A close-up photograph of a metal drill bit, likely made of high-speed steel, with a blue glow emanating from its tip. The drill bit is positioned diagonally, and the background is dark and out of focus, showing other parts of a machine.

MATERIALS AND MANUFACTURING

AN INTRODUCTION TO HOW THEY WORK AND WHY IT MATTERS

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MARK A. ATWATER

Materials and Manufacturing

About This Book

This book is meant to provide an introduction to materials, their properties, and common methods to make useful items from them. Materials and manufacturing are very deep topics, and a brief introduction is somewhat like introducing someone to the ocean by going for a boat ride. It is informative and meaningful, but ultimately you only experience the surface. There is so much more waiting just beneath the surface. The trouble is that if you dive in too enthusiastically, it is easy to get in too deep. The goal with this text is to find a balance between understanding the basics while appreciating the complexities. This textbook is aimed at readers without significant prior knowledge, or those who may not have understood the topics in previous studies. To keep the length manageable, some topics could not be fully explored, but hopefully it inspires you to go further in areas you find interesting.

You might find the writing in this book is different than in most others. It is meant to be read, so it is presented in a conversational tone, much like it would be verbally taught. The intention is to make the reader feel engaged and to explain and clarify the expected points of confusion. My hope is that it feels like you are being taught the material, not simply having facts and equations listed for your consideration. The scholar will find the descriptions too imprecise, but this text is not designed to be fully quantitative. The goal is to be accessible. If your career requires you to get more quantitative or to develop your knowledge in a specific field, I suggest using this book to set a foundation and another, more focused book to build upon that foundation. What is presented here is an attempt to combine my passion for manufacturing and materials with straightforward and engaging discussion and to transfer both the knowledge and excitement to the reader. For both of us, I hope I am successful!

Materials and Manufacturing

**An Introduction to How They Work
and Why It Matters**

Mark A. Atwater



New York Chicago San Francisco Athens
London Madrid Mexico City Milan
New Delhi Singapore Sydney Toronto

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ISBN: 978-1-26-012232-9

MHID: 1-26-012232-8

The material in this eBook also appears in the print version of this title: ISBN: 978-1-26-012231-2,

MHID: 1-26-012231-X.

eBook conversion by codeMantra

Version 1.0

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About the Author

Mark A. Atwater, Ph.D., is an associate professor at Millersville University, where his areas of expertise include materials and manufacturing theory and practice. He has an undergraduate degree in manufacturing engineering technology and graduate degrees in mechanical engineering and materials science and engineering. He merges these fields in research on the development and production of nanostructured materials.

Acknowledgments

This book is the outcome of years of preparation, learning, and effort, and I am grateful to many who have aided that journey along the way. I am fortunate to have the opportunity to give my take on these important topics, and I am equally fortunate to have the students who inspired it, the facilities and equipment that are featured, and the colleagues who supported me at Millersville University. I believe one of the defining characteristics of this work is the originality of the figures, of which more than 500 were created to complement the text. As someone not specifically skilled in art, it was a massive undertaking to create the numerous drawings and other images. That is why I am particularly grateful for the work of Christopher Smith, an undergraduate student in Art and Design, who assisted with capturing many of the photographs. The best ones are undoubtedly his.

I am also grateful to the individuals and companies who assisted with, created, and/or granted permission to use other images and information for this text. These contributors include:

- Cindy English, MFA
- Lance Nelson
- Brian Monteith and Blaine Bracelin (American Keg)
- Rick Valverde and Henry Trabal (AMES)
- Matt Dabbo (Atlas Cutting Tools)
- Jeff Ostman (IHI Ionbond AG)
- Judy Bass (Industrial Press)
- Bill Young (Kent USA)
- Lisa Johansson (Koenigsegg Automotive AB)
- James Deisley and Jeffery Heger (Millersville University)
- Chief Pete Anders and Sgt. Jason Flood (Millersville University Police)
- Elena Howlin (Oerlikon Metco)
- Robert Ehrmann (Penn State Center for Nanotechnology Education and Utilization)
- Rick Hendricks, Keith English, and Tom Livingstone (Pennsylvania College of Technology)

xviii Acknowledgments

- Nikki Stokes (Sandvik Coromant)
- Dennis Sharples (Sharples Machinery)
- Evan Syverson (Sodick)
- Jonathan Lim (Structo)
- Beau Kibbey (Superior Tire and Rubber)
- Andrey Rudenko (Total Kustom)
- David Birunas and Michael McGarry (TRAK Machine Tools)
- Bruce and Andrea Van Sant (Van San Distributing/MetalAce)

Finally, I am most grateful to my wife, Cammie. This book is just one of many crazy endeavors she has supported me through, and I am deeply grateful to have her as a companion.

