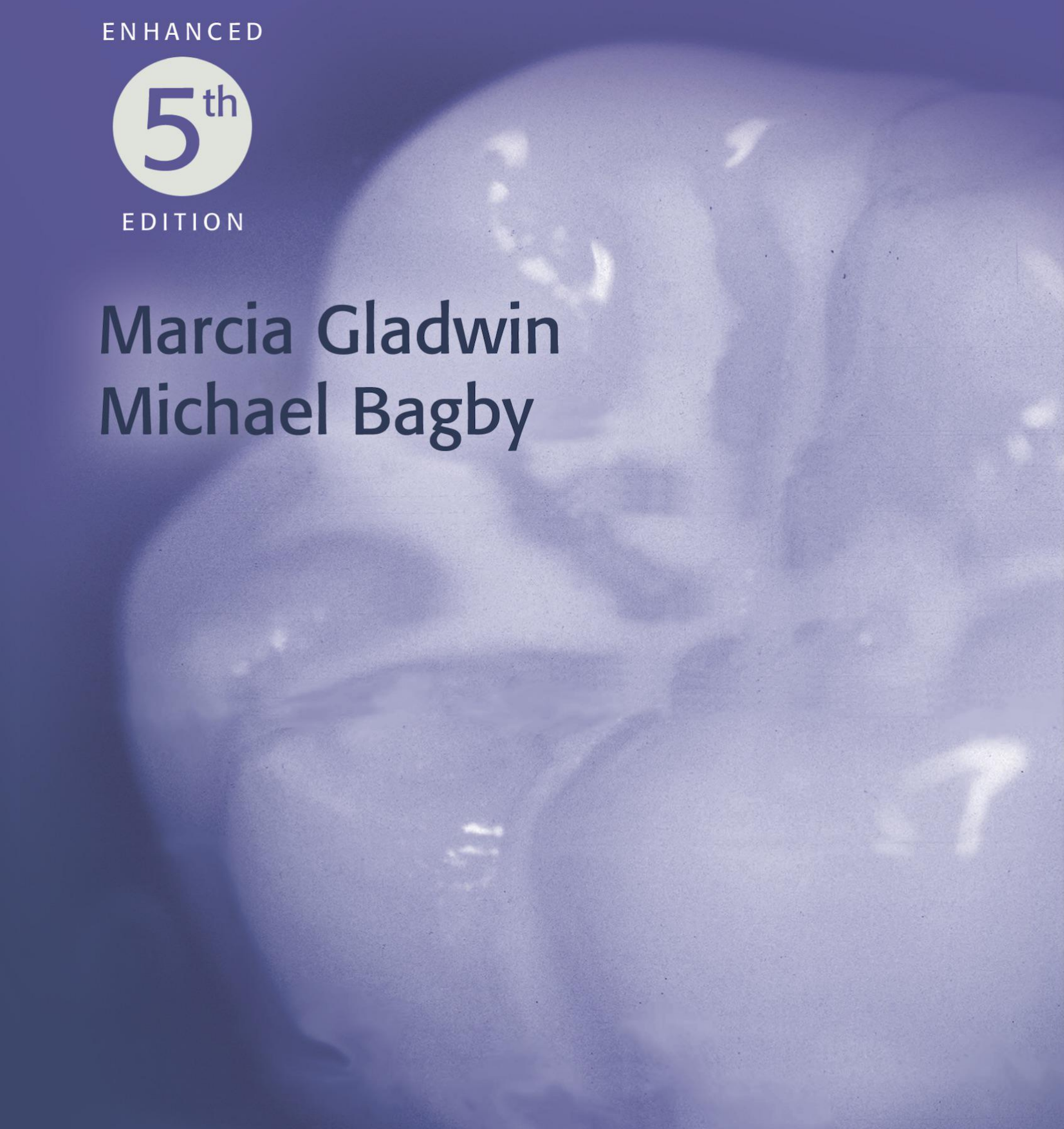
Clinical Aspects of DENTAL MATERIALS

Theory, Practice, and Cases

ENHANCED
5th
EDITION

Marcia Gladwin
Michael Bagby



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The authors wish to dedicate the fifth edition to two groups of individuals:

To all of the dental hygiene students for making the effort to grasp
the basic principles and manipulation techniques of dental materials
along with your other coursework. With dedication and determination
you will meet your career goals!

and

To the dental materials instructors for continuously updating and presenting lectures,
for preparing the lab, for demonstrating techniques, and for grading
and helping students in lab sessions.

We have experienced these same challenges.

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Preface

The objective of the fifth edition of *Clinical Aspects of Dental Materials: Theory, Practice, and Cases* is, first, to provide a dental materials background that emphasizes the clinical aspects of dental materials and, second, to introduce concepts of materials science. It is our hope that the student will become more familiar with the practice of dentistry through the use of this textbook.

In too many instances, the practice of dentistry and dental hygiene in an office setting becomes separated and disjointed. As a member of the dental team, the hygienist must be an advocate of dentistry. Although knowledge of caries, periodontology, and oral pathology are basic to the hygienist's daily responsibilities, a basic understanding of general dentistry and dental materials allows the hygienist to become a more effective member of the general dentistry team.

As new dental materials and techniques are continuously being developed, it can be difficult to keep abreast of all the new products, improvements, and their applications. And, as a member of the dental hygiene profession, the hygienist is obligated by our Code of Ethics to be a lifelong learner. This continual effort to "stay current" includes the science of dental materials. We need to understand the behavior of materials, how to handle materials, and how to assess the patient's oral condition. This knowledge then allows us to treat and educate the patient so that optimum oral health is achieved.

The authors hope that this publication provides a basic foundation for that lifelong learning.

ORGANIZATION

The text continues to be divided into three distinct parts: Theoretical Perspectives, Laboratory and Clinical Applications, and Case Studies. All chapters have been reviewed and updated. Two new case studies have been added. Six chapters reflect significant revisions: Chapter 4, "Adhesive Materials"; Chapter 7, "Dental Cements"; Chapter 10, "Materials for Fixed Indirect Restorations and Prostheses"; Chapter 16, "Polishing Materials and Abrasion"; Chapter 19, "Instruments as Dental Materials"; and Chapter 31, "Vital Tooth Whitening Procedures."

Two appendices complete the text sections: Appendix 1 provides the Answers and Justifications to Review Questions and Case Studies, and Appendix 2 comprises the Skill Performance and Evaluation Sheets that correspond to Part II of the textbook, "Laboratory and Clinical Applications."

TEXTBOOK FEATURES

Objectives: All chapters list the information the student is expected to know by the end of the chapter subject matter.

Key Words and Phrases: These are listed alphabetically at the beginning of each chapter, appear in bold, and are defined as they occur within chapter content.

Summaries: At the end of each chapter, a distinct summary section reviews the major components presented.

Learning Activities: Part I, Chapters 1–22, includes a list of small group and classroom activities that promote understanding and application of the chapter content.

Review Questions: Multiple choice review questions in each chapter will reinforce student comprehension and aid in quiz and exam preparation.

Precautions and "Tips" Boxes: Part II, Chapters 23–39, of the text, "Laboratory and Clinical Applications." contains distinct text boxes labeled "Precautions" and "Tips for the Clinician."

The "Precautions" box promotes safety while working with the materials, and the "Tips for the Clinician" box offers advice so that the best results are achieved.

Answers and Justifications to the Review Questions: Appendix 1 includes the correct answers and justifications for the review questions in Chapters 1–36 and the Case Studies. This section will also aid in preparing for exams and quizzes.

Skill Performance Evaluations: Appendix 2 contains "lab sheets" that correspond to Part II, "Laboratory and Clinical Applications." These perforated, tear-out sheets allow for student self-assessment as well as instructor evaluation.

ANCILLARIES

The ancillaries for this textbook are available on the book's Navigate 2 Advantage Access site. There are both "Student Resources" and "Instructor Resources." The Student Resources include learning objectives, assessments (chapter review questions), student aids, videos, appendices, case studies, and suggested readings. The Instructor Resources include PowerPoint presentations, image banks, and LMS course cartridges.

TO THE INSTRUCTOR

The textbook continues to be written in outline format. This provides a clear organization of the topic and facilitates the reading of both the theory and laboratory chapters. Some sections of many chapters continue to be labeled as optional. The instructor should feel free to designate other sections as optional as well.

The learning activities can serve as homework assignments, or individual or group activities in the lab or classroom. Certain activities could also serve as part of a laboratory practical exam.

The videos and image bank on the Navigate 2 Advantage Access site are available to make lectures and lab sessions less labor intensive and more time efficient.

The skills evaluation sheets in Appendix 2 are to serve as a criteria list for properly manipulating that particular material in a laboratory session. They are single-sided, perforated, and provide areas for both student and instructor evaluation. The chapters in Part II of the book can serve as a lab manual for these same selected materials.

With the review questions, the answers, and justifications (Appendix 1), we made an effort to not only explain why the answer is correct but to also explain why the other answers are incorrect. This section of the book is an additional learning opportunity. Please guide your students to it as they study for quizzes and exams.

It is hoped that Chapter 16, "Polishing Materials and Abrasion," is included in your topical outline for the course. This key chapter is pertinent to dental hygiene practice. It addresses the various polishing agents, the process of polishing as it relates to tooth abrasion and also presents air–powder polishing, specific abrasion rates, and dentifrices.

TO THE STUDENT

Despite the hopes of the authors and the reality of teaching dental materials, there may not be enough time in the academic term for the instructor to cover all the chapters in the text. The instructor chooses the chapters to be taught based on the dental materials curriculum set forth by your specific dental hygiene program. If that is the case, we hope that you will take it upon yourself to read over two specific chapters: Chapter 19, "Instruments as Dental Materials" (because you have paid a great deal of money for these) and Chapter 37, "Tips for the New Hygienist" (because it gives you a little insight on the "real world" of dental hygiene practice). These may not be assigned as required course reading but lend themselves to better preparing you to become part of the professional dental team.

In addition, if the case studies and review questions at the end of the chapters are not assigned or discussed, please use these on your own to prepare for quizzes, exams, and national, regional, or state board examinations. And, as mentioned above to the instructors, Appendix 1, "Answers and Justifications to Review Questions/Case Studies," provides not only the correct answer but also an explanation of why that answer is correct and the other choices are not. This can be considered as "extra" review material to help you to be better prepared.

SUMMARY

The authors have made a concerted effort to thoroughly edit and update not only our chapters but also have reviewed and made suggestions to improve those of the many contributors. We contacted two additional educators to revise content in existing chapters and to add new cases so the text is "that much better" as a teaching and learning tool.

We hope that the fifth edition of *Clinical Aspects of Dental Materials* is user-friendly, appropriately updated, and instrumental in helping students gain a basic understanding of dental materials. We wish all the instructors and students a very successful academic year!

Acknowledgments

The authors wish to express their thanks to the following individuals for their contributions to this edition:

To the eight contributing authors who provided their expertise for this edition, we appreciate your acceptance of our suggestions and editing. To those that are long-standing contributors, thank you for your ongoing cooperation and dedication to this project in the midst of busy schedules. To the two newest ones, Andrea and Ashlee, thank you for giving your time, effort, and knowledge to improve and expand the final manuscript.

A special thanks to a long-term contributor, Ms. Caren M. Barnes, RDH, MS, who has retired from the University of Nebraska Medical Center. In the arena of dental and dental hygiene education, she has made vast contributions to the professions with five editions of her own textbook, more than 30 additional textbook chapters and over 90 publications in refereed journals. She persevered through a serious, but temporary, illness to revise one of our more important chapters. We wish her the best in all future endeavors.

To the team, Jonathan, John, and Amy at the publisher, Dharma at SPi, and all others behind the scenes, your guidance has been most appreciated.

And lastly, and by no means least, is Mrs. Karen Gierach, our friend and retired English educator, who has been our own personal editor. Her expertise with grammar, syntax, and diction has "saved" us on more than one occasion. A heartfelt thanks for all your time and effort.

Contents

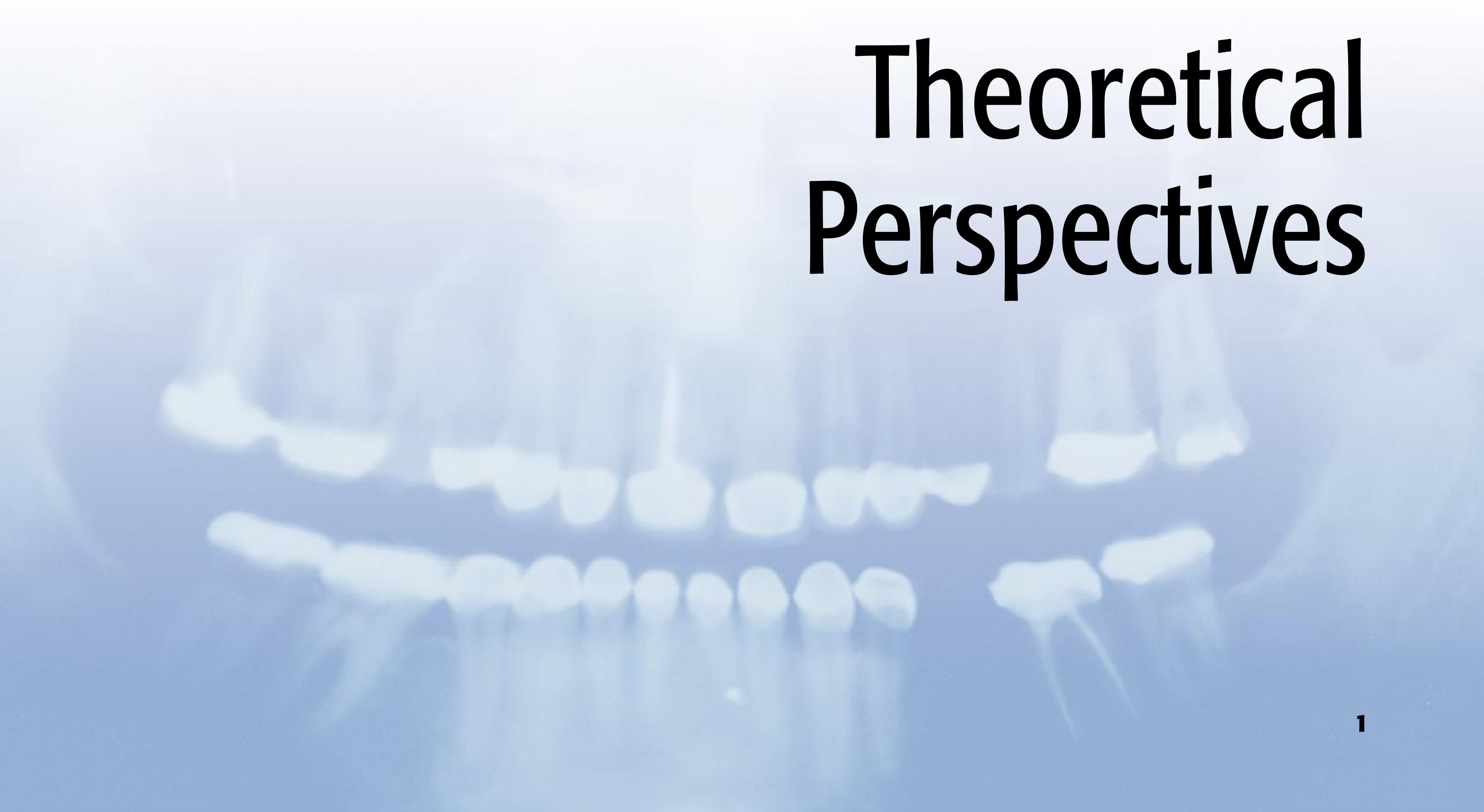
Part I Theoretical Perspectives

Part II Laboratory and Clinical Applications

Part III Case Studies

I

Theoretical Perspectives



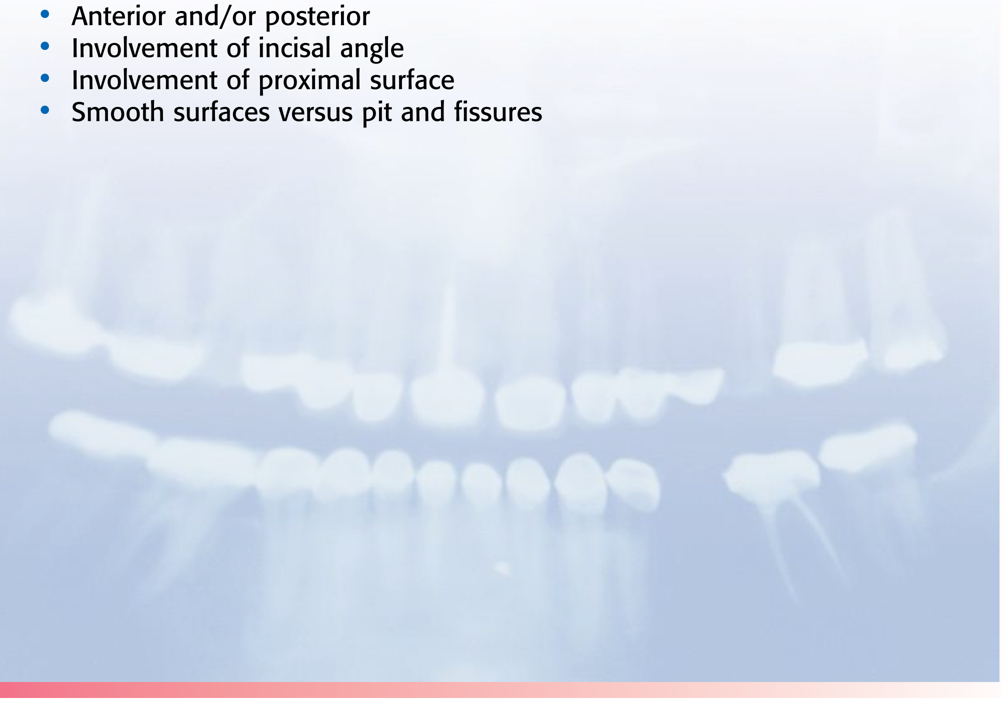
Introduction

1

Objectives

After studying this chapter, the student will be able to do the following:

1. Summarize the reasons why a dental hygienist should be knowledgeable in the science of dental materials.
2. Explain the difference between biomaterials and dental materials.
3. Discuss some of the conditions that make the oral cavity a hostile environment.
4. Identify four characteristics or properties a dental material must possess to survive in the oral environment.
5. Explain how the following organizations evaluate and/or classify dental drugs, materials, instruments, and equipment:
   - American Dental Association (ADA)
   - U.S. Food and Drug Administration (FDA)
   - International Standards Organization (ISO)
6. Name three ways dental materials may be classified, and discuss each.
7. Specifically discuss the locations of all six cavity classifications and the appropriate restorative material to be used for each. Include the following in your discussion:
   - Anterior and/or posterior
   - Involvement of incisal angle
   - Involvement of proximal surface
   - Smooth surfaces versus pit and fissures



Key Words/Phrases

abutment
base
biocompatibility
biomaterials
bridge
cast
cavity preparation
dental implants
dental materials
denture
diagnostic cast
direct restorative materials
esthetic materials
fixed partial denture
impression
indirect restorative material
interim restoration
liner
luting agents
maxillofacial prosthesis
polishing
pontic
prosthesis
provisional restoration
removable partial denture
restorations
restorative materials
retainer
specifications
study model
temporary crown
temporary restoration

Introduction

What is "dental materials"? It is a subset of materials science, an applied science that combines chemistry, physics, and engineering with a little biology. Other important examples of materials science include food science, parts of pharmacology, and textiles. After all, we want our chips to be crunchy, our time-release medications to slowly dissolve, and our colored fabrics to stay bright. In dentistry, we do not want our fillings to break, our molars to dissolve, nor our incisors to "yellow." Understanding what makes one material strong and rigid while making another stretchy and snap back to its original shape will help us utilize the vast array of dental products to care for our patients.

