, Chemistry, or Biology without taking even one class in MSE. The second answer is that materials are like air: all around us and necessary for life, but paid attention to very little. Thus, we tend to pay no attention to materials—until objects made from those materials begin to disappear.

If somehow you are not yet convinced that materials are as important as air is, consider the implications of a few simple questions about materials:

- Why does one use gasoline as a fuel, but one cannot use water instead?
- Why can we elongate a rubber band seven times its original length, but this is not doable for steel?
- Why can we skate with metal blades on ice but not do so on a wooden floor?
- Can water blow up a five-story house?
- Can water be non-transparent and iron transparent?
- What is a mirror made of, apart from glass?

We are not going to answer these questions right now, but answers will be provided later at appropriate locations in the text.

1.4 BASIC RULES OF MSE

Materials Science and Engineering provides us with description, explanation, and prediction of materials behavior. Our basic tool is the following statement: <u>The macroscopic properties of physical systems are determined by structures and interactions at lower levels, such as microscopic, molecular, and atomic</u>. Thus, there is a constant traversing back and forth between *fundamental theories* and *prediction of macroscopic properties*. This principle is represented schematically in Figure 1.1.

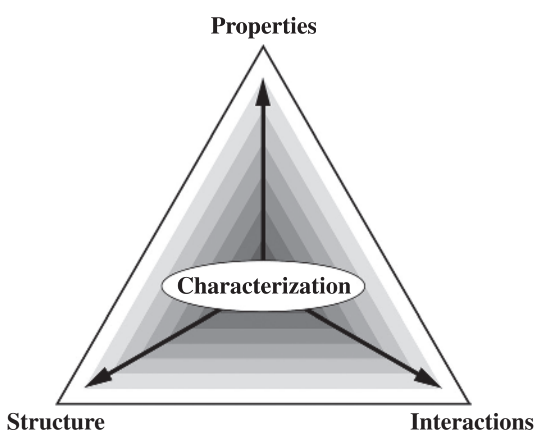

FIGURE 1.1 The basic triangle of Materials Science and Engineering.

The triangle in Figure 1.1 has the following important property: complete knowledge of two vertices of the triangle provides us with knowledge of the third vertex. Thus, if we had available full knowledge of structures and interactions at the atomic and molecular level, we would not need to go to a laboratory to determine macroscopic properties; they would be calculable from the other two vertices. In practice, we typically have fractional knowledge of structures and fractional knowledge of interactions, while some properties of interest but not all have been measured in a laboratory. Thus, we "run around the triangle" to acquire missing information, and the acquisition is called characterization. The word characterization is applied to the experimental techniques used in determining the three elements of the triangle: (1) structure (such as spatial location of phases in multi-component systems seen in microscopy), (2) interactions (such as hydrogen bonds in water which are quite important for water properties), and (3) properties (such as the melting temperature, impact strength, dynamic friction, electrical conductivity—and all other properties).

Some people add processing to the triangle, converting it into a tetrahedron. We think the triangular structure has more perspicuity—but this does not mean that processing is not important. Processing affects all vertices of the triangle. For a material, important events in its history occur during processing; a small change in processing can affect a large number of properties in the final product. In essence, knowledge of a material's history helps us to understand better its current behavior. Certain phenomena occur also during, say, sitting on a shelf, but changes caused by such phenomena are usually slow and not drastic.

The business of characterization is conducted by experimentation. There is no single correct approach to experimentation, but framing the right question is key to success. Theory-oriented experimentation, which was typical of the work of Isaac Newton, is also the classic approach in the philosophy of science. Experiments "are designed with previously demonstrated theories in mind and serve primarily to test or demonstrate them" [4]. On the other hand, an approach known as exploratory experimentation concentrates less on a global explanation of isolated experiments and more on the connections between closely related experiments. Such a method involves "the systematic and extensive variation of experimental conditions to discover which of them influence or are necessary to the phenomena under study" [4]. Clearly, both kinds of experimentation can take us towards deeper understanding. At the core lies keen observation, to see what is the structure of a material and how does it interact with its environment.