Materials and Manufacturing

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CHAPTER 1

Considerations in Materials and Manufacturing

1.1 Introduction

In Daniel Defoe's novel, *Robinson Crusoe*, the title character states, "I had never handled a tool in my life, and yet in time, by labour, application, and contrivance, I found at last that I wanted nothing but I could have made, especially if I had the tools ..." Crusoe was stranded on an uninhabited island with limited resources and in need of basic shelter and provisions. He spent a great amount of time and "infinite" labor concocting methods to make rudimentary items such as boards, wicker baskets, and ceramic vessels. He was able to live comfortably, even to the point of being pleased with his lot in life, because he could manufacture the goods he desired. Often the processes he employed were extremely slow and labor-intensive, but one thing he had plenty of was time.

In our modern society, it is no less important that we are capable of providing products to make life more comfortable, convenient, and prosperous. The challenge we are faced with is much different than Crusoe's. Whereas he had limitations regarding tools and skill, he had an abundance of time. We have highly advanced tooling and skilled labor but must reduce the time investment as much as possible. To maintain quality and improve efficiency is the goal of nearly all manufacturing processes. Consumers are not inclined to pay more for something that does not add value to the final product. The challenge facing manufacturing now is to decrease cost and increase value. This is not a trivial problem.

1.2 How It Works

How is this balance of lower cost and higher quality achieved? There are many methods to reach this goal. One way is through executive changes, such as lean manufacturing, continual improvement (Kaizen), statistical control (Six Sigma), and design engineering (improve manufacturability, use lower cost materials, redesign products to use less material, etc.). We will look primarily at process-level methods in manufacturing. In order to make intelligent decisions about what techniques and materials to use in producing a product, it is important to understand the materials and processes themselves. That is where we will build our foundation.

By starting from the basic principles of materials and manufacturing processes, we can make informed decisions regarding any future changes in the industry. Specifically, if we understand the way materials respond to temperature, pressure, and environment, we can judiciously choose the process or processes most appropriate for creating a specific product. Conversely, if we know what our manufacturing capabilities are, we can determine what materials we can readily work with and what order of processing to use.

This knowledge is highly transferable. By knowing the underpinnings of materials and processes, you are able to apply that in any field whether it involves casting steel pipe fittings, injection molding plastic cups, or machining titanium implants. This text is not written so as to make you an expert in any one material or process. Rather, it is designed to provide enough depth for you to be immediately effective in any manufacturing field. Of course, learning does not happen all at once and end there. It is likely that you will be or are even currently required to increase the depth and breadth of your knowledge further. By the end of each chapter, you should be able to explain *how it works*, how the material is useful, how the process is accomplished and/or how the parameters of processing (temperature, force, etc.) affect the interaction of the material and equipment. Based on knowing how it works, you should then be able to determine and describe why you would or would not apply it in a given situation. That is, *why it matters*. Interactions between the process and the product must be understood before they can be controlled and exploited. We will start by looking at this from a historical view point.

1.3 Historical Perspective

To illustrate the importance of materials and processes, we will take a moment to consider milestones in manufacturing and materials advancements. Perhaps you already know that the periods of civilization are defined by the materials in use during that time, such as the Stone Age, Bronze Age, etc. In absence of any other evidence, the fact that materials have continually defined the progress of civilization should be convincing proof of their importance. Materials and processing have developed together and have enabled one another. Advances in one area allowed advances in both areas. This relationship has been critical in allowing societies to thrive in the past, but they are still relevant to our progress today. We will start our investigation into this importance with the oldest of the “materials” ages*: the Stone Age.

