Michael Pfeifer

MATERIALS ENABLED DESIGNS

THE MATERIALS ENGINEERING PERSPECTIVE TO **PRODUCT DESIGN** AND **MANUFACTURING**

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The Materials Engineering Perspective to Product Design and Manufacturing

Michael Pfeifer

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Materials Enabled Designs

To Jenny, Jordan, and David

Preface

This book covers the materials considerations required to improve the likelihood of designing, developing, and manufacturing successful products. Such considerations are important in view of the significant role that materials play in the success of a product and the many decisions during product development and manufacturing that influence the performance, reliability, and cost of the materials used in a product. Some of these decisions include product design concept selection, materials selection, manufacturing process selection, and supplier selection.

The idea for this book came about after I taught a class in the Manufacturing and Design Engineering (MaDE) program at Northwestern University. The course focused on the materials engineering considerations for product design, development, and manufacturing. As I assembled the reading material for the class, I found that there were no texts that addressed product development and manufacturing from the materials engineering perspective.

There are several books about product design, but they are written from the mechanical engineering perspective. While some of these books discuss materials selection, they do so from a mechanical engineering viewpoint. That is, they discuss the process for selecting materials based on satisfying product performance requirements, but they neglect the many other design requirements that must be considered when selecting materials.

Other books discuss materials selection, but they do not cover all of the applicable design requirements and do not discuss the process of verifying that the materials do indeed satisfy all of the design requirements. Also, these books do not address in detail the materials engineering considerations for developing capable manufacturing processes and evaluating the reliability of materials for specific designs.

The concepts presented here complement the information provided in product design and materials selection textbooks. This book also complements books that focus on other design considerations such as design for manufacturing, design for reliability, and design for environmental variables. The only difference is that this book focuses on the materials aspects of the design for X approaches.

To avoid confusion and manage reader expectations, it is important to mention what is and is not presented here. First, this book's focus is on the materials engineering considerations for specific decisions made during product development and manufacturing; that is, only the decisions that benefit from the materials engineering perspective are considered. Second, the process and considerations for materials selection are covered; however, the selection of materials for specific applications is not covered because plenty of books are available on that topic.

Chapter 1 explains the materials engineering perspective; the role of materials and materials engineering in a product; and how a product is ultimately an assemblage of materials that must be selected and whose properties must be controlled. The chapter also defines terms used throughout the book.

Chapter 2 discusses the design requirements that the materials in a product must satisfy and explains how the requirements are derived from the wants and needs of the product's intended customer. Chapter 3 outlines the process of choosing materials based on materials selection criteria.

Chapters 4 through 6 present background information about materials engineering and related considerations for performance, reliability, and product manufacturing. Chapter 4 discusses the aspects of materials that must be controlled to obtain the desired properties and the resources available for technical information about materials.

Chapter 5 covers the aspects of manufacturing processes that influence the properties, performance, and reliability of the materials that go through a manufacturing process. This chapter briefly discusses various manufacturing processes, explores the general aspects of manufacturing processes that must be controlled in order for the materials that make up a product to be as desired, and addresses manufacturing process variations and their impact on the materials that constitute the process output. Chapter 6 examines the reliability of materials and presents strategies for evaluating that reliability.

Chapters 7 through 12 apply the information provided in the previous chapters to the various elements of product development and manufacturing that require the materials engineering perspective.

Acknowledgments

I would like to start by thanking Professor Ed Colgate from Northwestern University for his support and encouragement. Ed took me up on my idea to offer a course based on the materials engineering considerations for product development for the Manufacturing and Design Engineering (MaDE) program. This book is based on the material from that course. I also want to thank Ed for his insightful review of it. His comments and suggestions resulted in dramatic improvements.

Next, I want to thank Ron Scicluna. His insights and knowledge about the product development process were critical to helping me better understand the place of materials engineering and the importance of risk-assessment and mitigation strategies throughout every phase of the process. The many hours of discussion with Ron were educational and fun, and they helped me organize my thoughts.

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Finally, to my wife, Jenny, thank you for supporting my efforts to write this book. It seemed at times like the writing would never end.