To appreciate the importance of this simple triangle diagram, realize that by starting with knowledge of structure and interactions as a foundation, one is enabled to appraise and work with any type of material. A materials scientist or materials engineer who understands this approach does not limit him or herself to a narrow class of materials but is prepared with reasoning skills to analyze all kinds of materials and has a good chance of developing new ones.

1.5 STATES OF MATTER

Ancient Greek philosophers claimed that the whole world consists of just four elements: Air, Water, Stone (or Earth), and Fire. Scientists, particularly in the 18th and 19th centuries, made a much different claim: there are many elements such as copper, silver, oxygen, carbon…. This resulted in the generally held opinion that ancient Greeks simply made wild guesses since they did not have the necessary knowledge. Now, however, it is generally acknowledged that the ancient Greek philosophers had more knowledge than

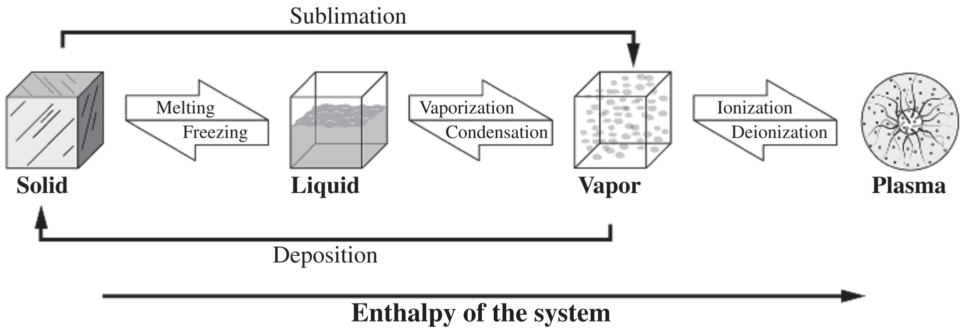

FIGURE 1.2 Basic states of matter and the transitions between them. Enthalpy of the system increases to the right. The melting transition is known also as fusion.

has historically been credited to them. They simply used a different terminology. There are four basic states of matter: gas, liquid, solid, and plasma. These correspond with the Greek elements: Air with gas, Water with liquid, and so on. Recognition of plasma as a separate state of matter is fairly recent; but investigations and experiments involving plasma now abound. An example of a process in the plasmatic state is described in Section 6.7. Many surface-modification techniques also utilize plasma processes. Transitions between the basic states of matter are shown schematically in Figure 1.2. There are also several kinds of mesophases, intermediary between solids and liquids (e.g., colloids, micelles, liquid crystals), that are discussed in subsequent chapters.

1.6 MATERIALS IN EVERYDAY LIFE

We have already pointed out that materials determine the way people live. This statement deserves reinforcement by some examples:

- In the 1980s, the best racing canoes and kayaks were made of wood by a small number of European craftsmen. The best paddlers could cover 1000 meters in about 4 minutes and 5 seconds, under ideal conditions. At the 2012 Olympics, Sebastian Brendel of Germany earned the gold medal with a winning time of 3 minutes and 47.176 seconds. The speed improvement was largely due to innovations in boat and paddle design: what was formerly a craft had turned into an industry, and new composite materials had made that innovation possible.
- A Ukrainian Olympic ice skating champion Viktor Petrenko said at Dartmouth College about electronic brakes built into skis and snowboards: “The change in friction you get is equivalent to going from being on ice to dry pavement” [5].
- If you do not care about racing in a canoe or skating on ice, think about this situation: you are driving a car on an icy and slippery road. You start skidding, and getting out of skidding depends on *friction* between the car tires and the road. This is a material property that can—literally—make the difference between life and death.
- If the above example seems to you overly dramatic, then consider a very simple situation at home: you are frying a couple of eggs on a frying pan. You can lift the eggs after they are fried because the pan surface is covered with Teflon, a low friction material. There is a connection between the story of the skidding car and the story of

frying eggs. On the road you wish as high friction as possible. On the frying pan you wish as low friction as possible. Just one—and the same in both cases—material property is involved.