I. Rationale for Studying Dental Materials

"Dental materials" is one of many required courses in the dental hygiene curriculum. It focuses on those items and products used in the prevention and treatment of oral disease and the promotion of health. The scope of practice of a dental hygienist includes the delivery of therapeutic, educational, and preventive patient services. Materials used in the practice of dental hygiene include instruments made from common industrial materials, therapeutic agents, and dental biomaterials used to prevent disease. At times, therapeutic dental products and preventive materials overlap.

The preventive aspects of dental hygiene include primary prevention, which attempts to reduce the occurrence of disease, and secondary prevention, which attempts to limit the destruction caused by disease. Both aspects of preventive dentistry involve the use of instruments (made from materials) and dental materials.

A dental hygienist should be knowledgeable in the science of dental materials for the following four reasons:

A. To Understand the Behavior of Materials

This will aid in the delivery of quality patient care. The dental hygienist must understand why specific materials behave as they do and why they are used for certain functions in certain locations to replace missing oral tissues. For example, the proper placement of sealants will prevent dental caries. The proper restoration of teeth and maintenance of restorations will limit the destructive effects of caries and periodontal disease. The proper care and maintenance of instruments (prevention of corrosion) are important when sterilizing and disinfecting. The proper use of dental materials is fundamental to the art and science of dentistry.

B. To Handle Materials Properly

Both preventive and restorative dentistry rely heavily on the proper use of biomaterials. While most of us can boil water, reheating pizza that does not result in a mushy crust requires the proper application of heat (try a low-temperature frying pan with a good dose of patience).

Biomaterials are man-made materials that are used to replace tissues or that function in intimate contact with living tissues. **Dental materials** are biomaterials used in or around the oral cavity. The hygienist may or may not be involved in the placement of restorations, but he or she plays a significant role in the placement of preventive materials and the maintenance of restorations. The proper handling of dental materials is important because improper handling will likely adversely affect their physical, chemical, and mechanical properties. In turn, this could affect the overall service to the patient.

Therefore, handling a dental material properly is a primary factor in the success or failure of its use. The goal of this text is to present dental materials and their manipulation from a clinical perspective. If materials are properly mixed and placed, improved patient care will result.

C. To Assess and Treat the Patient

The dental hygienist must be able to recognize all dental materials present in the mouth. These may be visible clinically and/or radiographically. Proper identification is important so that they are not mistaken for caries (radiographically) or improperly maintained. An example would be the clinical recognition of an all-ceramic crown. Acidulated phosphate fluoride (APF) gels can etch the surface of some ceramic materials. Using an APF gel is contraindicated for patients with ceramic restorations; instead, a neutral fluoride gel should be used.

D. To Educate the Patient

In many instances, patients may ask the dental hygienist to discuss the characteristics and properties of one dental material compared to another, both of which may be a reasonable option for the patient. Patients may also ask the hygienist to describe the steps involved in the fabrication of a certain type of restoration, or they may also inquire about home care regimens ("How will I take care of my new bridge?"). Knowledge of dental materials is critical so that the patient is given professional, complete, and correct answers.

II. Biomaterials and the Oral Environment

A. Oral Tissues as Biologic Materials

Whether a material is used for preventive or restorative purposes, the oral environment places great restrictions on which materials can be used and the manner in which those materials are used. When one realizes that oral tissues are themselves biologic materials, a variety of properties and functions are evident. All oral tissues must function in the hostile environment of the oral cavity.

1. Enamel

Enamel is a hard, wear-resistant surface material. It is able to resist the compressive forces of biting, but it is weak in its resistance to bending and other forces that occur when food is ground by molars. Enamel is well supported by dentin. Enamel will dissolve in oral fluids if the pH is too acidic; dental caries is the result of such an acidic attack. Enamel is also responsible for the tooth's pleasing esthetic appearance.

2. Dentin

Dentin makes up the bulk of the tooth. It acts as a cushion for the brittle enamel, and it provides strength to resist the complex forces that occur when biting. Dentin is more susceptible than enamel to acidic attack.

3. Pulp

Pulp is connective tissue that contains nerves and blood vessels. It provides nutrients to the dentin and responds to stimuli with pain or sensitivity.

4. Periodontium

Periodontium supports the tooth in a stable but dynamic position, and it provides feedback regarding the force placed on the tooth. Periodontium includes the periodontal ligament, cementum, and alveolar bone.

5. Gingival Tissue

A very important function of gingival tissue is to seal out the many noxious agents of the oral cavity. Gingival tissue prevents chemicals and microbes from gaining access to the periodontium and deeper tissues in the body. Gingival tissues surround and attach to teeth, forming a barrier. Although the oral cavity is considered to be inside the body, in many ways it is more like the outside. Biomaterials placed in the oral cavity have very different requirements from those of devices implanted inside the body.

B. Replacement Materials for Oral Tissues

1. Restriction on Materials Use

When oral tissue is lost, dental professionals attempt to replace it with a dental material. The replacement material mimics the function of the oral tissue, and it must withstand the same harsh environment. The biologic nature of the oral environment and the size of the oral cavity restrict the use of materials. These restrictions include the following:

a. Biting forces that may fracture teeth and replacement material
b. Degradation of:
  - Materials, such as corrosion of metal
  - Teeth, such as dental caries
c. Temperature changes that cause restorations to contract and expand differently than teeth, causing leakage around the restoration as well as tooth sensitivity
d. **Biocompatibility** (the lack of harmful effects to the patient)
e. Esthetic demands of the patient

2. Effects of Dental Materials and the Oral Environment on Each Other

The dental hygienist must understand the characteristics and properties of dental materials. This knowledge will provide insight regarding how a dental material may affect the oral environment. An orthodontic appliance makes oral hygiene difficult and increases the patient's susceptibility to gingival inflammation and caries. The oral environment affects the dental materials as well. Yeast or other microbes may colonize on a denture, causing it to become foul-smelling. These characteristics and properties may also limit the selection and use of a dental material.

III. History and Selection of Dental Materials

A. History

Why are certain materials chosen instead of others to serve as dental restorative materials? Actually, much has been learned throughout history by trial and error. Paraphrasing C.S. Lewis, "Experience is that most brutal of teachers." In ancient times, gold was used not only for its corrosion resistance but also for its "workability" or ease of processing. For centuries, humans have attempted to improve their appearance with adornments, such as jewelry and makeup. The replacement of lost teeth is an ancient practice. First, it was more likely for esthetics than for function. As dentistry developed throughout the ages, function became important. Some of the materials used included ivory, which was carved, and porcelain, which was fired into tooth shapes. By the 1800s, dentistry was becoming a scientifically based discipline. The pace of development of new materials quickened. Amalgam, a silver filling material, was frequently used. Porcelain could be crafted into inlays and crowns.

In the 20th century, dental materials science had developed into its own discipline. Numerous materials and techniques were developed. Precise casting techniques were developed for a variety of metals. Polymers and composites were adapted for nearly every dental material need. In the 21st century, new ceramic materials and processing technologies have been adapted by dentistry. Computer-aided design and manufacture are common along with other digital technologies. The pace of dental materials development is so fast that some of this text will be outdated before it is published.

Luckily, the basic concepts of materials science and their use do not change. Both the student and the practitioner need to understand the behavior of the materials they use. After all, they are the ones who must select a product from a rather long list of possibilities.

B. Selection of Dental Materials and Products

The knowledge gained in a dental materials course will aid in the selection of products. Manufacturers readily provide data regarding strength and a variety of other properties. At times, they also provide the results of short-term clinical trials. How reliable is that information? More importantly, how useful is that information? It has been a goal of dental materials scientists to predict the performance of a material from its strength and other mechanical properties. Unfortunately, success has been elusive. Clinical trials are the most reliable source of information for most products. The clinician must evaluate the product information, but he or she must also consider the source of that information.

IV. Standards for Dental Materials

Standards for dental materials have been developed in dentistry in the same manner as in other industries. Standards describe the properties of a product so that a user may select the proper material for a particular use. Standards are common in everyday life. Examples include the octane rating of gasoline, DVD formats, the size of nuts and bolts, computer communications protocols, and even the size of eggs. In the United States, standards are published and administered by the American National Standards Institute (ANSI). Many industries have organizations that work under the guidance of ANSI to develop and administer the standards for the products of that industry; the American Dental Association (ADA) is the institution that represents dentistry.

A. Council on Scientific Affairs of the American Dental Association

In the United States, standards and guidelines for evaluating dental products are developed and administered by the Council on Scientific Affairs of the ADA. The Council evaluates dental drugs, materials, instruments, and equipment. A successful evaluation culminates in awarding of the ADA's Seal of Acceptance. The applicant (e.g., a toothpaste company or any manufacturer of a dentally related product) submits data for their product following the ADA guidelines. On approval of the product, the applicant is permitted to use the ADA's Seal of Acceptance. The Seal is illustrated in *Figure 1.1*. It is commonly seen on accepted brands of toothpaste and toothbrushes. The ADA Seal is awarded for a period of 3 years, after which the applicant must resubmit the product. In addition, advertising for products that have been awarded the ADA Seal is reviewed by the ADA.

Some of the ADA guidelines have very specific requirements for physical and mechanical properties that are measured in the laboratory and are called **specifications**. Specifications have been developed for many (but not all) dental materials. Unfortunately, researchers have not been able to develop a series of tests that adequately predict the clinical performance of many dental materials. As a result, the Acceptance Program relies on clinical data for the evaluation of many dental products. If a product is shown to be safe and effective, it can be given the Seal of Acceptance.

The Acceptance Program of the ADA is voluntary. Manufacturers are not required to have the Seal to market dental products in the United States. Although products might be approved for sale by the U.S. Food and Drug Administration (FDA), some products fail to meet the ADA

FIGURE 1.1. Seal of Acceptance of the American Dental Association. (Courtesy of the American Dental Association, Chicago, IL.)

specifications when tested. The ADA Professional Product Reviews are an excellent summary of dental materials and their properties.

B. Medical Device Amendments of 1976

The federal government, under the auspices of the U.S. FDA, has the authority under the Medical Device Amendments of 1976 to ensure the safety of all medical devices. The U.S. FDA considers dental materials to be medical devices. Medical devices are grouped into three categories:

1. Class I

These devices are the least regulated. Only good manufacturing practices are required. Prophy paste or brushes are two examples of such products.

2. Class II

Class II devices gain approval from the FDA after being shown to be equivalent to products currently in use. Equivalency is demonstrated by meeting performance standards, such as the ADA's Seal of Acceptance Program. Some dental products have been "grandfathered in," because they were marketed before 1976. Composite and amalgam restorative materials are two examples of Class II products.

3. Class III

These devices are the most regulated; they require premarket approval. Clinical data must be submitted to the U.S. FDA for evaluation before Class III devices are sold. If safety and efficacy of the device is supported by the data, the U.S. FDA then gives approval to market the product. Bone graft materials are common examples of such products.

C. International Standards Organization

Many other countries have dental specifications or standards and governmental regulations. To simplify the mass of regulations, the International Standards Organization (ISO) attempts to unify standards throughout its member countries. The ISO standards for many dental materials have been developed (and continue to be developed) under the guidance of the Fédération Dentaire Internationale, the international equivalent of the ADA.

Many dental products carry the "CE" marking symbol of the European Union on their packaging, as shown in *Figure 1.2*. CE stands for Conformité Européenne, and the marking is required for sales in most of Europe. The CE symbol indicates compliance with ISO standards and European Union marketing requirements for dental products.

FIGURE 1.2. Photograph of dental products from several companies displaying the CE marking symbol.

D. Selecting Products

Dentists are fortunate because several products usually will meet the needs of a particular clinical situation. It is important to select and use materials that result in quality service to the patient. The same product may not do so for all practitioners. It is acceptable to select products based on handling characteristics, a company's reputation and service, or packaging. If two products have been shown to have excellent clinical performance, the ill-defined characteristics of "feel" or "handling" may be the final criteria that result in its selection. A product with the "right feel" will likely result in superior use and service to the patient. In the words of Dr. Karl Soderholm of the University of Florida, "the material must be your friend."

It is important to realize that most products require some time to learn to use them properly. If the clinician is always changing products to have the latest and greatest "widget bonder," he or she may be spending so much time learning to use new products that patient care may be affected. Of less consequence, that clinician will also have drawers, closets, and refrigerators filled with expensive, partially used dental products.

V. Classifications of Dental Materials

Like oral tissues, dental materials serve a variety of functions. Some materials replace lost tooth structure and restore the function of the teeth. These materials must withstand biting forces and therefore be strong and wear-resistant. Other materials are used to make impressions of oral tissues from which replicas are made. Many impression materials are soft and stretch a great deal when removed from the mouth. In dentistry, as in other disciplines, properties of a material must be matched to the use of that material. Dental materials can be classified in a number of ways but are typically classified by their use or function. Restorative materials are also classified by the location of fabrication or by the longevity of use.

A. Classification by Use

Materials used to replace lost oral tissues are called **restorative materials**. As mentioned earlier, those that replace lost tooth structure and restore the function of the teeth must be strong and hard (*Figs. 1.3–1.5*). Some restorative materials simulate the appearance of the tissues that are being replaced (see *Figs. 1.6 and 1.7*). Tissues simulated by restorative materials include the enamel of teeth (fillings and crowns), the mucosa of the periodontium (dentures), and even the skin of the face (maxillofacial prostheses). Materials that are tooth-colored are often called **esthetic materials**.

1. Restorations

Depending on the degree of destruction of a tooth, different restorations or fillings are used to replace lost tooth structure. Some **restorations** replace a small to moderate amount of tooth structure and are supported by the remaining tooth structure. Such restorations are held in the tooth by undercuts (mechanical locks), adhesion, or both. An inlay is a restoration that is made outside the mouth, usually in a dental laboratory. Inlays do not have undercuts and are cemented or "luted" into the tooth (*Fig. 1.3*).

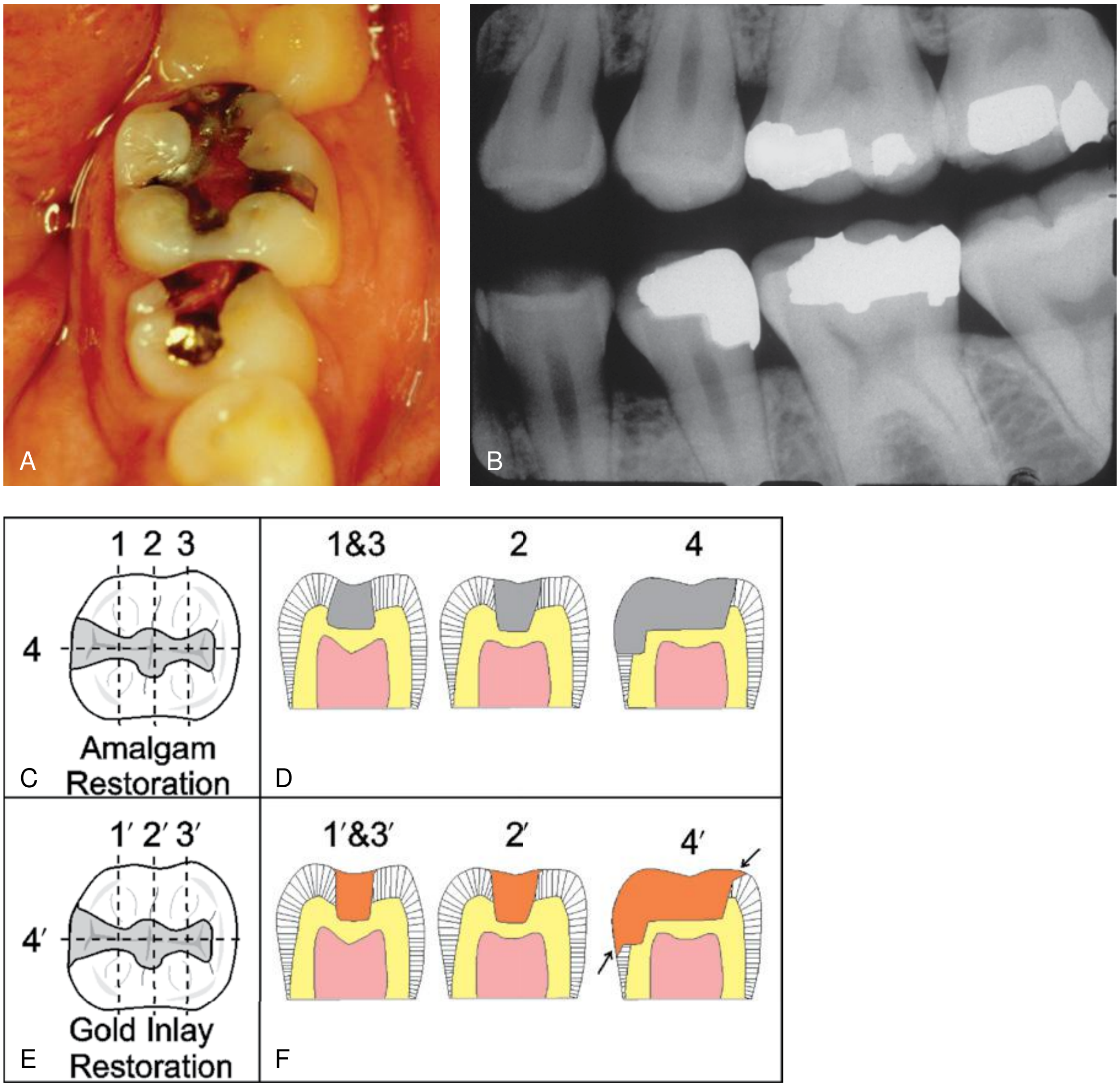


FIGURE 1.3. Photograph **A.** and radiograph **B.** of inlay (tooth #20) and amalgam (tooth #19) restorations. Drawings show the convergence and divergence of preparations for the two materials. The amalgam **C** and **D** has several convergent walls (undercuts) at 1 and 3. The inlay **E** and **F** has only divergent walls at 1′, 2′, and 3′. *Arrows* indicate bevels for a metallic inlay.