1.3.1 Stone Age

The Stone Age (approximately 3300 B.C. and earlier) is typically divided into Paleolithic, Mesolithic, and Neolithic eras, but taken as a whole, we can consider the reason it pre-dates others. Why is stone, the first of the historical materials[†] periods? When we talk of materials, there are two major divisions that can be made: naturally occurring and those that must be processed before being available. Stone is naturally occurring, so there is

*Materials ages overlap and are generally reported to start/end at different times. The years identified are for illustrative purposes, but they are generally accepted.

[†]“Materials” is often plural even if it seems like it should be singular. For instance, the study of materials is known as *materials science*, not material science.

no processing to form the material and little processing to create tools from it. To form tools, two rocks could be hit together, a very simple manufacturing procedure. By choosing different types of stone, one would be preferentially broken. This could be applied to materials such as flint, which will cleave to form a sharp edge so that arrow heads and cutting tools could be made.

In addition to stone, other “natural” materials such as wood, bone, and animal skins can be used to form tools and products. Because these materials are readily available does not mean that production in the Stone Age was trivial. Very much the opposite, without the advantage of precision machinery to produce items, there was a great need for craftsmanship in producing reliable products. Some examples are shown in Fig. 1.1.

1.3.2 Bronze Age

The Stone Age was characterized by using naturally occurring materials, but a transition to more advanced processing occurred in the Bronze Age (approximately 3300–1200 B.C.). During this period, the ability to process raw material into different, more useful forms was exploited. Copper ore, a rock and ceramic, was converted to a more useful, metallic form through a high-temperature process called **smelting**. Pure copper is rather soft, and to increase the strength, it may be alloyed (mixed, see Sec. 3.2.4 for more) with other metals such as tin. The hot metal can be formed readily at high temperature and this allowed for creating tools and weapons which were not brittle like stone, but still strong enough to survive repeated use (Fig. 1.2).

Here we see the change from using native materials to material design where specific elements were combined to create new, more useful structures. This material conversion requires much more sophisticated processing and measurement and created a precedent for materials research that is still ongoing.



FIGURE 1.1 Tools were originally made from natural materials such as stone, wood, bone, and skins. These primitive tools were essential but very limited in their use.

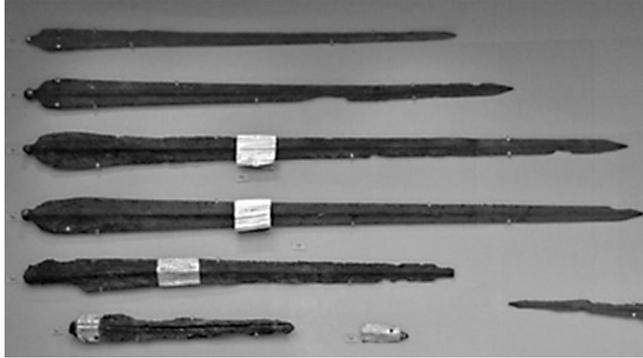


FIGURE 1.2 Advances in the Bronze Age allowed for durable tools to be made. Bronze is less brittle than stone (its toolmaking predecessor) and can be more easily shaped, allowing for intricate tools to be developed.

The invention of bronze and the utilization of smelting allowed for tailoring tools with specific properties. The amount of tin added to copper will change its strength and therefore durability. To create uniformity in the tools and weaponry, the process would have to be repeatable. No doubt much experimentation and testing would be required to perfect the process and products, but that design approach continues today.

1.3.3 Iron Age and Beyond

The next stage of materials development comes in the Iron Age (approximately 1200 B.C. to 50 A.D.), where the practices of the Bronze Age were carried over to new materials. Specifically, iron and steel (a mixture of iron and carbon) were brought into prevalent use. The smelting conditions required for iron ore are more exacting than for copper-based materials such as bronze. The temperature must be higher and the atmosphere must be controlled. Iron is stronger than bronze and requires hot working (e.g., blacksmithing) whereas bronze can be cold worked (formed and hammered near room temperature). See Sec. 9.2.1 for discussion of cold working. The major advantage with iron is that, when a small amount of carbon ($< 1\%$) is present, the iron is greatly strengthened. This alloy of iron and carbon is the basis for steel, which is the most common structural material today. Some iron tools are shown in Fig. 1.3.