1.7 HOW TO MAKE NEW MATERIALS

Some students might later go on to designing new materials. How does one do that? Well, we already noted that past history, including processing, determines the properties. Thus, the first stage before creating a new material is investigation of the way the current ones are made. Often one is *not* told by the manufacturer how a given material was made. We have to play a detective, analyzing a structure to figure out what happened before the present structure materialized (a technique known as reverse engineering). This is a capability which is useful also outside of MSE. For instance, look at the scene in Figure 1.3. What occurred before the situation shown in the artwork materialized?

Once we have some knowledge of the materials already used for a desired application, we can begin to think about better ones. Do not assume that you have to follow the path already established; **there might be better options, just nobody thought of them before**. **Originality** and **innovation** are the keys. Do *not* assume something because it seems obvious.

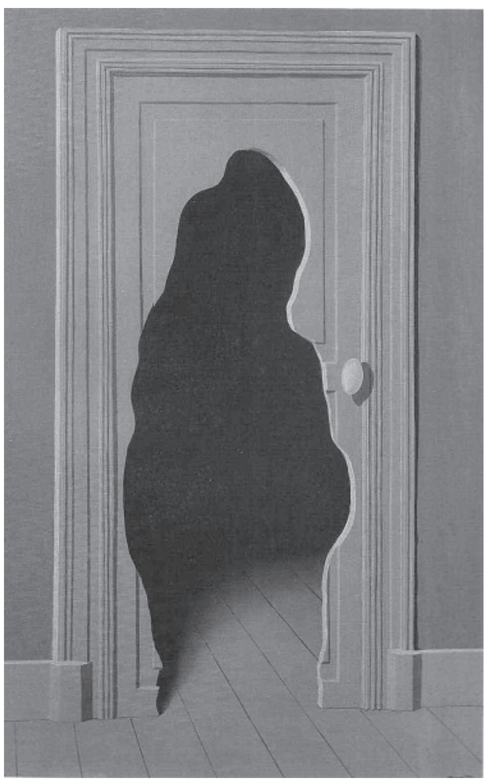

FIGURE 1.3 *La Réponse imprévue* by René Magritte. *Source*: René Magritte: © 2013 C. Herscovici, London/Artists Rights Society (ARS), New York. Reproduced with permission.

1.8 HOW TO USE THIS BOOK

There is a problem typical for practically all students: “I have listened to the lecture, participated in a laboratory since there was one, read this chapter, but I am not sure whether I am getting enough knowledge. I am taking several courses this term/semester. Should I put more effort in the MSE course and less in my Y and Z courses, or the other way around?”

There is a way to deal with this problem. Assessment questions are listed at the end of each chapter. If you can answer them all without consulting this chapter (and your lecture notes if such exist), then you better focus on the Y and Z classes you are taking. If you cannot answer any, this means you were asleep in class and also went through a chapter in a perfunctory way; you now need to read the chapter with some attention. If—a frequent situation—you are able to reply to some questions “off the bat” but not to all questions, this tells you which parts of the chapter you need to return to.

There is a temptation to use wording from the chapter itself, the cut-and-paste procedure. Avoid it! When you use your own words, your understanding gets better. Also note that there might be questions such that more than one answer is a good one. There is an infinity of good answers to the first assessment question in this chapter.

The two-level approach described in the Preface will help you also to manage the material you need to learn. You as a student have to make some choices there—and so has your instructor. Consult your instructor when in doubt; he or she wishes you to acquire useful knowledge and on this basis to be proud of you when the course is completed.

Finally, pay attention to italics and boldface, they convey extra information. Throughout the text, boldface is mostly used whenever important terms are first defined.

1.9 SELF-ASSESSMENT QUESTIONS

1. Describe your favorite material. Give reasons why it is your favorite.
2. Why do historians tell us that the way people live is determined by MSE?
3. Explain the meaning and purpose of the basic triangle of MSE.
4. Discuss transitions between the states of matter known to you.

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