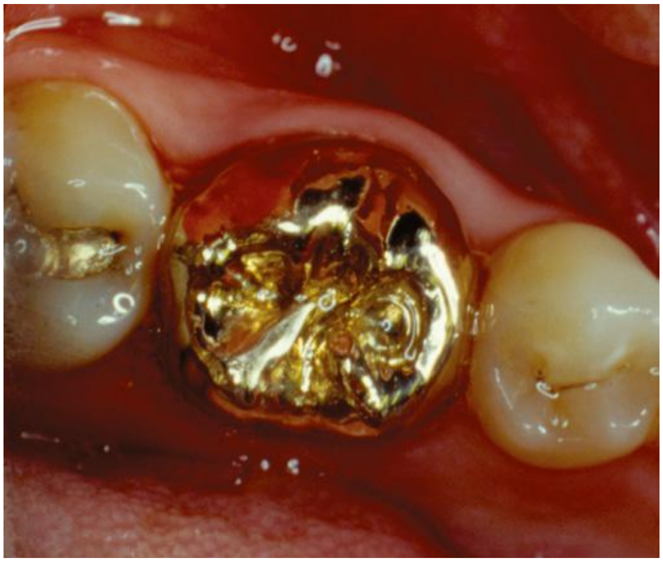


FIGURE 1.4. Photograph of a full gold crown.

Restorations are restricted to the physical size of the missing tooth structure. Excessively large restorations could affect speech or the patient's bite, or overwork the chewing muscles.

2. Crowns

Crowns are used to restore teeth when a substantial amount of tooth structure is missing. Crowns encircle and support the remaining tooth structure (*Fig. 1.4*). Crowns are cemented in place similar to an inlay. If a crown or filling is too large or overcontoured, it will be detrimental to the health of the gingival tissues.

3. Bridges

A dental **bridge** replaces a lost tooth or teeth (*Fig. 1.5*). A typical dental bridge is much like a bridge over a river. At each end, the dental bridge is supported by an actual tooth called an **abutment**. Each abutment tooth is prepared and then restored with a crown called a **retainer**. The missing tooth is replaced with a false tooth called a **pontic**. A pontic is a replacement tooth, but only the crown portion of the tooth is replaced. The pontic and abutments are strongly joined together so that biting forces will not break the bridge. The dental bridge is cemented onto the prepared abutment teeth in the same manner as a crown or an inlay. Like all restorations, the physical size of a bridge is limited by the physiology and anatomy of the mouth.

4. Complete and Partial Dentures

Because of the ravages of caries or periodontal disease, some people lose many or all of their

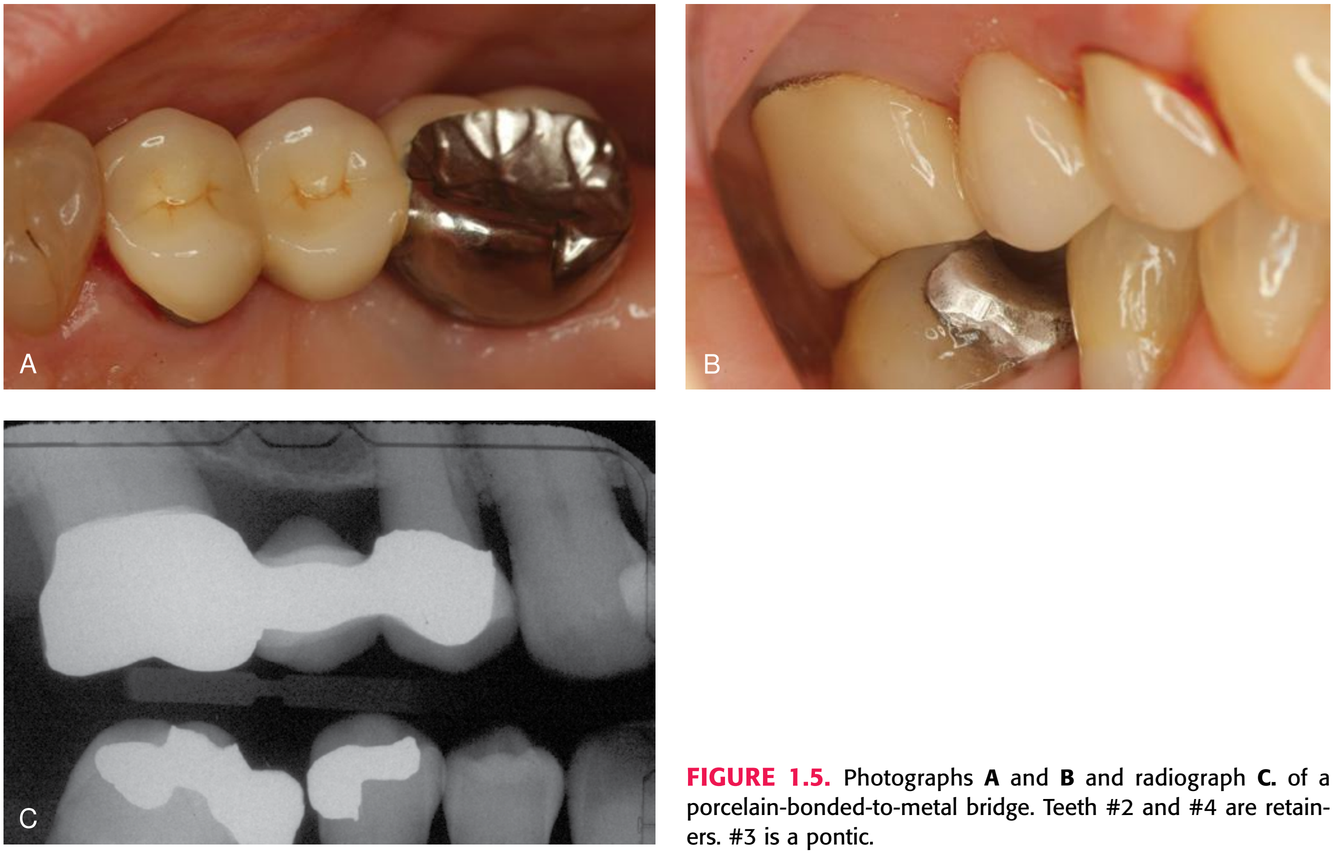


FIGURE 1.5. Photographs **A** and **B** and radiograph **C.** of a porcelain-bonded-to-metal bridge. Teeth #2 and #4 are retainers. #3 is a pontic.

FIGURE 1.6. Photographs of **A.** an edentulous maxillary ridge and **B** and **C** denture in place. (Courtesy of Dr. Henry Miller, Greenburg, PA.)

teeth. If all the teeth of an arch are missing, the teeth are replaced by a prosthesis called a complete denture, as shown in *Figure 1.6*. A **prosthesis** is an artificial device that replaces a lost organ or tissues. A **denture** replaces missing teeth, bone, and gingiva after the teeth have been lost or extracted. A complete denture is supported by and precisely rests on the mucosal tissue covering the maxilla or mandible. The functions of a complete denture include chewing food (mastication), proper speech, and esthetics. Frequently, dentures improve a patient's self-esteem, appearance, and oral function.

If some teeth are present in an arch, the replacement prosthesis is called a partial denture. A bridge is often called a **fixed partial denture** because it is cemented into place (*Fig. 1.5*). A **removable partial denture** is sometimes referred to as a "partial" and replaces few or many teeth. A removable partial denture is placed and removed by the patient in the same manner as a full denture (*Fig. 1.7*). Typically, a removable partial denture has several metal clasps that are designed to encircle several remaining teeth so that the prosthesis is stabilized, somewhat like the abutments of a fixed bridge. The replacement teeth of a removable partial denture are much like a section of a full denture. As with a complete denture, the teeth and gingival tissues are simulated to make an esthetically pleasing prosthesis for the patient. The remaining natural teeth greatly stabilize the partial denture and significantly improve function.

5. Impressions, Casts, and Models

When a restoration or prosthesis is constructed in a dental laboratory, a precise replica of the supporting tissues of the patient is required. To produce the replica (or positive copy), an impression is made of the prepared tooth or remaining alveolar ridge. The dental **impression** (or negative copy) is then filled with a material that solidifies to form the replica, as shown in *Figure 1.8*.

If a restoration is constructed on the replica, it is called a **cast**. If the resulting replica is used to study the size and position of the oral tissues,

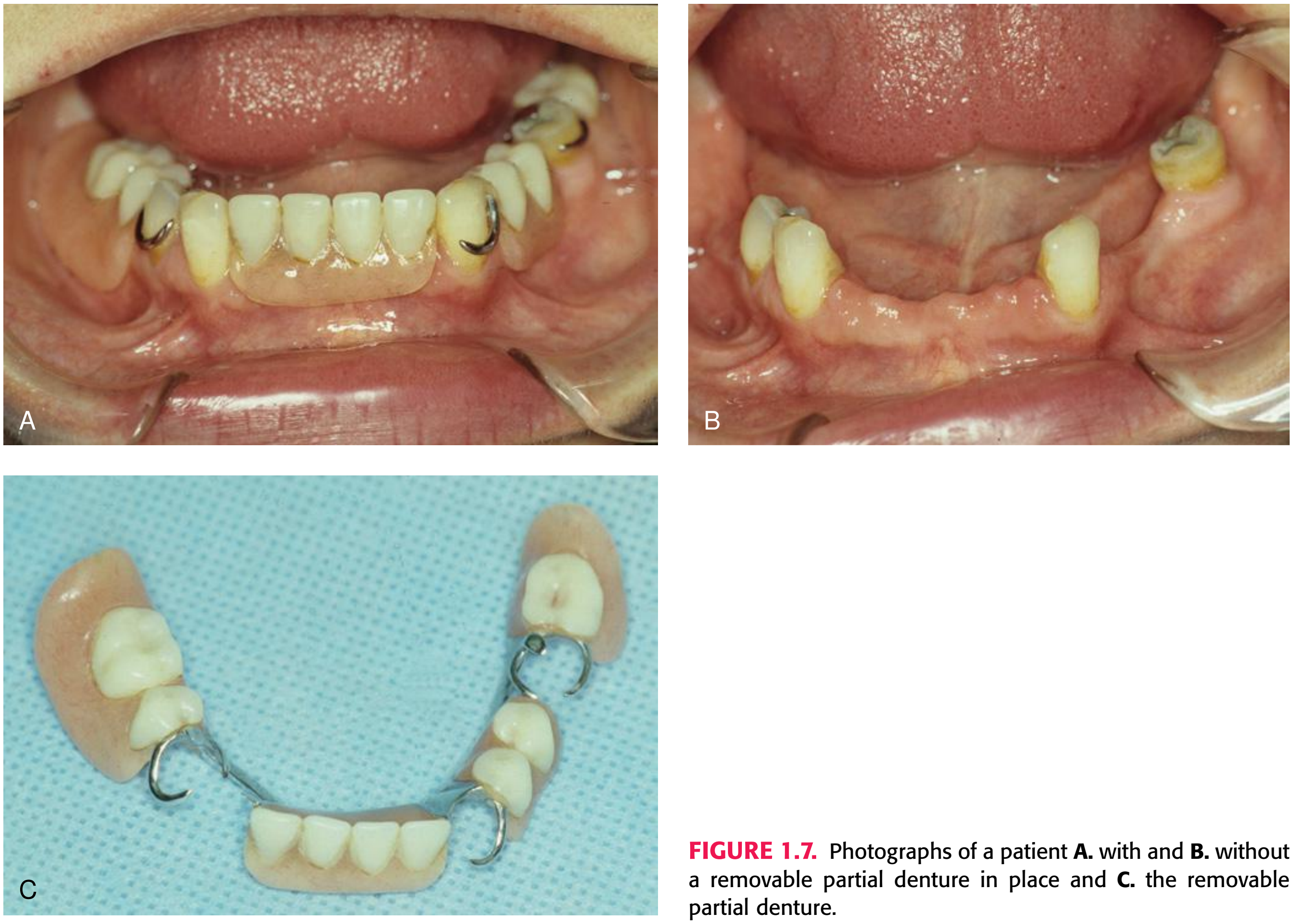


FIGURE 1.7. Photographs of a patient **A.** with and **B.** without a removable partial denture in place and **C.** the removable partial denture.

it is called a **study model** or **diagnostic cast**. A replica of the patient's oral tissues is frequently used for both functions. First, it is used to study the position of teeth and other oral tissues. Second, it serves as an opposing cast to aid in the construction of a restoration.

A variety of impression materials are used in dentistry. Most models and casts are made with gypsum materials, which are very similar to plaster of paris.

Intraoral optical scanners that can generate digital impressions are becoming popular, as shown in *Figure 1.8*. The digital impression can be used to make a restoration in the dental office via CAD/CAM technology or sent to a dental laboratory. Digital impressions can also be "interfaced" with 3D digital radiographs for treatment planning for orthodontics or implant placement.

6. Cements

a. *As Luting Agents*

After a crown has been made, it must be held in place (or "luted") to the prepared tooth. Luting is the same as gluing two objects together, and it is also called cementing. **Luting agents** are frequently called dental cements. The cement holds the crown onto the prepared tooth and fills in the microscopic gaps between the tooth and the crown. After mixing, cements must flow like a thin liquid so that a precisely made crown will fit properly. Several minutes after setting, the cement is expected to be strong and insoluble in oral fluids. Requirements of dental cements are quite rigorous. Proper handling of all materials, especially dental cements, is critical to successful patient care.

b. *As Bases and Liners*

Many of the materials used for luting crowns, bridges, or inlays may also serve other purposes. These include protecting the pulp from irritating materials, such as acids, or serving as insulating layers under metal restorations. Metals conduct hot and cold much more quickly than do dentin and enamel. Using a base or liner under a

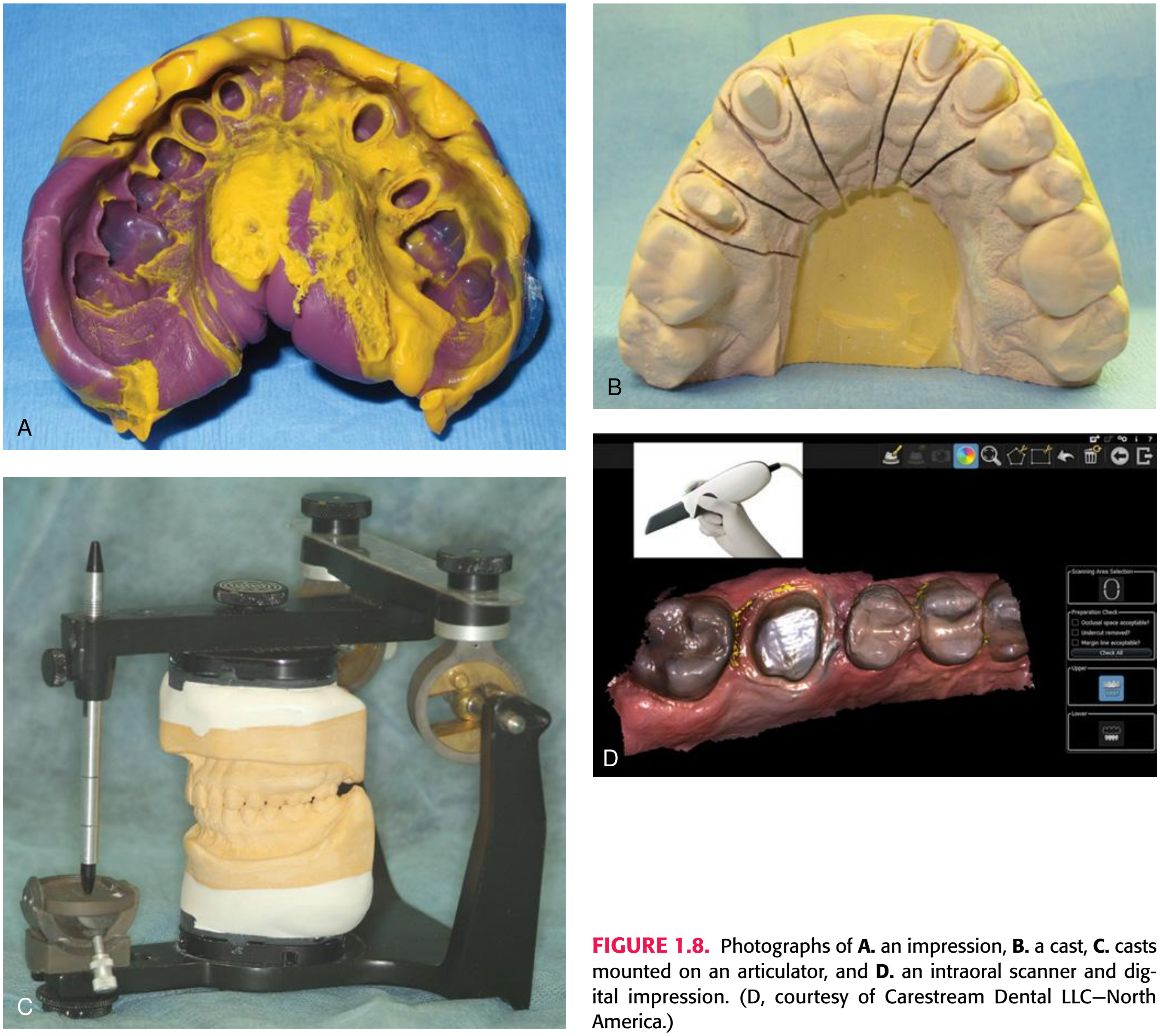


FIGURE 1.8. Photographs of **A.** an impression, **B.** a cast, **C.** casts mounted on an articulator, and **D.** an intraoral scanner and digital impression. (D, courtesy of Carestream Dental LLC—North America.)

metal restoration (between the pulp and the filling) can reduce or eliminate sensitivity to cold and hot foods and beverages (*Fig. 1.9*). The term **base** implies a degree of strength and thermal insulation, whereas the term **liner** does not. Historically, bases and liners were distinct groups, but now much overlap exists. The use of both terms best describes the function of these materials. A liner would be a relatively thin layer of material painted on to protect the underlying dentin from chemical irritation. A base has greater bulk, which serves to restore part of the missing tooth structure and to provide thermal insulation.