The improvements in mechanical properties allowed for stronger weapons and tools, and the advancement of smelting techniques allowed for new alloys to be created. Although the Iron Age is the last of the “material” ages, the process for improvement has not changed. Iron became important due to improvements in processing and better understanding ways to modify the properties through adding secondary elements, now known as alloying. Processing continued (and continues) to improve with advancements such as the Bessemer process in the mid-19th century (Henry Bessemer, 1813–1898), and now other processes that offer more control.

Our current technological state has been referred to as the Silicon Age. That is because computing has become integral to so many applications, and much of the hardware that makes it possible is based on the element silicon. There is little doubt silicon will be replaced eventually and a new age will reign. Even if silicon still plays an



FIGURE 1.3 The development of iron tools allowed high-strength weapons and tools to be made. These held a sharp edge better than bronze and were more durable.

important role, it will be in support of new materials which enable the boundaries of current technology to be surpassed.

Transitions from age to age are not immediate and complete. The progress of processing and materials went hand in hand and occurred incrementally. Stone was used even after bronze was invented. Bronze continued being used even when iron gained popularity. Indeed, materials are developed and modified and can be perpetuated along in some capacity forever. There are a limited number of elements (about 92 naturally occurring*) that make up every single material we have and will use. Even fewer (closer to 10) are common structural materials. By combining materials in a thoughtful way, we can achieve “ideal” balances between strength and weight or other properties. Even advanced composites, which have allowed for space exploration and exceptional performance under extreme conditions, are not new. The ancients understood that mixing clay and straw together resulted in a superior material, which we now classify as a composite (see Sec. 6.4 for other examples). They constructed magnificent structures from this “advanced” composite long before any materials were studied scientifically, at least by our modern standards.

New research is revealing that the periodic table (see Fig. 2.1) is three dimensional, so to speak, and the properties of materials are size dependent. This extends the possibilities well beyond our historic applications. The nanoscale version[†] of a material can respond differently to heat, light, electricity, etc. The melting point, color, reactivity, and strength can change drastically at the nanoscale. For example, stained glass (Fig. 1.4) produced in antiquity was colored by mixing in metals, which formed nanoparticles that appear as different colors (e.g., gold can appear red). Although they did not understand the exact reasons, craftsman knew how to control the outcome. We now know much more about these size-dependent properties. They present new tools for the engineer, but they also present new challenges in controlling

*This number is debated depending on how “naturally occurring” is defined.

[†]“Nanoscale” refers to 1 billionth of a meter, or about 1000 times smaller than the thickness of a hair.



FIGURE 1.4 The properties of materials are size dependent. For instance, the color of gold changes based on size, and gold and other metals have been used to dye stained glass for centuries thanks to this property.

and manufacturing these materials. As society advances, wood and stone are still popular and appropriate in many applications and bronze and iron are now better understood and applied than ever before, but the importance in continuing to advance materials and manufacturing lies in the benefit that can *still* be realized today and tomorrow.

1.4 Present Challenges

As mentioned in the introduction, there is a grand challenge in manufacturing of maximizing quality while minimizing cost. We briefly looked at the progress of materials and the basic concepts of the processing required for their production, but there is much left to be said about the current circumstances of production technology. Historically, advancements have significantly shifted the way products are made and what is possible. This includes technology and methods such as interchangeable parts, mass production, and automated manufacturing. These took manufacturing from being a slow, custom, skill-intensive business, to be a rapid and universal process. This forever changed the way products are made, but is not applicable to all sectors of manufacturing. That is to say, there is no one-size-fits-all solution to achieving the cost/quality balance.

Manufacturing is highly competitive. This competition exists locally, regionally, nationally, and globally. The decision to use one company over another is a complex mix of considerations about costs for labor and shipping, production rate and capacity, quality constraints, etc. For large orders where high volume and **continuous manufacturing** will be used, the equipment tends to be a principal cost. Highly specialized, equipment designed for high-rate production is often used. The specialization of the equipment reduces the need for **skilled labor**, but also reduces flexibility (i.e., the equipment is dedicated to one specific job and has little use other than that).