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CHAPTER

The Materials Engineering Perspective

1

1.1 INTRODUCTION

A person can look at any engineered product and see that it is made of a wide variety of materials that have been manipulated into a wide variety of shapes for the purpose of enabling specific product features. Just consider an automobile with its painted steel body, plastic knobs, rubber tires, and glass windows, or a computer mouse with its plastic shell and buttons and rubber tracking ball and wheel, or a bicycle with its painted aluminum frame, steel gears and chain, and foam padded and plastic covered seat. In fact, a product can be considered to be a collection of materials such as metals, polymers, ceramics, composites, and semiconductors. Furthermore, the materials used in a product account for up to 60% of the total cost to manufacture a product (Nevins & Whitney, 1989). Based on both of these facts, it seems that the engineering processes for selecting the materials used in a product and the means by which the properties of the materials are controlled are of the utmost importance to the success of a product.

Even though the materials used in a product have a huge impact on its performance, reliability, and cost, many companies vastly undervalue the importance of proper materials engineering considerations for product development and manufacturing decisions. Consequently, these companies struggle with problems such as new products that are behind schedule, cost overruns, poor supplier quality, poor manufacturing quality, and products that do not work as expected. All of these problems have a negative effect on the success of a product and a company's competitiveness. These struggles do not have to be accepted as a normal part of doing business. In many cases, product development and manufacturing problems, and their costs, can be avoided if comprehensive materials engineering considerations are employed when making certain design and manufacturing decisions.

A successful product enjoys good profits, good market share, and good customer satisfaction. Developing and manufacturing a successful product requires the following:

- That the product has the performance and reliability to satisfy the wants and needs of the intended customer
- That the costs to develop and manufacture the product are within budget
- That the product is released to the market on time

Meeting the first two requirements depends on a design team's ability to select materials that enable the product to satisfy its performance, reliability, and cost requirements. Furthermore, controlling the variation of the properties of the materials is critical for making a product that consistently meets its performance and reliability requirements while keeping manufacturing costs within budget. Releasing a product to market on time depends on avoiding delays associated with problems with the materials.

In short, this book asserts that a product's success depends on the attention paid to the materials engineering aspects of decisions that occur during product development and manufacturing.

It is not the intention here to diminish the role of other engineering perspectives or to imply that materials engineering alone can solve all the problems encountered during product development and manufacturing. The materials engineering perspective is just one perspective of many that are required to make good decisions that increase the likelihood of producing a successful product. However, it is the intention of this book to instill a better appreciation for the role that the materials engineering perspective can play in product success.

1.2 THE MATERIALS ENGINEERING PERSPECTIVE

This book teaches a perspective that focuses on materials engineering concerns as they pertain to achieving overall product success. This perspective, referred to here as the *materials engineering perspective,* is based on the following three considerations:

1. The *performance*, *reliability*, and *cost* of a product are highly dependent on the properties of the materials that make up the product.
2. Proper *selection* of the materials used in a product is crucial to satisfy its performance, reliability, and cost requirements.
3. *Control of the variation* of the properties of the materials that make up a product is crucial for enabling its consistent performance, reliability, and cost.

The first consideration is important because it shifts the attention away from viewing any single component within a product solely in terms of its mechanical, electrical, optical, or chemical functionality. Instead, seeing a component in terms of its materials moves attention to the properties of the materials required to obtain the desired functionality and reliability at the desired cost.

The second consideration may seem obvious because most engineers recognize that specific materials have specific applications and that the optimum mate-

rials must be selected for any given application. However, the proper selection of materials demands thorough and accurate knowledge of all of a product's performance, reliability, and cost requirements. Many design teams make the mistake of trying to select materials without knowing all the selection criteria and based on inaccurate criteria. Furthermore, there are selection criteria that are based on requirements in addition to performance, cost, and reliability. For example, industry standards, government regulations, intellectual property rights, and manufacturing constraints place requirements on a product's design. This is discussed in more detail in Chapter 2.

The third consideration about the control of material properties is based on the fact that there are many sources of variation of the properties of the materials used in a product. The sources of variation are related to the processes used to manufacture a product and the materials used in the processes. Controlling variations requires an understanding of the relationship between a manufacturing process, the properties of materials used in the process, and the properties of the material that makes up the process output. Excessive variations in the materials' properties result in products that cannot be easily manufactured and do not have the desired performance and reliability. This is discussed in more detail in Chapter 5.