7. Temporary Materials

a. *Temporary Crowns*

When a crown is made in the dental laboratory, the dentist and patient must wait days or weeks before it can be cemented into place. What happens to the tooth that has been prepared for a crown? Such preparation requires that a surface layer be removed from the tooth. The thickness of the layer to be removed depends on the material that will be used to replace the missing tooth structure. Frequently, most of the enamel not already destroyed by decay is removed. If the tooth is vital (the pulp is alive), the patient will likely experience pain when eating, drinking, and, at times, breathing if the

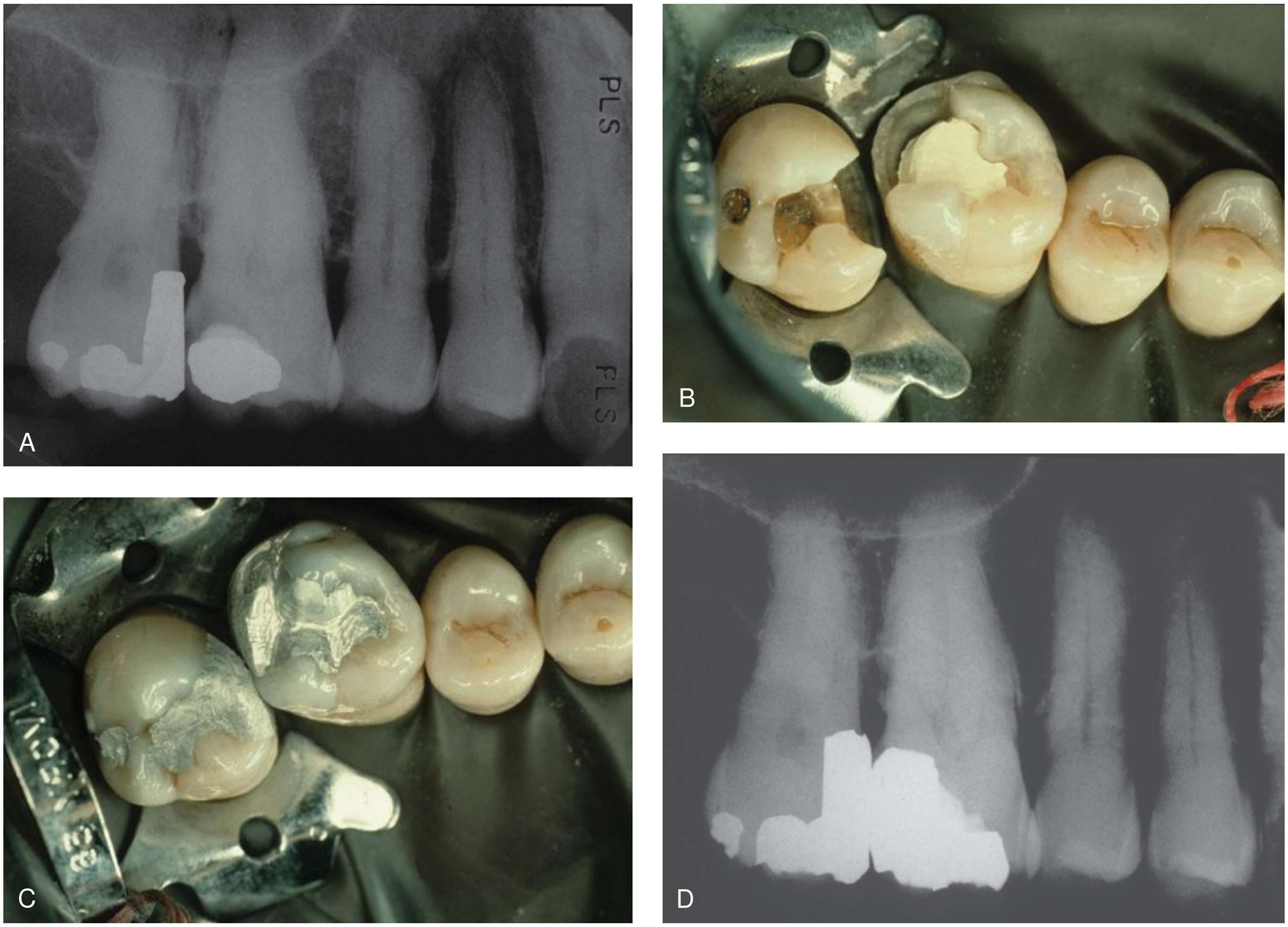


FIGURE 1.9. Example of a base and amalgam restoration. **A.** Preoperative radiograph with recurrent caries distal of #3. **B.** Photograph of cavity preparations in teeth #2 and #3. Tooth #3 has a base. **C.** Completed amalgam restorations. **D.** Postoperative radiograph. (Courtesy of Dr. Henry Miller, Greenburg, PA.)

crown preparation is not protected in some manner. Many times, the appearance of a front tooth that is prepared for a crown also is not esthetically acceptable. What is done to solve this problem? A temporary crown is made before the patient leaves the office (*Fig. 1.10*).

The **temporary crown** is constructed and luted during the same appointment in which the crown preparation is performed. Temporary crowns are not as strong or esthetically pleasing as permanent restorations, but they provide adequate service while the permanent crown is being made. Temporary crowns are typically made from plastics that are formed in the mouth. These replicate the missing tooth structure very closely. Other types of temporary crowns consist of metal or plastic shells (shaped like crowns of teeth) that are lined with the same plastic materials. Construction of temporary crowns is presented in Chapter 35.

Temporary crowns must be removed when it is time to cement the permanent crown. Temporary crowns are cemented with “weak” temporary cements so that they may be easily removed.

b. ***Temporary Restorations***

At times, a dentist is unsure of the best treatment for a patient or a particular tooth. The exact condition of the pulp may not be obvious from the patient’s symptoms. A dentist may remove all or part of the decay from a tooth and then place a **temporary restoration** to give the pulp time to heal before determining the specific treatment that is needed.

8. Preventive Materials

Several materials are used predominantly to prevent disease or trauma. These include the following:

a. Pit and fissure sealants, to prevent decay (*Fig. 1.11*).
b. Mouthguards, to prevent injury during athletic activities (*Fig. 1.12*).

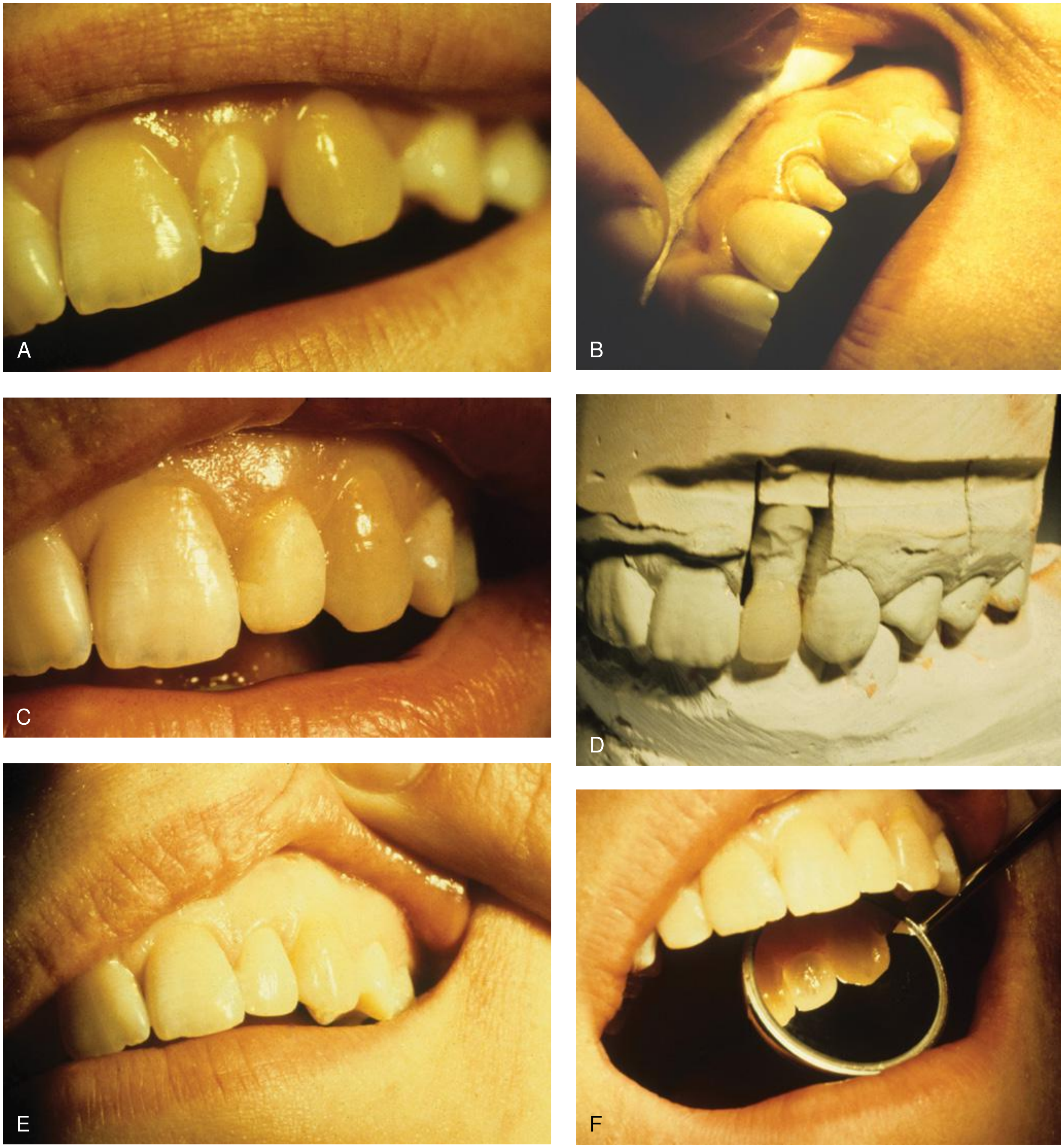


FIGURE 1.10. Restorative photographic series. **A.** Preoperative "peg-shaped" lateral incisor. **B.** Crown preparation. **C.** Temporary crown. **D.** Articulated casts with a permanent all-ceramic crown. **E** and **F.** Cemented crown in place.

c. Fluoride trays, custom and stock, which fit over the teeth to apply topical treatments. Custom fluoride trays look very much like custom mouthguards or bleaching trays (see *Fig. 1.12* and Chapter 18, Oral Appliances).

9. Polishing Materials

A tremendous amount of time in a dental practice is spent in polishing teeth, restorations, and appliances. Use of a rubber cup with an abrasive agent is termed **polishing**, but the predominant function is to remove stain, plaque, and debris

FIGURE 1.11. Photograph of tooth #19 with an opaque sealant.

from the tooth surface. True polishing involves moving an abrasive over the surface of an object to remove a thin layer of material. This action results in a surface that is clean, smooth, and lustrous. Dental professionals use many different devices and materials to polish teeth and restorations. Understanding the polishing process is important to achieving the desired result and is presented in Chapter 16.

10. Implants

Dental implants are considered to be part of restorative dentistry, but because of their specialized nature, they are segregated from other materials. **Dental implants** are typically screws or posts that are anchored into alveolar bone and protrude through the gingiva into the oral cavity. An illustration of a dental implant is shown in Chapter 12. Implants are used to replace the root portion of lost teeth. Implants are unique in that they are both inside the body (in the alveolar bone) and outside the body (exposed in the oral cavity). Keeping the contents of the oral cavity from seeping along the surface of the implant into the supporting bone has been a very difficult problem. Luckily, this may be accomplished with the use of several materials if they are manufactured and handled properly.

Dental implants are used to support a great variety of restorations or prostheses. Single crowns, bridges, and dentures can be supported by dental implants. Often, a **maxillofacial prosthesis**, which is a combination intraoral and extraoral prosthesis such as an artificial nose/denture combination, is retained with intraoral and extraoral implants. Implants have had an extraordinary impact on patient care when traditional restorative treatments have failed to provide adequate function.

11. Specialty Materials

Many specialties in dentistry have products and materials unique to that field. At times, these products overlap (e.g., sutures), whereas others are limited strictly to that specialty (e.g., "rubber bands" or elastics used in orthodontics). Many times, the specialties of oral surgery and periodontics use the same (or very similar) materials for bone regeneration. These materials that are used in the dental specialties are discussed further in Chapter 13.

B. Classification by Location of Fabrication

1. Direct Restorative Materials

Some restorations are constructed directly in the oral cavity and are called **direct restorative**

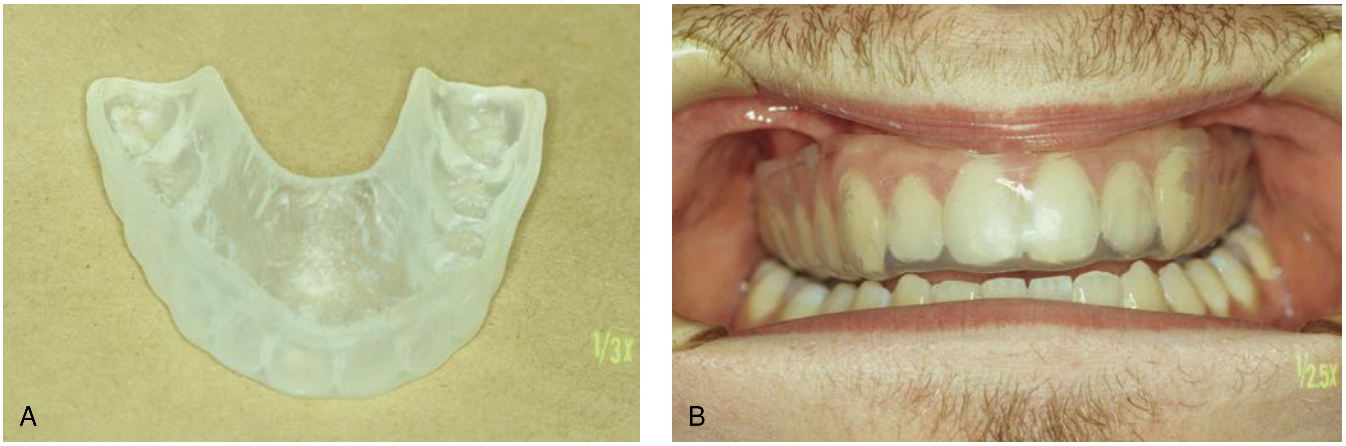


FIGURE 1.12. Photographs of **A.** a mouthguard and **B.** the mouthguard in place.

materials. A typical direct restorative material is placed in the **"cavity preparation"** that was "drilled" by the dentist when removing the decay (see *Fig. 1.9*).

Each material has its own requirements for the design of the cavity preparation. When initially placed, a direct material is a putty-like material that sets to become a hard, strong material. Direct restorative materials include the following:

a. Amalgam, a metallic material that is formed by combining liquid mercury with powdered metals. The freshly mixed amalgam is placed directly in the cavity preparation, is carved to resemble the missing tooth structure, and then hardens (see *Figs. 1.3 and 1.9*).
b. Composites, which are esthetic materials that polymerize in the mouth. These are supplied as pastes that are placed into the preparation and are set by a specific chemical reaction (*Fig. 1.13*).
c. Glass ionomers and other cements, which are mortar-like materials that set by an acid–base chemical reaction in the mouth (see *Fig. 1.13*) and resemble tooth material.

2. Indirect Restorative Materials

Other materials must be fabricated outside the mouth because the processing conditions of many materials would harm oral tissues. Such materials are called **indirect restorative materials** because they are made indirectly on a replica of the patient's oral tissues. Indirect materials include the following:

a. "Gold" crowns and inlays, which are restorations that are made by melting metals and pouring (forcing) them into molds of the exact size and shape needed for each patient (see *Figs. 1.3 and 1.4*).
b. Ceramic materials, which are processed by a number of techniques. Many times, a ceramic powder is fired at a very high temperature and becomes a solid object (just as a clay pot is fired). An example would be a porcelain crown (see *Fig. 1.10E and F*).
c. Indirect restorative polymers, which are plastics typically processed or cured at elevated temperatures and under high pressures. An example would be the pink "gingival" portion of a denture (see *Figs. 1.6 and 1.7*).

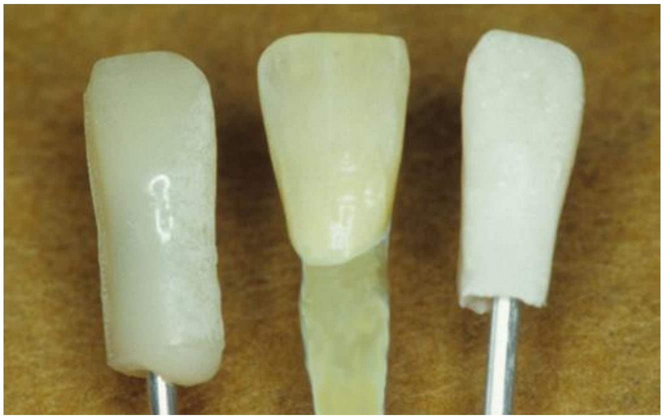


FIGURE 1.13. Photograph of, from *left* to *right,* a composite sample, an extracted tooth, and a glass ionomer sample.

C. Classification by Longevity of Use

1. Permanent Restorations

Permanent restorations are those restorations that are not planned to be replaced in a particular time period. Although they are referred to as permanent, they are not. Fillings, crowns, bridges, and dentures do not last forever. All restorative dentistry wears out and fails! Quality restorative dentistry in a well-maintained oral cavity, however, will give the patient years and years of service. It is best to prevent the need for restoration and replacement of teeth by aggressive preventive dentistry. The cycle of restoration and re-restoration of teeth is becoming an important factor in the practice of dentistry. What is best for the patient for a lifetime of oral health must be considered along with the immediate dental needs of the patient.

2. Temporary Restorations

Temporary restorations are restorations that are planned to be replaced in a short time (e.g., a week or a month). As discussed earlier, temporary crowns are placed after the tooth is prepared for a permanent crown and are used to protect the tooth while the final restoration is being made at the dental laboratory (see *Fig. 1.10C*). Temporary restorations are sometimes called **provisional restorations**.

3. Interim Restoration

At times, dental treatment requires long-term temporary restorations or **interim restorations**. An example would be a patient who has a fractured front tooth and needs a crown but is presently undergoing orthodontic treatment. A large composite restoration may be adequate until orthodontic treatment is completed or the tooth is close to its final position, and a permanent crown may then be fabricated.

VI. Classification of Dental Caries and Restorations

Dental caries are not evenly distributed throughout the mouth. Certain surfaces of the teeth are particularly susceptible to carious lesions; others are nearly immune. In the late 1800s, Dr. G.V. Black classified the most common sites for dental caries. His classification system adequately describes most simple carious lesions. In high-caries patients, a single tooth may have more than one lesion. These lesions may be of the same class or of different classes. At times, extensive lesions could be described as being a combination of two classes.