For **medium- to low-volume manufacturing**, the equipment becomes more generalized and the labor must be more highly skilled. The equipment can often be used to

produce many different types of products, but must be carefully setup and qualified when the process is changed. This is where the skill is required to ensure that quality is maintained. The trade-off here is that there is higher cost associated with labor and the down time while the machine is being converted to run another product. In this type of processing, scheduling becomes critical and a host of considerations must be made to ensure efficient process flow is maintained.

In any type of manufacturing, material cost is another important aspect. Following customer design specification such as strength, weight, dimensional tolerance, etc. is required, but the way in which the specifications are met can vary. For example, assume a structural member can be made from hollow steel or solid aluminum and still meet weight and strength requirements. Which one will you use? Where possible, cheaper material and easier processing will always win out. This is assuming there is no explicit design requirement on the material. For example, if the component cannot be magnetic, aluminum would be required since steel *is* magnetic. If there are few constraints, it is more a matter of whether it can be processed using the equipment currently available or that can be purchased for a reasonable cost.

Typically, the steel component will be cheaper from a material perspective, but what other considerations remain? Processing steel and aluminum will proceed quite differently. Take machining for example (see Chap. 13 for more on machining). Aluminum is a softer material and generally can be machined at a faster rate and cause less wear on tooling. The steel equivalent will end up costing more in supplies (tooling) and time (machine cycle time and operator wages). The difference between material and processing cost must be established to determine the more cost-effective choice.

There are many process-oriented variables that must be weighed, but other aspects of service or design requirements must be considered as well. Is there a specified service temperature (hot or cold)? Is this component likely to be loaded and unloaded repeatedly? How much will that load be? Is the service environment corrosive? What is the expected lifetime of the product this component will go into?

The steel can withstand elevated temperature more readily, but the aluminum will tend to corrode less in most environments. Steel performs better under cyclic (repeated) loading, known as fatigue (see Sec. 7.6.5), but aluminum may be considered more aesthetically pleasing (do not underestimate this aspect). Either material can be treated to perform better in any circumstance or a different grade of the material can be selected.

This is only the tip of the iceberg when considering a material and process! Machining was mentioned, but similarly, forging, casting, welding, or any other process can run through a similar set of questions to determine which material is the best to process by which technique. The designer's job (possibly *your* job) is to know how to make these decisions. This book is intended to help you get started.

The challenge in processing and material selection is to meet both the desired specification (customer requirements) and the company's interest (minimizing cost and maximizing profit). There is global competition for manufacturing, and to win in that game, you must find the route by which to maximize value. Choices, such as automating processes, ultimately come down to whether it will eventually improve the company's competitiveness and profit margin. A company's most valuable investment is in skilled employees capable of identifying methods to achieve that end. The goal of this text is to increase your knowledge and versatility in this competitive environment and to help you identify the best practice in processing.

1.5 Future Considerations

After considering where materials and processing originated from, the question arises, “Where do we go from here?” Advances in manufacturing commonly take place by improving rate and repeatability. This is often accomplished by automation of processes. Faster computers, more accurate controllers, and improvements in tooling have all allowed for processes such as high-speed machining, robotically controlled work cells, computer-integrated manufacturing (CIM), rapid prototyping, advanced casting techniques such as directional solidification, etc. (see Chap. 22 for more on advanced manufacturing). Any process can benefit from being both faster and more accurate.

With regard to materials, the push for new breakthroughs is equally alive. The demand is for stronger, lighter, and cheaper. Advancement in composite materials has allowed a whole host of new, lightweight structures to be designed. Biologically inert or active materials are allowing for quicker healing, better performance, and longer life from medical devices such as artificial heart valves and joint prostheses. New alloys enable new engine technologies and more efficient operation. Add to this the profound changes that have arisen due to advances in semiconductor processing. Advanced electronics has driven the technological advancement in just about every field.