Looking at a product from the materials engineering perspective can help design teams frame decisions and understand the information required to make better design and manufacturing decisions. An example of the application of this perspective can be provided through consideration of the scissors shown in Figure 1.1. From just a functional perspective, the scissors is a mechanical device capable of cutting paper. From a materials engineering perspective, the scissors is a set of materials that must have certain properties, such as the following.

FIGURE 1.1

Pair of scissors.

- Two pieces of corrosion-resistant material hard enough to maintain a sharp edge and ductile enough so as not to fracture when used to pry something open
- Handles rigid enough to transfer a user's force to the blades, but with enough strength and impact resistance so that they do not crack or break when the scissors are used or dropped
- A pivot pin made of a hard, corrosion-resistant material with a surface smooth enough so that the blades pivot with little effort

Furthermore, there are common requirements for all the materials. Namely, that the materials enable the blades, handles, and pivot pin to be easily manufactured and that the materials are of reasonable cost.

Recognition of all these requirements and their importance helps engineering teams focus on the possible materials that can be considered for use and selecting the materials that optimize a product's performance, reliability, and cost to produce.

The materials engineering perspective also helps engineering teams focus on how to control the variation of the material properties to ensure that a product consistently satisfies the wants and needs of the customer. This involves understanding the effects of variations in the manufacturing process on the materials' properties variations, developing capable manufacturing processes, and selecting capable suppliers.

Now, imagine designing more complicated products that have performance and reliability requirements that are much more demanding than for a pair of scissors (e.g., a jet engine, a hip implant, or an automobile fuel level sensor) and that are exposed to much harsher environments. What is the likelihood of the success of these products if the optimum materials are not selected and are not well controlled?

The materials engineering perspective may seem like a narrow topic on which to write a book aimed at product design, development, and manufacturing. However, many decisions occur during product design, development, and manufacturing that have an impact on the materials selected for use in a product and how well the properties of the materials are controlled. These decisions will be discussed from the materials engineering perspective. The chances of these decisions resulting in favorable outcomes improves when a materials engineering perspective is brought into the decision-making process.

This book is different from others on materials engineering in that the science and engineering of materials is not the focus. Instead, the focus here is on the considerations and information required to make better and faster decisions that affect the materials used in a product. These decisions occur throughout every phase of product design, development, and manufacturing. Furthermore, these decisions go well beyond just material selection and failure analysis—two aspects of the product life cycle that are associated with materials engineering. Some of the decisions that will benefit from a materials engineering perspective will seem

obvious. Others are not as obvious and may even appear counterintuitive at first. However, the discussion of the materials engineering perspective for the specific decision will illustrate its significance. Only those decisions that involve or impact the materials are considered here.

The information in this book conveys how knowledge of materials engineering and the materials engineering perspective can provide a competitive advantage that will reduce the costs and time to develop and manufacture a product. However, readers should be aware of the subjects on which this book does not focus.

First, even though certain aspects of the design process are discussed, what is here will not teach product design and development. Instead, it is intended as a complement to textbooks that focus on product design and development (e.g., Ullman, 2003; Ulrich & Eppinger, 2004; Pahl & Beitz, 1996). Second, although we provide some explanation of materials science and materials properties, it is not the purpose of this book to teach materials science or materials selection for specific applications. Resources for this information will be provided in later chapters.

The concepts discussed here are in practice at a few companies. At those companies, new products are brought to market with fewer problems compared to companies that do not have materials engineers. Also, new materials for performance improvement, reliability improvement, and cost reduction are continually being evaluated and implemented.

1.3 WHAT IS MATERIALS ENGINEERING?

In order to understand the materials engineering perspective it is helpful to understand what materials engineering is. It involves understanding the relationship between the properties of a material, its composition, its microscopic structures, and how it was processed. This knowledge is put to use to develop and improve products and manufacturing processes.

Materials engineering education includes the study of the following:

- Microscopic structures within materials
- Atomic and molecular motion, and the interactions and reactions between atoms and molecules within materials
- Macroscopic material properties
- Effects of microscopic structures and composition on macroscopic material properties
- Effects of the manufacturing processes on the microscopic structure and macroscopic properties
- Methods for characterizing microscopic structures and macroscopic properties
- Mechanisms by which materials degrade