A. Class I

The pits and fissures of teeth, particularly posterior teeth, are the most susceptible to dental caries. Pit and fissure caries are called Class I lesions, and the associated restorations are called Class I restorations. *Figures 1.14* and 5.10 show Class I caries and restorations in a molar.

B. Class II

The area of the tooth just below the interproximal contact is also susceptible to caries. If such a lesion occurs in a posterior tooth, it is called a Class II lesion. Dental radiographs are commonly used to diagnose Class II caries. *Figures 1.3*, *1.9*, *1.14*, 6.10, and 15.6 show Class II caries and restorations in molars and premolars.

C. Class III

If interproximal caries occur in an anterior tooth, it is called a Class III lesion. Dental radiographs and clinical examination are commonly used to diagnose Class III lesions. *Figures 1.14 and 1.15* show Class III caries and restorations.

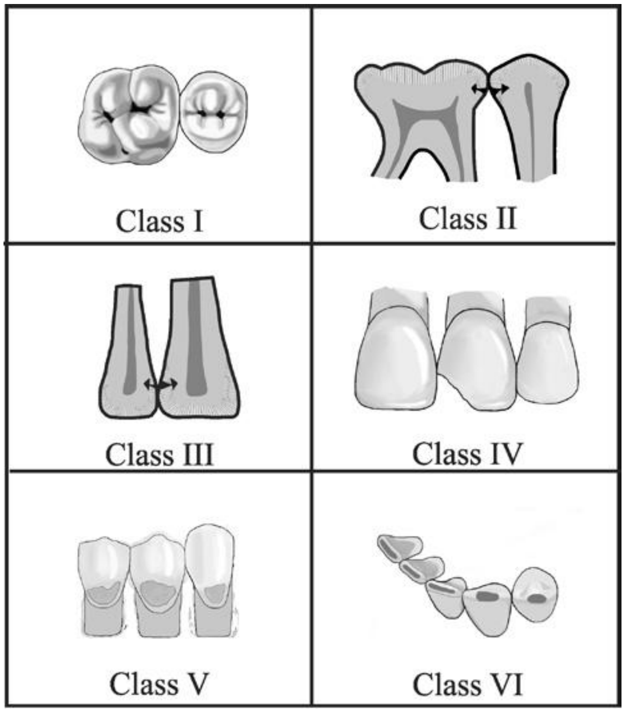


FIGURE 1.14. Drawing depicting the Dr. G.V. Black classification of caries.

FIGURE 1.15. Photograph showing a Class III stained composite on the distal of tooth #7 and a Class III lesion (white chalky area) on the distal of tooth #8. (Courtesy of Dr. Birgitta Brown, Stockholm, SE.)

D. Class IV

If a Class III lesion is left untreated, it may progress and involve the incisal angle of an anterior tooth. A lesion that involves the incisal angle of an anterior tooth is called a Class IV lesion (see *Fig. 1.14*). Class IV restorations are also used to restore the incisal angle of an anterior tooth that has been fractured as the result of trauma, as shown in Figures 5.9 and 13.1B.

E. Class V

The gingival third of the facial and lingual surfaces of both anterior and posterior teeth is susceptible to caries when patients have poor oral hygiene or a high-sugar diet. Class V caries and restorations are shown in *Figures 1.14*, 5.12, and 6.13.

F. Class VI

The Class VI lesion was a later addition to Black's classification. As shown in *Figure 1.14*, a Class VI lesion involves the cusp tip or incisal edge of a tooth. Actually, a Class VI carious lesion is quite rare. For most people retaining a large number of teeth later in life, however, wear of cusp tips and incisal edges is not uncommon. When attrition causes dentin to become exposed, it wears much faster than the surrounding enamel because enamel is much harder than dentin. The result is a "dished-out" area of worn dentin (*Fig. 1.16*). Some clinicians call these restorations of such worn cusp tips and incisal edges Class VI restorations.

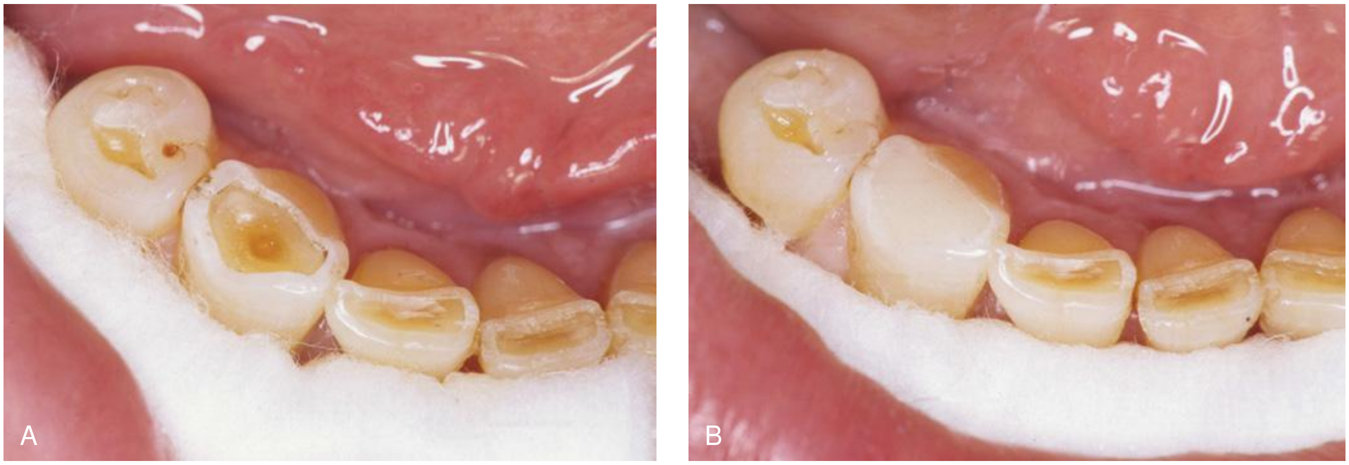


FIGURE 1.16. Photographs of **A.** severely worn teeth and **B.** a composite restoration protecting the dentin of tooth #27. (Courtesy of Dr. Birgitta Brown, Stockholm, SE.)

Summary

The dental hygienist should be knowledgeable in the science of dental materials for several reasons. It should be clear why a restorative material is prescribed for one restoration rather than for another. The best material is selected based on its behavior for providing function and service to the patient. Handling materials properly will enhance the function and longevity of the material that is placed into the patient's mouth. The hygienist must be able to recognize all dental materials so that they can be maintained in the proper manner. The ability to educate patients and answer their questions about the characteristics and properties of dental materials is yet another reason.

Dental professionals must remember that oral tissues, such as enamel, dentin, pulp, periodontium, and gingival tissues, are biologic materials and that they function in the hostile environment of the oral cavity. This environment places restrictions on which materials may be used to replace oral tissue. These restrictions include biting forces, degradation of teeth and materials, temperature changes, biocompatibility, and esthetics.

In the United States, standards are published and administered by ANSI. Other organizations work under their guidance to develop and administer standards for products of their industry. The ADA's Council on Scientific Affairs is one such organization that sets the standards and guidelines for evaluating dental products. The Medical Device Amendment of 1976 ensures the safety of all medical devices. The U.S. FDA considers dental materials to be devices, of which there are three classes. The ISO attempts to unify the standards of its member countries throughout the world.

Dental materials can be classified in three ways: by use, by location of fabrication, or by longevity. When classifying by use, a dental material would be listed under one of the following categories: restorations, crowns, bridges, and complete and partial dentures; impressions, casts and models, and cements; temporary materials; preventive materials; polishing materials; implants; and specialty materials. When classifying by location of fabrication, a dental material would be listed under one of the two categories: direct restorative materials, which are fabricated directly in the mouth and include materials such as amalgam, composites, and glass ionomer; and indirect restorative materials, which are fabricated outside the mouth and include materials such as gold, ceramics, and special polymers. When classifying by longevity of use, a dental material would be listed under one of the three categories: permanent, temporary, and interim restorations.

Dental caries and restorations are also classified into six categories. These categories were developed by Dr. G.V. Black during the late 1800s and are still used today.

Learning Activities

1. Discuss other examples of products used in everyday life that have standards on which we rely for their safety and effectiveness.
2. In the clinic, divide into pairs and, with the use of hand and/or mouth mirrors, look for different kinds of dental materials, such as restorations, sealants, orthodontic retainers, and temporary restorations.
3. Classify the restorations that you found in activity 2 using Black's classification system.
4. Using a large selection of extracted teeth, attempt to identify caries or restorations of each of Black's classifications (I–VI).
5. Classify five of the restorations found in activity 2 by the location of fabrication (direct or indirect).
6. Use de-identified patient charts and radiographs to look for restorations and other dental materials.
7. In a drugstore, see how many different kinds of over-the-counter dental products are available that carry the ADA Seal of Acceptance.
8. Referring to the following list of restorations, briefly discuss the specific home care instructions that would be necessary for your patient to maintain optimal oral health:
    - A four-unit, fixed partial denture
    - An implant
    - A removable partial denture
    - A porcelain-fused-to-metal crown.

Review Questions

Question 1. **In the United States, standards for dental materials are developed and administered by the:**

a. FDA (Food and Drug Administration)
b. ADA (American Dental Association)
c. AADR (American Association for Dental Research)
d. OSHA (Occupational Safety and Health Administration)

Question 2. **All of the following are reasons for a dental hygienist to have knowledge and understanding of dental materials EXCEPT:**

a. Explaining the different types of restorative materials available to the patient
b. Assessing the patient's oral condition
c. Deciding which material is best for the patient's restoration
d. Understanding the behavior of dental materials

Question 3. **An amalgam restoration located on the gingival third of tooth #3 would be a Class _____ restoration.**

a. I
b. II
c. III
d. IV
e. V
f. VI

Question 4. **The biologic nature of the oral environment and the size of the oral cavity restrict the use of dental materials. One restriction is the degradation of restorations.**

a. The first statement is true; the second statement is false.
b. The first statement is false; the second statement is true.
c. Both statements are true.
d. Both statements are false.

Question 5. **When the temperature changes in the mouth, the teeth and most restorative materials expand and contract by the same amount. No leakage occurs around the restoration.**

a. The first statement is true; the second statement is false.
b. The first statement is false; the second statement is true.
c. Both statements are true.
d. Both statements are false.

Question 6. **Which of the following oral tissues provides feedback to the individual regarding the forces placed on the tooth?**

a. Pulp
b. Dentin
c. Periodontium
d. Gingival tissue

Question 7. Which of the following restorations is utilized when a substantial amount of a tooth is missing?

a. Crown
b. Pontic
c. Implant
d. Fixed partial denture

Question 8. The design of a cavity preparation aids in the retention of a restoration. The walls of an amalgam preparation diverge while the walls of an inlay converge.

a. The first statement is true; the second statement is false.
b. The first statement is false; the second statement is true.
c. Both statements are true.
d. Both statements are false.

Question 9. If a restoration is fabricated on a replica (positive reproduction) of a patient's teeth, it is referred to as a:

a. Student model
b. Cast
c. Diagnostic cast
d. Any of the above terms may be used

Question 10. An example of an indirect restorative material would be:

a. Amalgam
b. Glass ionomer cement
c. Composite
d. Ceramic (porcelain)

Question 11. Medical devices are grouped into three categories according to Medical Device Amendment of 1976. Which class of devices is most regulated?

a. I
b. II
c. III
d. IV

Question 12. Using *Figure 1.9A and D*, which of the following best describes the roots of the teeth?

a. Calculus is visible on the distal of tooth #2.
b. Calculus is visible on several roots.
c. The roots are radiographically foreshortened.
d. The roots are radiographically elongated.

Materials Science and Dentistry

2

Objectives

After studying this chapter, the student will be able to do the following:

1. List the phases into which materials are classified. Discuss the varying amounts of attraction between the molecules and atoms of each phase. Recall the differentiating characteristics of each phase.
2. Explain the basic difference between primary and secondary bonds.
3. Name the three types of primary bonds and describe the differences between them.
4. Summarize the similarities and differences of secondary bonds, which include permanent dipoles, hydrogen bonds, and fluctuating dipoles.
5. Contrast the bonding characteristics of metals, ceramics, plastics, and composites.
6. Compare any similarities and differences of colloids and emulsions.

Key Words/Phrases

amorphous
ceramic
colloids
composites
covalent bonds
cross-linking
crystalline
dental materials
emulsions
fluctuating dipole
hydrogen bonds
ionic bonds
long-range order
materials science
metallic bonds
metals
permanent dipole
polymers
primary bonds
secondary bonds
short-range order
valence electrons

Introduction

Many different kinds of materials are used to make the products we use in everyday life and in the profession of dentistry. Understanding the behavior of materials is important in the selection, placement, and maintenance of dental materials. The behavior of any given material is based on the atoms and the atomic bonds in that material. Many will think the material covered in this chapter is too theoretical for dental hygiene students. If so, the authors urge you to skip this chapter and read only the summary at the end.

I. Materials Science

Materials science is the part of the physical sciences that seeks to explain the properties and performance of materials by examining their internal structure. Materials science is a combination of chemistry, physics, and engineering rather than a separate scientific domain. Materials science tries to explain why materials behave as they do, based on the atoms and molecules in materials and the bonds that exist between these atoms and molecules. Materials science also tries to understand the effects of manufacturing processes on materials and any changes in materials that may occur during the useful life of a product. In dentistry, a subgroup of materials science has developed. This subgroup, called **dental materials**, is part of the larger field of biomaterials and, at times, is called dental biomaterials. Whatever term we use, however, the goal is to understand why materials behave the way they do and how the clinician can maximize the performance of these materials.

In this book, the handling (processing) of dental materials will be stressed, and a discussion of the underlying materials science will be included as well. At times, simply memorizing step-by-step procedures will seem to be much easier, but understanding their nature will simplify the use of the vast number of materials currently on the market. No other branch of scientific inquiry has a greater impact on our day-to-day lives than the development of new materials and the innovative ways in which these materials are being used.

Another branch of materials science, food science, is important to our everyday lives. The same laws of nature that govern dental materials also make ice cream creamy, fudge chewy, and Jell-O jiggle. Whenever possible, everyday examples of these concepts are included in this text.

II. Atomic Bonding

How do teeth withstand the forces that occur when we bite and grind food? To understand the strength of teeth, we need to understand the nature of atomic bonds. Teeth and restorative materials need to be stronger—and to have stronger atomic bonds—than the food we eat.

A. Phases

We commonly classify materials into one of the three phases: solid, liquid, or gas. Familiarity with these phases will provide a foundation for understanding the nature of the forces that hold atoms together in materials. Later in this chapter, we discuss colloids, which are a mixture of two of these phases.

1. Gases

The atomic bonds between gas molecules are very weak. These bonds are easily broken by the normal microscopic vibrations of atoms at room temperature. These atomic vibrations are the result of the thermal energy of the material. Gases have no molecular organization and will take on the three-dimensional shape of the container that they fill. If thermal energy is removed by cooling, gases condense into liquids. An example is the condensation of water vapor on the outside of a mug of ice-cold root beer on a hot, humid day.

2. Liquids

Liquids have stronger attraction between molecules than gases do, but this attraction is not strong enough to carry a load or to maintain a shape without support. The attraction between molecules results in short-range order. **Short-range order** is a consistent spatial relationship among atoms or molecules 5 to 10 neighbors apart. Liquids lack long-range order. Molecular attraction keeps liquids from boiling, but not always from evaporating. Other characteristics of a liquid are vapor pressure, boiling temperature, viscosity, and surface tension.

3. Solids

Solids exhibit the strongest attraction between atoms and molecules. The atomic bonds of solids maintain the shape of objects and resist external forces placed on them. Solids can be classified as crystalline or amorphous. **Crystalline** solids have a consistent spatial relationship of atoms or molecules repeated hundreds to thousands to millions of times that is called **long-range order** (*Fig. 2.1A*). The distances and angles among such atoms or molecules are uniform, much like rooms in a dormitory or hotel. Table salt, diamonds, and the hydroxyapatite of teeth are crystalline solids. Crystalline solids have both short-range and long-range order of their atoms or molecules.

Amorphous solids (*Fig. 2.1B*) have the same strong atomic bonds present in crystalline

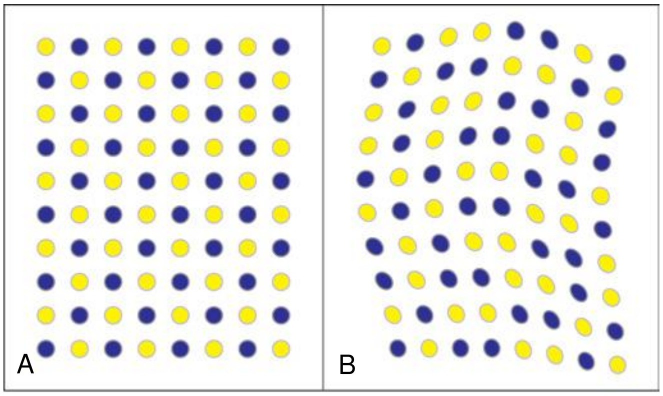


FIGURE 2.1. A two-dimensional depiction of the arrangement of atoms in a crystal **A.** and an amorphous solid **B.**

materials, but have only short-range order, much like liquids. The long-range order of an amorphous solid is more irregular or disorganized. The glass in a window or a dental mirror is an amorphous solid.

Some solid objects are strong, while others are weak. The difference is determined by the type of atoms that make up the material and the strength of the atomic bonds that hold the material together.

B. Atomic Bonds in Solids

How does a strong solid object know how much force it needs to resist the load of an object resting on its surface? If you place a 2-lb book on a table, the table pushes up with 2 lb of force, just enough to support the book—not too little and not too much. How does the table know to push up with 2 lb of force? This "smart" behavior is a characteristic of solid objects and a function of the nature of atomic bonds in materials.

Atomic bonds are a result of electromagnetic (EM) force. For this discussion, we will focus on the electronic part of the EM force. The electronic force causes positive charges to attract negative charges and negative charges to attract positive charges. Positive charges are repelled by positive charges, and negative charges are repelled by negative charges. The magnetic force exhibits similar attraction and repulsion and is easily demonstrated with two magnets. We will use the familiar magnetic force to help us understand attraction and repulsion. The north pole of a magnet attracts the south pole and repels the north pole. It takes force to bring the north poles of two magnets into proximity. The closer they get, the harder you have to push, much like a spring. In fact, the atomic bonds between atoms act much like the springs of a mattress or a car.