Research to improve current processes and materials is largely in the details. By using computer simulation, processes can be modeled and studied without ever touching a production machine. The vast amount of data that can be collected from simulations can be cost effective in determining the feasibility of new processes. This simulation process can be extended to materials also. New alloys are being developed at the atomic scale, and new processes are being employed to surpass traditional “limits” in alloying, strength, and other properties.

Nanotechnology, the study and manipulation of materials at the atomic or molecular level, is being employed to create new materials with unique properties and holds promise to advance our society to a level unfathomable at present. The difficulty in making these “nano” materials and devices is that nanofabrication or nanomanufacturing techniques must be used to make them, and these techniques, broadly speaking, are in their infancy.

To put nanoscale processes and materials into perspective, we will compare them to common objects. For example, a human hair is approximately 80,000 nanometers (nm) across, and a red blood cell is about 5000 nm across. There are 1 million nanometers in 1 millimeter, and 25,400 nm in one *thousandth* of 1 inch (in) (0.001 in). Nanoscale materials and technologies must be controlled at scales significantly smaller than cells. The challenge with these advanced techniques and materials is to control the quality and repeatability and to bring them to production rates of traditional manufacturing. Though many exciting technologies and materials can be demonstrated on a small, laboratory scale, transferring the techniques to a level that would make them feasible for consumer-level distribution is not trivial. Imagine machining gears smaller than a dust mite (Fig. 1.5). This presents an entirely different manufacturing challenge where nanoscale devices and phenomena must have production scaled up reliably and cost-effectively. This is the reality of manufacturing. Challenges do not tend to get easier with time. New techniques, not commonly associated with production manufacturing, are used to meet the challenge. Solving unconventional problems requires unconventional thinking. Innovative approaches must be applied to take these cutting-edge technologies from science to society.

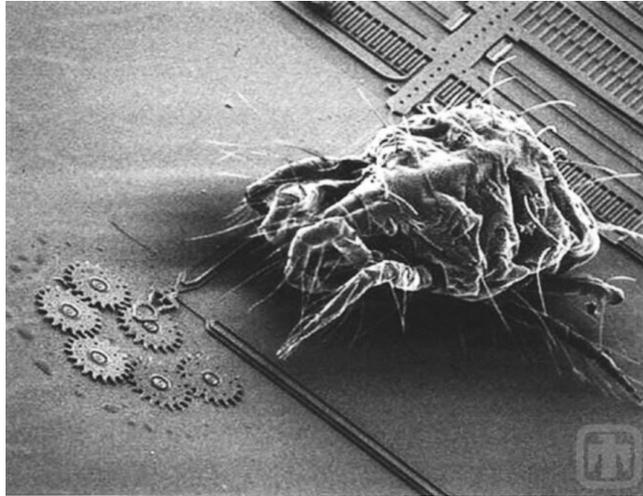


FIGURE 1.5 Dust mite approaching micrometer-sized gears ($1\ \mu\text{m} = 0.00003937\ \text{in}$). The current stage of society's development is largely due to silicon processing which allows for microprocessors and miniaturized technologies to exist, but other developments in materials and processing are being made concurrently. (Photograph from Sandia National Laboratories, SUMMIT Technologies.)

1.6 Why It Matters

Technology tends to benefit from itself. As manufacturing advances, materials can advance, and as materials advance, equipment for manufacturing can also advance. It is a self-perpetuating cycle. Technology is not simply marching forward. The pace of technological development is gaining speed. The last century has seen more scientific advancement than all of the preceding centuries combined.

Often people do not see the science behind technology; they simply see the result. This can be thought of as a growing tree (Fig. 1.6) where the root system is scientific understanding and technology (the visible result) is the trunk, branches, leaves, etc. As the understanding of fundamental scientific laws has advanced, the roots have grown deeper. This has allowed for technologies to be developed, first as the foundation (trunk), but later as more advanced off-shoots (branches) which have spurred a number of improved devices and techniques (the leaves). As the roots grow deeper, they can support the above-ground development, which gives shade (ease of living) to the societies which harness them. This, of course, is assuming that we can responsibly apply the technology we create, which is not always the case.