To compress a spring, it must be pushed. To stretch a spring, it must be pulled. When no force is applied to a spring, it is said to be unloaded and has an equilibrium length. When force is applied, the spring changes length and resists the applied force by developing an equal and opposite force. Solids can be thought of as a collection of millions and millions of springs or atomic bonds. When you place a book on a table, the atomic bonds of the table are compressed and oppose the force of the book. The heavier the book, the more the bonds are compressed and the greater the force that is developed in the table. Is this really true? We do not see the table change height when we put the book on it. We must remember that the table has millions and millions of atoms and, therefore, millions and millions of atomic bonds. Each bond is compressed a submicroscopic distance. The total of the change in length of these bonds is still microscopic, too small to be seen by the unaided eye, but the change in height of the table can be measured with specialized equipment. Again, the atomic bonds of the table are compressed when a book is placed on it, and these bonds act like springs. When one stretches a rubber band, the same phenomenon occurs, but it can be seen by the unaided eye. Different kinds of internal atomic bonds respond to external forces in different manners.

The change in the height of the table when a book is placed on it is an example of something that happens we cannot see. These changes may be microscopic, or they may occur very slowly and, thus, may not be noticed. Such changes occur in dentistry: teeth compress when biting, erupt into the mouth, change color during a person's lifetime, wear, or dissolve in acid, forming caries.

C. Primary Bonds—Optional

Primary bonds are the strong bonds between atoms that involve the transfer or sharing of electrons between atoms. In high school and college chemistry classes, the ionic and covalent bonds are presented. Another bond that is important to the understanding of certain materials is the metallic bond. All bonds are a result of the EM force and the distribution of positive and negative charges of atoms and molecules.

The atom is made of protons, neutrons, and electrons. The protons and the neutrons make up the nucleus; the electrons move around the nucleus in shells. Electrons in the outer shell of atoms are involved in chemical reactions and atomic bonding. They are called **valence electrons**. When discussing atomic bonding, it is easier to group the nucleus with the nonvalence electrons into what is called the "positive core." The remaining valence electrons are those that are principally involved in atomic bonds. We can therefore restrict our discussion to the positive core of the atom and the valence electrons. Explaining why some elements form metallic bonds and others form covalent bonds is beyond the scope of this text (and its authors' understanding of the subject). However, understanding how atoms fill up their outer shell with electrons from other atoms will help us to understand the nature of atomic bonds and give us some insight regarding why materials behave as they do.

1. Ionic Bonds

Ionic bonds are the result of an electron being given up by one atom and being accepted by another. Why does an atom give up or accept an electron? Atoms are "content" when their outer shell of electrons is full; in this situation, they have a lower state of energy. An element like sodium has one valence electron in its outer shell, and it will readily give up this valence electron. If a sodium atom gives up this valence electron, the next inner shell becomes the outer shell and is a full shell. The atom then becomes an ion with a charge of +1. An element such as chlorine, however, is one electron short of filling its outer shell. Therefore, chlorine readily accepts an electron and becomes an ion with a charge of –1. When sodium and chlorine atoms have full outer shells, the opposite electrical charges of these ions attract each other and form atomic bonds. The result is NaCl or sodium chloride (table salt).

Chemical reactions, in which atoms fill their outer shells with electrons and form bonds, are examples of nature lowering the energy of a system. Other examples of systems lowering their energy include a ball rolling downhill, water flowing over a waterfall, a candle burning, and a battery powering a flashlight. The conversion of energy from one form to another (whether chemical, electrical, mechanical, or thermal) is governed by the laws of thermodynamics. Again, such forbidding subjects are beyond the scope of this text.

Let's get back to the ionic bond. A grain of table salt (sodium chloride) has billions and billions of sodium and chloride ions. Ionic bonds hold the ions together. Oppositely charged ions attract each other (negative chloride ion and positive sodium ion). Ions with like charges repulse each other. The strength of the salt grain is the sum of the attraction of opposite charges minus the repulsion of like charges.

The distance between ions has an important effect on the strength of the attraction or repulsion. The strength of both is inversely proportional to the square of the distance between the ions. Thus, the force between the ions falls rapidly as the distance between the pair increases.

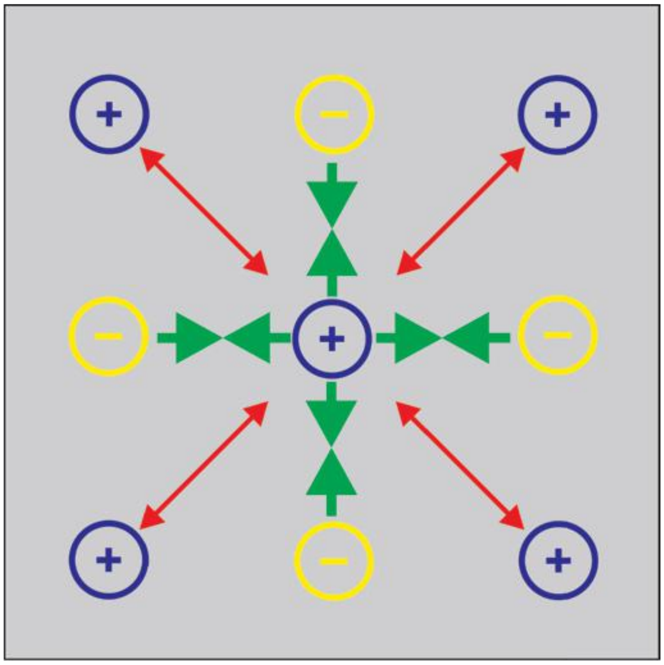


FIGURE 2.2. A two-dimensional depiction of an ionic material. The *green arrows* pointing toward each other represent the attraction of unlike-charged ions. These ions are closer; therefore, the force is stronger. The *red arrows* pointing away represent repulsion of like-charged ions. The like-charged ions are farther apart; therefore, the force is weaker.

The arrangement of ions in sodium chloride results in the negatively charged chloride ions surrounding each positively charged sodium ion. Likewise, each negative ion is surrounded by positive ions. The familiar checkerboard pattern is a two-dimensional example of such an arrangement. As a result, the attraction between oppositely charged "next-door neighbors" is strong because they are close together. The repulsion of similarly charged ion pairs is weaker because they are farther apart (*Fig. 2.2*). The attraction forces overpower the repulsive forces, and the result is a strong material.

2. Covalent Bonds

Covalent bonds between two atoms are the result of two atoms sharing a pair of electrons (*Fig.* 2.3). Sharing electrons with other atoms allows an atom to fill its outer shell with electrons and, thus, to lower its energy. How does sharing a pair of electrons bond two atoms together?

The physical space that an electron occupies around the nucleus is called an orbital, and it is centered around the nucleus when not involved in an atomic bond. When two atoms share an electron, the shape of the orbital changes. When a pair of electrons is shared and forms a covalent bond, the orbital surrounds both

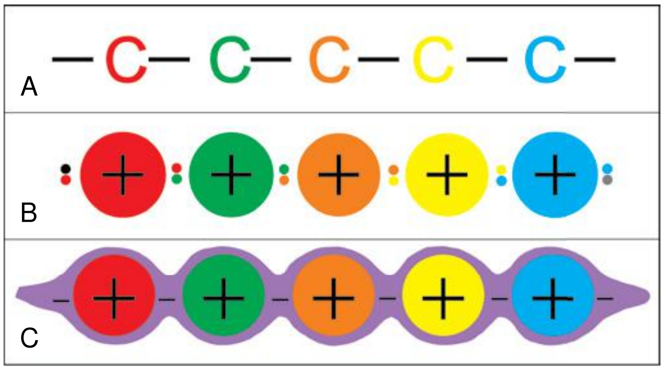


FIGURE 2.3. Three representations of covalent bonds between carbon atoms. In **A.** *lines* represent the bonds. In **B.** pairs of shared electrons represent the bonds. In **C.** the distribution of the electrons is shown. Note in **C** the alternating negative charges of the electrons and positive charges of the cores.

atoms. Now the electrons spend some time in the physical space between the two atoms. By spending time between the two atoms, bonding of the two atoms occurs. A partial negative charge is created by the presence of the electron pair between the two atoms. The partial negative charge of the bond is attracted to the positive cores of the two atoms that are sharing the electron pair. The positive core of the first atom is attracted to the relatively close partial negative charge (because of the electron pair spending time there) between the atoms. The same is true for the second atom that shares the electron pair.

The attraction of the partial negative charge to the two positive cores is greater than the repulsion between the positive cores because the distance between the two positive cores is greater. We have probably set organic chemistry back a century with this simplistic description of the covalent bond, but it will serve our purposes and help to explain the behavior of polymers (and it's the best the authors can do).

Covalent bonds between the two atoms sharing the electron pair are strong and very directional. However, few materials are bonded with only covalent bonds. One well-known material that is covalently bonded is diamond. Each carbon atom is bonded to four other carbon atoms by a covalent bond. One of the hardest materials known results from this bonding. Many materials are the result of long chains of covalently bonded atoms. The chains are strong, but the materials are not always strong. This is because their properties are determined by the manner in which the long chains are bonded to each other. Polymers are long chains of covalently bonded carbon atoms. Examples of polymers include man-made plastics and rubbers as well as many biologic macromolecules, such as proteins and DNA. The varied properties of polymers and plastics will be better explained in the discussion of secondary bonds.

3. Metallic Bonds

Metals have characteristic properties that allow us to easily identify a material as being a metal. Metals are typically dense, heavy materials. They are good conductors of both electricity and heat, are cold to the touch at room temperature, and, if shaped properly, will ring like a bell if struck. All these properties of metals are a result of metallic bonds. **Metallic bonds** are similar to covalent bonds in that valence electrons are shared between atoms. The difference is that the electrons in a metal object are not shared by two atoms; instead, they are shared by all the atoms that make up that object (*Fig. 2.4*). We can illustrate this difference by comparing a marriage to students in a school. In a marriage, the relationship is between two people, and the sharing is between those two. Within a school, however, all students are part of the student body. They have a less intense relationship, but they all share the feeling of being part of the school.

Metals can be thought of as positive cores in a cloud of negative mobile valence electrons, much like chocolate chips in ice cream. The chocolate chips are the positive cores, and the ice

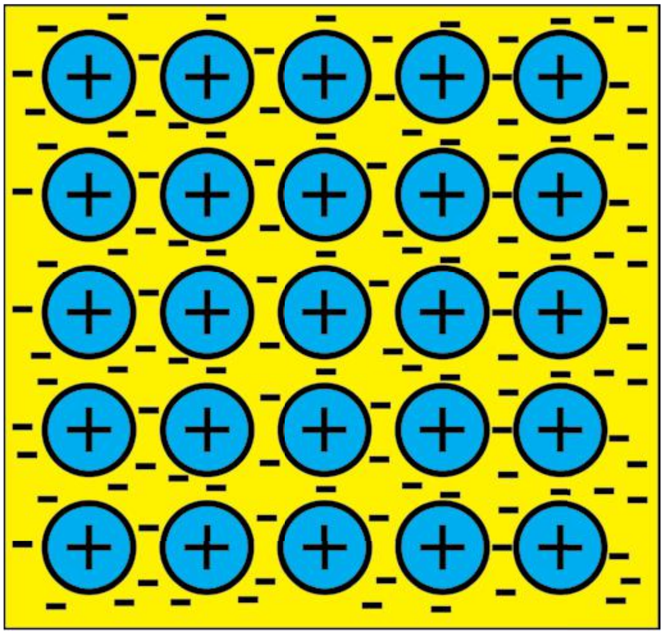


FIGURE 2.4. A two-dimensional representation of the metallic bond. Note that the positive cores (nuclei and nonvalence electrons) are surrounded by an electron "cloud."

cream is the electron cloud. Because the positive cores (the chips) are surrounded by electrons (the ice cream), the negative–positive electric charges cause the electrons to be attracted to the positive cores. Again, the positive cores are repelled by each other, and the negative electrons are repelled by each other. And again, the electrons are closer to the positive cores than the positive cores are to each other, so the attraction is greater than the repulsion. This results in a weak primary bond in all directions. The enormous number of bonds in a metal results in a strong material. Later, we will see that the nondirectional nature of metallic bonds has an important effect on the properties and use of metals.

D. Secondary Bonds—Optional

Secondary bonds, or van der Waals forces, are the result of partial charges from an uneven distribution of electrons around an atom or a molecule. The partial charges can be temporary or permanent, very weak or somewhat strong. Secondary bonds are important in determining the properties of polymers because they determine the interaction of the polymer chains and, thus, the properties of the polymer itself.

1. Permanent Dipoles

Depending on the type of atoms bonded by a covalent bond, the shared electrons may not be shared equally. Some atoms are “greedy” and pull the shared electrons more strongly toward themselves. The result is an uneven distribution of the electron pair around the atoms involved in the covalent bond. One atom involved in the bond is partially positive, and the other is partially negative. A permanent partial charge, or a **permanent dipole**, thus occurs (*Fig. 2.5*). When one molecule with such partial charges encounters another, the negative attracts the positive, and vice versa. Permanent dipoles result in weak bonds, but they have a significant effect on the behavior of many materials.

The dipoles that result from the chlorine atoms on the chain of a polyvinyl chloride (PVC) molecule make PVC a strong and stiff material. The bond between the carbon atom and the chlorine atom is not an equal sharing of electrons. Electrons are pulled toward the chlorine atoms, making it partially negative. The carbon atom is partially positive. The interaction of these partial charges reduces the slippage of the carbon chains by one another in molecules of PVC. This results in a strong, stiff plastic (commonly used for drainpipes in houses). When electrons are more evenly distributed, the dipoles are much smaller, and the material is much weaker and much less stiff. An example of such a material is polyethylene, which is commonly used as a plastic wrap for food.

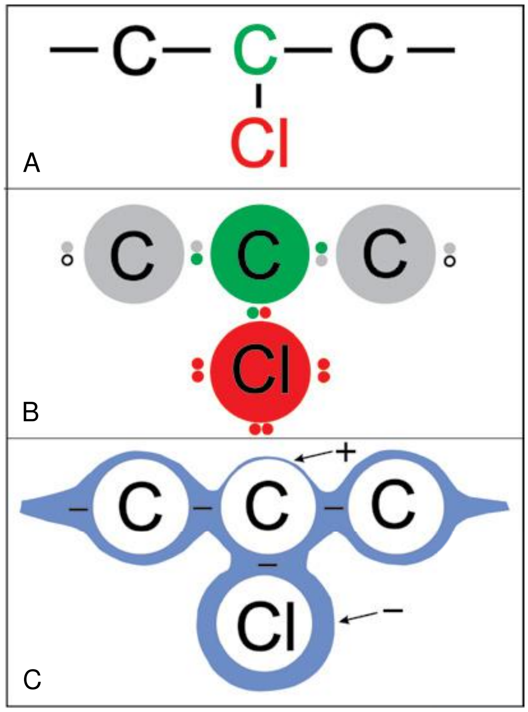


FIGURE 2.5. Three representations of a permanent dipole. In **A.** *lines* represent the bonds. In **B.** pairs of shared electrons are shown. In **C.** the distribution of the electrons is seen. The electron density is greater around the chlorine atom and less around the middle carbon atom. Note in **C** the uneven distribution of the electron density that results in partial charges or dipoles.

2. Hydrogen Bonds

Hydrogen bonds are a special case of a permanent dipole. The hydrogen atom contains only one electron. When this single electron is pulled away from the hydrogen nucleus by a “greedy” atom, such as oxygen, the nucleus is left partially unshielded, but to a much greater extent than in other elements with multiple electrons. The resulting interaction between molecules results in a bond that is much stronger than other secondary bonds.

We can understand the significance of unshielding the hydrogen nucleus if we consider four children in two beds during the cold of winter. Two children in one bed have one blanket, and the other two children have three blankets. If the blankets of both pairs of children were shared equally, then the partners in each pair would be equally comfortable. Each pair of children in a bed would have two blankets. However, our story has one bed with one blanket and one bed with three blankets. What happens if one child of the pair with three blankets gets cold and pulls one of the blankets completely over to his or her side of the bed? The other child is left with two shared blankets and might not notice much difference. What if the same thing happens with the other pair of children, the two with only one blanket? When the single blanket is pulled away, one child will get cold while the other child stays warm.

So is the case of the hydrogen atom: when its partner pulls away its only electron, its nucleus is more unshielded than the nucleus of other elements with multiple electrons in the same situation. A strong dipole occurs, and significant bonding between molecules results. Hydrogen bonding is important in biologic polymers, such as proteins and DNA. The three-dimensional structure of enzymes is determined by hydrogen bonding as the protein chain folds back on itself. In DNA, it is the hydrogen bonds that pair thymine with adenine and cytosine with guanine in the cross-links of the double helix.

3. Fluctuating Dipole

What about atoms or molecules without a permanent dipole (partial charges)? How do they stay together as solids or liquids? The noble gases, such as helium (He), have a symmetrical charge distribution; they have no dipole. Molecules of two of the same atoms, such as nitrogen gas, theoretically have a symmetrical charge distribution. Such atoms and molecules with a symmetrical charge distribution have very weak bonds between molecules. These gases need to be cooled to very low temperatures to liquefy. Their bonds are the result of an intermittent, uneven distribution of electrons around the atoms or molecules. These weak bonds are called a **fluctuating dipole**. Although this uneven distribution lasts only for an extremely short time and is always changing, positive and negative charges result, as does a very weak attraction between these atoms or molecules.

If one thinks of an outside light at night during the summer, one can get a feeling for this ever-changing distribution. The insects flying around the light can be thought of as electrons, and the light is the positive core. The insects seem to fly around the light as if attracted by some unseen force. They are unable to escape the close proximity of the light, similar to the relationship of an electron and a positive core. If one observes the insects and the light for a few seconds, one sees that the insects are not always evenly spread out around the light. Sometimes, for a just a second or so, they congregate more to one side than to the other. The unevenness then quickly changes.

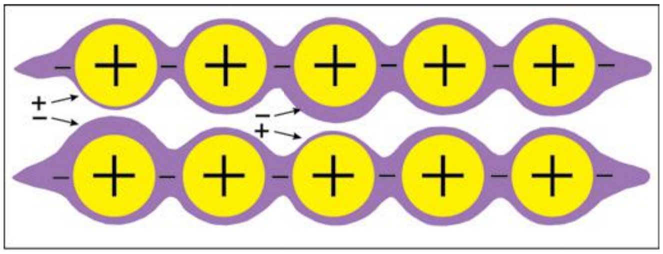


FIGURE 2.6. A fluctuating dipole. The intermittent, uneven distribution of the electron density (*purple area*) results in a constantly changing, or fluctuating, dipole.

Electrons around uncharged atoms and molecules behave in the same way. (Of course, the physical size of their orbits and the duration of the unevenness are millions and millions of times smaller than those of the insects and the light.) The result is a constantly changing, very weak attraction that allows uncharged atoms and small molecules to be cooled down and liquefied, but only at very low temperatures. The fluctuating dipoles of large uncharged molecules, such as some polymers, result in weak materials at room temperature (*Fig. 2.6*).

4. Summary

Secondary bonds are the result of uneven electron distribution around atoms and molecules. The more uneven the distribution is, the stronger the charge, the greater the attraction, and the stronger the bond. Secondary bonding in materials is most important when combined with covalent bonding, as in polymers.

III. Materials and Their Atomic Bonds

The atoms that make up a material and how these atoms are bonded determine the properties of that material. Weak bonds make for weak materials, and vice versa. Materials can be classified into three categories based on their primary atomic bonds: metals, ceramics, and polymers. A fourth category is composites. Composites are "mixtures" of two materials from two different categories. Dental composites are a combination of a ceramic and a polymeric material.

A. Metals

Metals are held together with metallic bonds. Few metals, however, have pure metallic bonds. Most metals have bonds that are predominantly metallic but that also show some covalent or ionic tendency. The broad range of mixtures of metallic and other primary bonds results in metallic materials with a range of properties. In this chapter, we focus on metals in which the metallic bond predominates. A good example is 24-carat gold, which is pure gold. Gold is ductile, meaning that it can easily be bent without breaking yet retains its strength. Gold behaves differently than a ceramic material, such as porcelain, or a plastic material. This mechanical behavior is a result of the metallic bond.

What happens when an object is bent? Some atoms are pushed together. Others are pulled apart. Still others slide past one another. We will focus on the atoms' ability to slide by one another because this is an important determinant of mechanical properties. In a metal, each atom (positive core) is surrounded by an electron cloud. The positive core "feels" the attraction and repulsion of all the charges that make up the object, but what the core feels is dominated by the outer electron cloud. What happens if an atom slides by another atom? Does the atom feel any difference in its surroundings? The electron cloud is still there and has not changed. Thus, the atom feels little (if any) difference. The surroundings (or the atomic bonding) have not changed, so the properties do not change. The ease with which metals can be bent and shaped enabled early humans to make strong tools that were tough and resisted fracture. What would happen if you tried to make a hammer out of a ceramic or a polymeric material rather than a metal?

In dentistry, we bend orthodontic wires and clasps of partial dentures. We also use instruments to adapt (marginate) the edges of a gold restoration closely to the tooth. All are examples of bending metals, a process that forces the atoms to slide against each other. It is the metallic bond that enables metals to have such useful properties.

B. Ceramics

The atoms of a **ceramic** material are bonded with ionic bonds. Table salt (NaCl) is a good example. Salt is strong but brittle. If enough force is applied to a grain of salt, it can be crushed. Why is salt so brittle? What happens if a Na ion slides away from its original position next to a Cl ion? Each Na ion is surrounded by Cl ions and vice versa. The nearest neighbors have opposite charges and the result is attraction. Therefore, as a Na ion slides past a Cl ion, it approaches another Na ion with the same charge, and now, there is repulsion where there once was attraction. The Na ions push away from each other, and the material breaks or fractures.

Many ceramic materials used in everyday life, such as dishes, concrete, china, and bricks, are bonded by both ionic and covalent bonds. The ionic bond dominates the behavior of the material, resulting in strong, brittle materials. The strong nature of the bonds of these materials is reflected in the high temperatures needed to process many ceramic materials and their chemical stability.

In dentistry, the notable advantage of ceramic materials is the range of esthetics that can be produced. Crowns made of ceramic materials are colored to match the appearance of the patient's natural teeth. These materials are also translucent, meaning that some light passes through, as in natural teeth. This translucency gives the ceramic crown a more natural appearance that other materials cannot provide (see Fig. 1.10F).

In summary, ceramic materials are strong when compressed, because the atoms are forced together. However, ceramic materials are weak and brittle when pulled or bent.

C. Polymers or Plastics

Polymers are composed of long chains of covalently bonded, repeating units. The chains are thousands of units long and consist of carbon, hydrogen, and other elements. A wide variety of polymers are used in everyday life. Some are soft, weak, and flexible; these are called "plastics." They make good toys, garbage bags, and fabrics. Others are hard, stiff, and fairly strong; these are called glassy polymers or resins. Such polymers are used to make parts for cars, outdoor furniture, plumbing pipes, and dishes. Another important group can be stretched out a great deal and still return to their original shape; these are called rubber materials. Where would we be without elastic waistbands or rubber gloves?

Why do polymers exhibit such a wide range of properties? Some properties of polymers are dependent on the covalent bonds between the carbon atoms that make up the backbone of the polymer molecule or chain. However, it is the variety of bonds between polymer chains that results in such a wide variety of polymeric materials.

The weakest bond between chains is the fluctuating dipole (rapidly changing partial charges). It occurs in polymers that do not have significant permanent charges in the backbone of the chain or side groups (*Figs. 2.6 and 2.7A*). Fluctuating dipole bonds are easily broken, and the chains readily slide by one another at room temperature. At room temperature, these polymer chains tend to resemble a plate of spaghetti. The polymer chain or piece of spaghetti is twisted and winds its way through the mass, which can easily be bent and pushed about. Plastic bags are made of such materials. If they are bent or stretched, the chains readily slide against one another. Such linear polymers are processed by heating (melting), which increases chain slippage; they are then molded or extruded. In dentistry,

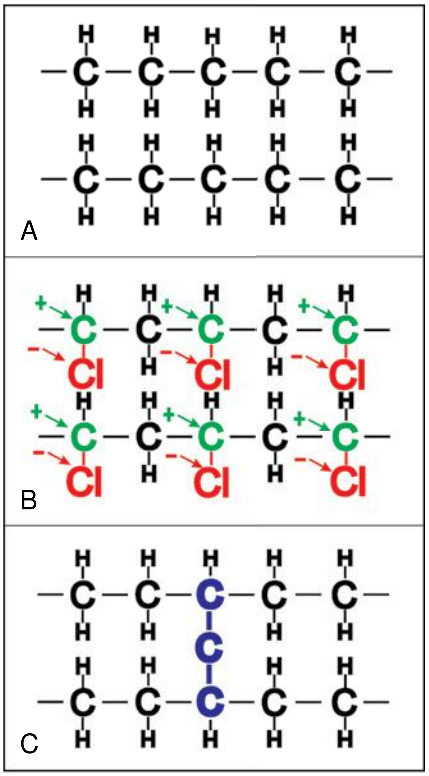


FIGURE 2.7. Three kinds of chain-to-chain interactions in a polymer. **A.** Linear polymer has weak secondary forces, as in *Figure 2.6*. **B.** Polymer with a permanent dipole is stronger. **C.** Cross-linking covalent bonds result in an even stronger polymeric material.

moldable polymers are used to make bleaching trays and fluoride trays; see Chapter 18, Oral Appliances, and Chapter 31, Vital Tooth Whitening.

If the polymer chain has a side group or atom that results in an uneven distribution of electrons, a partial charge will result. This is illustrated in *Figure 2.7B*. A greedy atom, such as chloride of PVC, will pull electrons away from some carbon atoms and cause the chain-to-chain interaction to greatly increase. In our pasta example, the spaghetti sticks to itself to a small extent. Now our polymer chains are much more "sticky" and the material is stiffer and stronger. As the number and intensity of the charges increase, the strength and stiffness of the polymer increase. Also, higher temperatures are required to melt these polymers when they are processed. Some dental instruments are made from these stiff, plastic materials.

Polymers have been developed that go beyond the weak bonding of secondary bonds and incorporate primary atomic bonds between the chains in their polymeric structure. These polymers have cross-links between the chains (*Fig. 2.7C*). The chains are linked by covalently bonded atoms to form a three-dimensional structure and can no longer slide past each other, resulting in stiff, strong material. The structural biologic polymers, such as collagen fiber in animals and wood fiber in plants, fit into this group. Dental composite filling materials use cross-linked polymeric materials. Heat will not melt these polymers; the chains cannot slip by each other. If these materials are heated to a high-enough temperature, however, decomposition results, such as the burning of wood or Mike's "blackened mystery meat."

A few man-made polymers have charged groups hanging off the polymer backbone that result in ionic bonds between chains. Such polymers are not widely used in everyday life, but one is used in dentistry: polyacrylic acid, which will be discussed later. In biology, several amino acids have groups that ionize. These charged groups are the part of a protein that greatly affects its three-dimensional structure and function. The three-dimensional structure of protein is critical if an enzyme is to function properly.

Why do we keep using examples from biochemistry? The typical dental hygiene student has a good background in biology. Man-made polymers follow the same "rules" as those of the biologic polymers with which the student is familiar. Biologic polymers, such as collagen and DNA, form helical structures. It is the stretching of these helixes (coils) that enables biologic polymers to stretch when we bend our joints. Man-made polymers have the same coiled three-dimensional structures. However, what keeps the coils from sliding by each other when they are stretched? A few covalent cross-links along the polymer chain keep the coils in place and prevent their movement. Depending on the interaction of the coils, some man-made polymeric materials can also stretch and return to their original shape.

Just like biologic rubbery materials, man-made rubber materials have polymeric coils that stretch out and recoil, similar to the springlike toy called a "Slinky." Rubber bands and polymeric impression materials are examples of materials that stretch and return to their original shape. A better description of a rubber material is a pile of Slinkies tangled together, with a few wired together. The linking of one coil (or polymer chain) across to another with wire (or a covalent bond) is called **cross-linking**. The mass can be stretched, but it cannot be untangled. The more cross-links that a rubber material has, the stiffer it will be. If too many cross-links are present, the rubber is too strong and hard, and it behaves more like a stiff plastic.

D. Composites

Composites are materials that are made of two or more different materials. Common composites are mixtures of a polymer and a ceramic, such as fiberglass. Each material that makes up a composite is called a phase. Materials or phases are chosen and combined so that the resulting composite has properties better than those of either component material. A composite is a kind of "team" of materials and is usually best appreciated on a microscopic level. The properties lacking in one material are compensated for by those of the other material. Strong, lightweight materials and products result. Sporting goods, such as skis, rackets, and golf clubs, are made from composite materials to minimize weight while retaining strength and flexibility. In dentistry, composites were first used as an esthetic restorative material, but today, they are commonly used for a variety of purposes. Enamel is a composite of apatite (a ceramic material) and protein (a polymer).

E. Colloids

Colloids are also two-phase materials. Colloids are mixtures of gases, liquids, or solids at the microscopic level. Colloids are not true solutions of one material dissolved in another, such as saltwater. Colloids are suspensions of one material in another, such as fog (a suspension of water droplets in air). Properties of composite materials are a result of the properties of the component materials. Properties of colloids, however, are a result of the properties of the components but are also greatly affected by the properties of the surfaces of the component phases. It is the large amount of surface area around the small particles that gives colloids their properties. When we discuss adhesion and bonding, we will again discuss the subject of surface science. Common colloids are Jell-O, foam, milk, smoke, and emulsions. Several dental impression materials are also colloids, as are fluoride foams.

Emulsions are a type of colloid composed of two liquids that do not blend together to form one liquid. When the two liquids are vigorously mixed, tiny droplets of each liquid are formed and dispersed among droplets of the other liquid. Oil-and-vinegar salad dressing is a good example. The oil and vinegar do not blend, but when they are vigorously shaken, a new liquid seemingly results. This new liquid is an emulsion of oil and vinegar. The surfaces of the two liquids are temporarily stable, and the dressing is neither vinegar nor oil. The resulting dressing, however, combines the taste of both and the spices dissolved in each. Milk as well as liquid soaps and lotions are emulsions.

The transformation from a liquid to a gel is the important feature of other colloid materials. Jell-O and jellies are good examples. If warmed, these materials become liquid. If cooled, they become a semisolid gel. In dentistry, hydrocolloid impression material behaves in this manner.

F. Teeth and Food

One of the main functions of teeth is to start the digestion of food. Food varies a great deal in texture, from mashed potatoes to rock candy. Teeth chop, tear, and grind a variety of materials to allow the digestive fluids to access the greater surface area that is inherent in smaller pieces of food. Teeth, jaws, and muscles are able to apply a great amount of force to food to crush it. The teeth must withstand these forces for a lifetime. Luckily, teeth are made from materials that are able to resist these forces. Teeth are stronger than the food we eat. The dental restorative materials that are used to replace tooth structure must have these same characteristics. In the next chapter, we discuss the mechanical and physical properties of materials. We will compare dentin and enamel to restorative and other materials used in dentistry.

Summary

Properties of materials are a result of their atomic bonds. Materials can be classified into one of the three phases: solid, liquid, or gas. A solid object exhibits the ability to support itself and other objects because solids have the strongest atomic bonds. Liquids have weaker bonds and need to be confined on most sides by a container. Gases have the weakest of all bonds and their atoms need to be contained in all the three dimensions.

Atoms of materials are held together by two types of atomic bonds: primary and secondary. Primary bonds are those that involve the transfer or sharing of electrons between atoms. There are three kinds of primary bonds: ionic, covalent, and metallic. Ionic bonds result when an electron is given up by an atom and accepted by another. The atom that gives up the electron becomes a positive ion, while the atom that receives the electron becomes a negative ion. The positive and negative ions attract each other by the electromagnetic force and form an ionic bond. When two atoms share a pair of electrons, a covalent bond is formed. A metallic bond involves sharing many electrons by all the atoms in the material. Covalent and metallic bonds are also the result of positive and negative electromagnetic attraction of atoms and their electrons.

Secondary bonds occur when a partial charge is created from an uneven distribution of electrons. The three types of secondary bonds are hydrogen bonds, permanent dipoles, and the fluctuating dipole. Of the three, the hydrogen bond is the strongest, and the fluctuating dipole is the weakest. The hydrogen bond is important in biologic molecules such as DNA and proteins, and biologic materials such as ligaments and cartilage.

Materials can be classified into three categories based on their primary atomic bonds: metals, ceramics, and polymers. Composites are a combination of two solid materials and may be considered a fourth category. Metals are ductile, yet retain strength when bent because the metallic bond allows atoms to slide by one another and not disrupt the bonds in the metal. Ceramic materials are strong when compressed, but weak and brittle when pulled or bent. When the arrangement of the positive and negative ions in a ceramic material is changed, attraction may change to repulsion and a break or fracture is likely. Polymers or plastics have a range of properties because they have covalent bonds and a range of secondary bonds in their atomic structure. Many different polymers are used to make everyday products. Those that are soft, weak, and flexible are termed plastics or rubber. Those that are hard, stiff, and strong are called resins or glassy polymers. Composites are a mixture of two or more distinct materials. An example is fiberglass, made of both a polymer and a ceramic.

Learning Activities

1. Pick out several objects in the room. Discuss the type of materials used to manufacture those objects, the kind of atomic bonds in the materials used, and the properties that result.
2. Describe the advantages and disadvantages of using a metal, a ceramic, or a polymer as a restorative material.
3. Using the Internet, search for "colloid." Visit several sites that list everyday examples of colloids. Which of these colloids have you seen? Touched? Eaten?

Review Questions

Question 1. **The molecules found in a pane of glass can be best described as:**

a. Crystalline solid, having short-range order only
b. Crystalline solid, having both short-range and long-range order
c. Amorphous solid, having long-range order
d. Amorphous solid, having short-range order

Question 2. **A partial charge resulting from an uneven distribution of electrons around an atom forms a bond known as:**

a. Metallic
b. Secondary
c. Covalent
d. Ionic

Question 3. **What type of bond is formed when the electrons are shared by all the atoms that make up that object and may be thought of as "positive cores" in a "cloud of negative mobile valence electrons"?**

a. Metallic
b. Secondary
c. Covalent
d. Ionic

Question 4. **A notable advantage of using ceramic materials in dentistry is the property of:**

a. Transparency
b. Translucency
c. Opacity
d. Brittleness

Question 5. **A dental polymer with many cross-links as compared to one with no cross-links would be a dental material that is:**

- **a.** Flexible but strong
- **b.** Flexible and weak
- **c.** Stiff and strong
- **d.** Stiff but weak

Question 6. **All of the following are examples of a composite except:**

- **a.** Set Jell-O with sliced peaches
- **b.** Enamel
- **c.** Fiberglass
- **d.** Tin foil

Question 7. **When the shared electrons of a covalent bond are not shared equally, and one of the bonded atoms is partially positive and the other is partially negative, a __________ is formed.**

- **a.** Permanent dipole
- **b.** Fluctuating dipole
- **c.** Hydrogen bond
- **d.** Primary bond

Question 8. **The sliding of atoms past each other allows this material to bend, not fracture, and maintain its strength. This material is an example of a:**

- **a.** Metal
- **b.** Ceramic
- **c.** Polymer

Question 9. **A mixture of two liquids that do not blend together to form one liquid is termed a (an):**

- **a.** Composite
- **b.** Emulsion
- **c.** Colloid
- **d.** Solution

Question 10. **When two atoms share a pair of electrons, the resulting atomic bond is termed a (an) __________ bond.**

- **a.** Secondary
- **b.** Ionic
- **c.** Covalent
- **d.** Metallic

Physical and Mechanical Properties of Dental Materials

3

Objectives

After studying this chapter, the student will be able to do the following:

1. Describe or define the key words and phrases.
2. Relate the physical properties of materials discussed in this chapter to their use in dentistry.
3. Define wetting. Include in the definition a drop of liquid and the contact angle formed with the surface.
4. Name the units of measure for the following properties:
   - Density
   - Heat capacity
   - Stress
   - Strain
   - Modulus of elasticity
5. Define "proportional limit," and name two other nearly equivalent terms.
6. Name the four types of stress, and provide an example of each found in everyday life.
7. Describe two situations in which dental materials are subjected to bending stresses when in function.
8. Compare the properties of "toughness" and "hardness," and provide examples.
9. Explain the difference between stress relaxation and creep.
10. Discuss the phenomenon of stress concentration, and compare its effects on a poorly placed amalgam restoration as well as on a properly placed one.

Key Words/Phrases

abrasion resistance
bending
biologic properties
chemical properties
coefficient of thermal expansion
color
compression
creep
density
elastic deformation
elastic limit
elasticity
fatigue
force
fracture toughness
galvanic shock
Goldilocks principle
hardness
heat capacity
heat of fusion
heat of vaporization
load
mechanical properties
modulus of elasticity
percolation
permanent deformation
physical properties
plastic deformation
Poisson's ratio
proportional limit
resilience
shade guide

(*continued*)

Key Words/Phrases *(continued)*

shear
solubility
specific heat capacity
strain
stress
stress concentration
stress relaxation
tension
thermal conductivity
torsion
toughness
ultimate compressive strength
ultimate strength
ultimate tensile strength
vapor pressure
viscosity
water sorption
wetting
yield point

Introduction

When substituting one material for another, as in the restoration of teeth, we must be aware of the requirements for the new material. It seems obvious that the replacement material should have the same characteristics as enamel, which is very hard and strong. Should dentists restore teeth with the strongest and hardest material? In certain situations, the replacement material should have the same appearance as teeth for proper esthetics. Several other questions also need to be addressed: Is the material as good a thermal insulator as enamel and dentin are? Is the material "kind" to the pulp of the tooth? Does the material break down and release toxic chemicals?