What is important to realize from this is the interconnectedness of the fundamental understanding of materials and processes and the products they facilitate. Discoveries and improvements in either materials or processing work to advance both. Processing is consistently happening at higher speeds, stresses, temperatures, etc. More extreme conditions demand more extreme materials. Materials and manufacturing are truly inseparable. It is in that disposition that we can begin unraveling the exciting facets of each.

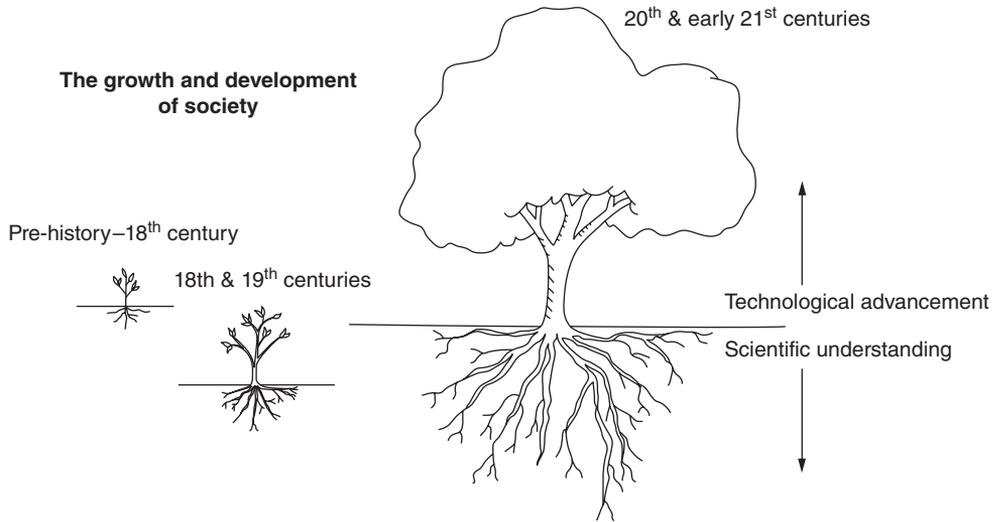


FIGURE 1.6 Society, in general, has benefited from advanced technology. That technology is generated through scientific study. Although important advancements were made in the early centuries, the 20th and 21st centuries have greatly outpaced previous ones. (Illustrations courtesy of Cammie Atwater.)

1.7 The How and Why of Considerations in Materials and Manufacturing

1.7.1 Chapter Review

1. Robin Crusoe, much like the earliest societies, had no formal training in manufacturing. He developed processing methods by trial and error. What limits does this put on designing new products and processes? What negative consequences might arise?
2. Natural materials were the foundation for technological advancement in early civilization. What are some natural materials in use today?
3. Stone is a common material, still in wide use today. Name three applications it can be found in.
4. What are two benefits and two disadvantages of creating stone tools by hand?
5. Bronze is made primarily of which element?
6. What are the three advantages of bronze over stone? What is the disadvantage?
7. How was the development of iron and steel tools an advantage over bronze?
8. Steel is a mixture of which two elements?
9. Steel is the most common structural material. Name five applications of steel.
10. What is the “grand challenge” in manufacturing?

11. As the number of products decreases, how does the manufacturing skill required change? What about the equipment used?
12. When making design decisions, how can you cut material cost?
13. Name three differences between processing steel and aluminum.
14. Name two active areas of material advancement.
15. Name two active areas of manufacturing development.
16. Give a general definition of nanomanufacturing. What is a fundamental problem?
17. Science and technology go hand in hand. Which has more of an impact on society? Which is more important?
18. Name an important technology. How has this technology been affected by advances in manufacturing and materials?

1.7.2 Concept Connections and Extensions

1. Is there value to knowing how things are made? Should the average consumer be concerned about it? Section 22.5 might help generate some ideas.
2. Is newer always better? Consider the phrase, "They don't build them like they used to." Is that a good thing or not?
3. Why is silicon considered the current age of material development by some? What properties make it useful? Sections 6.2.4.1 and 22.4.2.1 will be helpful.
4. Why is education in manufacturing becoming more important? Consider the changes in how we produce goods (e.g., Sec. 22.3). What roles do skilled and unskilled labor play?

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