We should also consider the cost of materials and labor when selecting restorative materials. As the list of requirements grows, we begin to realize that the criteria for an ideal restorative material are many and varied. Unfortunately, no ideal material exists, so we are always compromising in one way or another. The only sure way to eliminate this difficult dilemma is through prevention.

The important question is: what are the requirements for a particular restoration for a particular tooth and patient? Determining what is required and what will best meet the clinical situation are complex questions. Typically, a compromise is made among the many factors being considered. This chapter discusses many of these factors or properties of materials. In addition, this chapter describes the relationship between these properties and the materials science concepts previously discussed.

In everyday life, we notice that different materials have different properties. When we pick up an object, we feel its weight, which is an indication of its density. We also feel its temperature, which is an indication of its thermal "content" and its ability to transmit heat. Some objects feel strong and hard; others feel weak and flexible. Engineers have devised a variety of laboratory tests to quantify the properties of materials. Dental materials scientists use the same tests (as well as several others) to describe the physical properties of materials used in dentistry.

I. Properties of Materials

Properties of materials can be divided into three categories: physical, chemical, and biologic. **Physical properties** are based on the laws of physics that describe mass, energy, force, light, heat, electricity, and other physical phenomena. Color, density, and thermal conductivity are examples of physical properties. **Mechanical properties** are a subgroup of physical properties. Mechanical properties describe a material's ability to resist forces. Mechanical properties are dependent on the amount of material and on the size and shape of the object. Examples are strength and stiffness. **Chemical properties** describe the setting reactions as well as the decay or degradation of materials. For example, gypsum products (used to make study models) set by a precipitation process, whereas dental composites polymerize. **Biologic properties** of materials are the effects the materials have on living tissue. For example, a crown should not irritate the gingiva, tongue, or buccal mucosa.

The chemical and biologic properties of dental materials are discussed with each group of materials presented in the chapters that follow. This chapter focuses on the physical and mechanical properties.

II. Physical Properties

A. Density

The amount or mass of a material in a given volume is the **density** of the material. A common unit of density is g/cm^3. Density depends on the type of atoms that are present (as the atomic number increases, so does the density), the packing together of atoms and molecules, and the voids in the material. The high density of most metal objects makes them feel heavy. Most metals have high atomic numbers, and their atoms are packed closely together into solids. A metal maxillary partial denture will feel heavy and have a tendency to become "unseated" if it is not designed to adapt to the remaining teeth.

B. Boiling and Melting Points

Boiling and melting points are physical properties of materials. In analytical laboratories, they can be used to help identify chemicals. Mixtures often have a melting or boiling range rather than a specific melting or boiling point. Dental waxes are an example of mixtures with a melting range. When an object melts or boils, the atomic bonds between the atoms or molecules are broken by the thermal energy of the material. Some dental metals melt at very high temperatures and are very difficult to work with. Other materials do not boil or melt; instead, they decompose if heated sufficiently. Wood and cookie dough are common examples of materials that decompose.

C. Vapor Pressure

Vapor pressure is a measure of a liquid's tendency to evaporate and become a gas. As the temperature of a liquid increases, the vapor pressure also increases. We notice that steam rises from a pot of water more and more as it is heated because the increased thermal energy allows more atoms or molecules to escape from the liquid and become vapor. Materials with a low vapor pressure, such as cooking oil, do not evaporate quickly. Materials with a high vapor pressure, such as rubbing alcohol, evaporate readily at room temperature.

Materials with a high vapor pressure are very useful as solvents in the application of viscous (syrupy) liquids, such as glue or paint. The viscous liquid is "thinned" by mixing it with a solvent. This "more runny" mixture is then applied to a surface. As the solvent evaporates, it leaves behind a thin layer of the viscous liquid. In dentistry, we use solvents to apply a thin layer of a thick liquid, such as copal varnish or a dentinal adhesive. Rubber cement, oil-based paints, and perfumes use the same process: a mixture is applied and the solvent evaporates, leaving behind a thin film of the desired substance.

Methyl methacrylate, a component of dental acrylic resins (plastics), has a high vapor pressure and can evaporate easily when a denture is processed. Porosity may result, weakening the denture. Denture-processing techniques are designed to minimize the evaporation of methyl methacrylate and the resulting porosity (see Fig. 11.3).

D. Thermal Conductivity

In the kitchen, we use a wooden spoon to stir hot liquids. We do not use a metal spoon because it conducts heat well and would quickly become too hot to hold. In dentistry, we are also interested in the thermal conductivity of materials. **Thermal conductivity** is the rate of heat flow through a material. Measurement of thermal conductivity depends on the distance the heat travels, the area in which the heat travels (much like the size of the pipe through which water travels), and the difference in temperature between the source and destination. Because thermal conductivity is a rate, it is measured as heat flow over time. Thermal conductivity is measured as calories/second·meter·degree. Pulpal sensitivity is likely if conductive materials, such as metals, are placed in close proximity to the pulp. If caries are deep and a metal restoration is planned, an insulating base is placed beneath the metal restoration to insulate the pulp from hot and cold stimuli (see Fig. 1.9).

E. Heat Capacity

Some objects, such as a "microwave warming trivet," can store a lot of heat. The **heat capacity** of a material is a measure of the amount of thermal energy that a material can hoard. Some materials require more energy than others to heat. The **specific heat capacity** of a material is the amount of energy needed to raise the temperature of one unit of mass of that material by 1°C. Specific heat capacity is measured as cal/g·deg. The heat capacity of water is 1 cal/g·deg.

F. Heat of Fusion and Vaporization

The **heat of fusion** is the amount of energy required to melt a material. Conversely, the **heat of vaporization** is the amount of energy required to boil a material. Both are typically large in relation to the heat capacity. It requires 80 times more energy to melt a given quantity of ice than to increase the temperature of the same amount of water by 1°C. It takes 540 times more energy to boil that same quantity of water. The high heat of fusion allows a small amount of ice to effectively cool a much larger amount of beverage without excessive dilution as it melts. We shall see that the heat of fusion of metals must be overcome when melting gold for casting a crown. The solid metal must be heated to the melting temperature, and then, a significant amount of energy must be added to melt the metal.

G. Coefficient of Thermal Expansion

If a balloon filled with room temperature air is brought outside on a cold January day in West Virginia, the balloon shrinks. This is a visible example of what happens to nearly all materials when cooled: they shrink or contract. On the other hand, most materials expand when heated. The **coefficient of thermal expansion** is a measure of this change in volume in relation to the change in temperature. This concept, however, is slightly more complicated than that explanation suggests.

The coefficient of thermal expansion is a fractional change in volume or length. In *Figure 3.1*, several examples of expansion are illustrated. In *Figure 3.1A*, the 10-unit-long bar is extended by

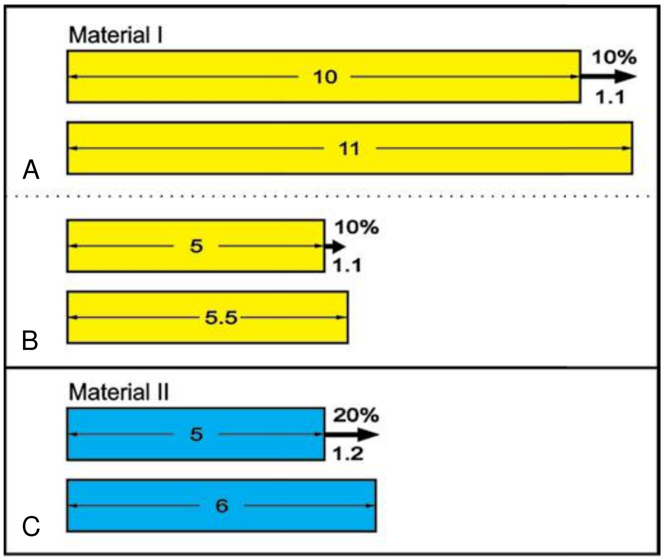


FIGURE 3.1. Three examples of expansion of a material in terms of percentage or fractional change in length.

1 unit (or 10%). The new bar is now 1.1 times the original length. In *Figure 3.1B*, the 5-unit-long bar is extended by 0.5 unit, becoming 5.5 units long. It is also 10% longer (or 1.1 times the original length). Therefore, larger objects of the same material expand more in quantity than smaller objects do, but larger objects expand by an equal amount in terms of the percentage or fractional change. In *Figure 3.1C*, a different material expands more, and the result is a 20% change in length. We look at fractional change of length again later in this chapter, when strain is discussed.

Our interest in the coefficient of thermal expansion of dental materials is in relationship to those of enamel and dentin. A polymeric material, such as polymethyl methacrylate (an early tooth-colored restorative material of the 1950s), shrinks and expands seven times more than tooth structures. Compared with that filling material, the restorative materials of today more closely match the coefficient of thermal expansion of teeth. When the mismatch is great, the restoration will shrink with cold beverages, opening gaps between the restoration and the tooth. When the tooth heats up again and expands, the gap is closed. The process of heating and cooling, and the accompanying opening and closing of the gap, is called **percolation**. Percolation results in microleakage, tooth sensitivity, and recurrent decay. Microleakage is discussed in Adhesive Materials.

H. Electrical Conductivity

Electrical conductivity is not typically thought of as an important property, but we should know which materials are conductive. Metals are good electrical conductors. Polymers and ceramics are poor conductors and are termed insulators. During electrosurgery or electronic pulp testing, it is important to know which restorations are conductive and which are not. Electrical conductivity also affects corrosion, which will be discussed in the section on instruments. Occasionally, a new amalgam filling will hurt when it is touched with a metal fork. This **galvanic shock** is the result of electricity flowing from the fork to the amalgam and through the pulp.

I. Viscosity

When placing materials, the handling characteristics of those materials are important. Some materials should flow easily and wet the surface. Other materials need to be more like putty, which can be adapted or formed into a desired shape. The **viscosity** of a material is its ability to flow. Thick or viscous liquids flow poorly, whereas thin liquids flow easily. Viscosity is a temperature-dependent property. For example, pancake syrup pours much more easily when it is warmed. Viscosity is measured as g/m·s, or as poise (P). Water at 20°C has a viscosity of 0.01 P, or 1 centipoise (cP). Impression materials have viscosities between 100,000 and 1,000,000 cP.

A low viscosity and the ability to wet a surface are important in the use of many dental materials. **Wetting** a surface with an adhesive material, such as a sealant, brings the material into intimate association with the surface so that chemical and micromechanical bonding can occur. Wetting is measured by determining the contact angle of a liquid on a solid, as shown in *Figure 3.2*. A low-contact angle, such as that of a drop of water on a piece of ice, indicates good wetting. A high-contact angle, such as that of a drop of water on most plastics, indicates poor wetting. Another example of wetting in dentistry occurs when a gypsum product (plaster) is poured into an impression. If the mixed material wets the surface of the impression

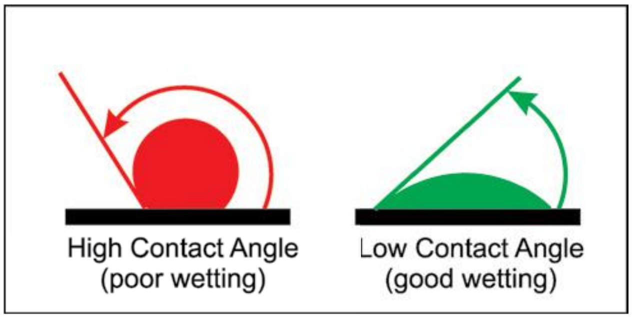


FIGURE 3.2. Contact angle measurements demonstrate a liquid's ability to wet a surface.

material, the fine details of the impression will be reproduced in the cast. If poor wetting occurs, bubbles will likely result in insufficient detail and an unusable cast.

J. Hardness

Enamel is the hardest biologic tissue in the human body. Hard materials resist scratching and indenting by soft materials. **Hardness** is a property that is measured by scientific instruments that press a special tip into the surface of the test material. The tip has a characteristic shape made of a very hard material, such as steel or diamond, as shown in *Figure 3.3*. The size of the indentation created is then measured. Hardness is calculated based on the size of this indentation. Several different methods can be used to measure hardness. The Brinell and Knoop methods are illustrated in *Figure 3.3*. Two other methods are called the Rockwell and Vickers hardness tests. The Knoop hardness number (KHN) of enamel is 350, whereas the KHN of dentin is 70. Some dental materials are harder than enamel. Porcelain has a KHN of 400 to 500. Other materials are not as hard as enamel. For example, acrylic denture teeth have a KHN of 20.

K. Durometer Measurements

Some materials are soft and even spongy. One example would be the rubber grip sometimes used on an instrument's shaft. A different kind of hardness test is used for these materials because a surface hardness indentation will not occur. A durometer measures how deep a steel ball will sink when pressed into the surface of a soft material. Durometers are used to measure the hardness of impression materials and other elastic polymers.

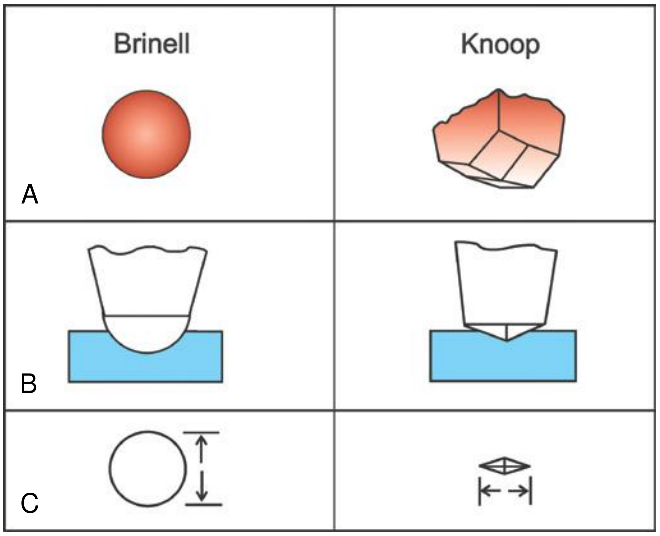


FIGURE 3.3. Comparison of two hardness indenter tips, the Brinell and the Knoop. **A.** Perspective views of the two tips. **B.** Cross-section of the tips in contact with test samples. **C.** Test material showing the indentation that is measured to calculate hardness.

L. Abrasion Resistance

Harder materials tend to be more resistant to abrasion than softer materials. In dentistry, we are interested in the **abrasion resistance** (wear resistance) of dental restorations to food, opposing teeth, and other dental materials such as ceramic crowns or porcelain denture teeth. We are also interested in the wear of natural teeth opposing dental restorations. If a restorative material is too hard, it will wear the opposing teeth at an unacceptably accelerated pace. An example is the excessive wear of natural teeth that oppose a denture with porcelain teeth. Therefore, a restoration must be hard enough so that the restoration does not wear away, but not so hard as to excessively wear away the opposing teeth. This is a good example of what has been called the **Goldilocks principle**: not too hard, not too soft, just right. More often than not, a material's properties need to fit within a particular range of values, not the maximum value, to be the material of choice.

M. Solubility

Materials placed in the oral cavity are exposed to various aqueous fluids. The solubility of materials in water is an important consideration. **Solubility** is the amount of a material that dissolves in a liquid, such as water. Sugar is a highly soluble material, but enamel is not. Restorative materials should not appreciably dissolve in the mouth. Additionally, some materials tend to dissolve faster in acidic environments. To measure solubility, a test sample is immersed in water. The weight of the material dissolved into the water is the solubility of that material. The solubility of some dental cements is measurable and clinically significant. Excessive solubility leads to loss of material and increases the risk of recurrent decay.

N. Water Sorption

Some materials absorb water. This property is termed **water sorption**. Water sorption is measured much like solubility. A test sample is immersed in water, and the weight that is gained by that sample is the water sorption. A cookie dunked in milk is an example of milk sorption. When materials absorb water, they tend to swell. Some materials both dissolve and absorb water at the same time, making measurement of one of these properties difficult. Many polymers absorb a small amount of water over time and slightly swell as a result.

O. Color

The appearance of a restoration for an anterior tooth can be a factor when choosing materials. The color and surface luster of the restoration are important. In addition, the shape and health of gingival tissues adjacent to a restoration are also noticed.

Color is a complex phenomenon that is a psychological response to a physical stimulus. The physical stimulus is the light reaching the rods and cones of the eye. Because processing of that stimulus by the brain is a psychological phenomenon, the perception of color varies between individuals. Two people may agree that two objects match in color, while a third person disagrees. In addition, the color of an object depends on the light in which the object is viewed. For all these reasons, matching restorative materials to a patient's teeth can be difficult.

Two types of systems are used to measure color. Both use three numbers to describe a color. One system involves matching the test object to color tabs resembling those available in a paint store. It is called the Munsell color system. Each tab has hue, chroma, and value numbers assigned. Hue is the fundamental color of an object, as in red, green, or blue. Chroma is the strength or color saturation of the hue, as in pink versus red. Value is the light or darkness of the color, as in shades of gray. In dentistry, esthetic materials have their own set of color tabs or shades, called a **shade guide**. Some manufacturers use a standard set, such as the VITA shade guide, which is shown in *Figure 3.4*. Recently, handheld devices have been developed that measure the color of teeth through a digital camera. These devices provide maps of the various shades of a tooth.

The other system involves measurement of color with a spectrophotometer or a colorimeter. A spectrophotometer measures the intensity of light that is reflected by an object at numerous wavelengths of visible light. The colorimeter measures light at several wavelengths, much like the human eye. For both devices, the data are mathematically manipulated by a computer to reduce the information to three numbers: L*, a*, and b*. The number L* is very similar to value. The number a* is a measure of the red–green character of a color. The number b* is a measure of the blue–yellow character of a color. The measurement of color with spectrophotometers is common in dental research. Several colorimeters and other digital devices are available for clinical use (see Fig. 31.2).

FIGURE 3.4. Photograph of several shade guides, including a VITA shade guide (*top right*).

The interaction of teeth and dental materials with ultraviolet light causes fluorescence and affects their appearance. Fluorescence of restorations is important when fluorescent lighting or "black" lights are present. Inadequate fluorescence will make a crown or a filling appear dark in certain lighting, but excess fluorescence will make a tooth "glow" in the same lighting.

P. Interaction of Materials with X-Rays

When interpreting radiographs, the dental hygienist must be aware of the appearance of the radiographic image of dental materials. Some materials are radiolucent and are not seen on radiographs. Examples are some ceramic materials and denture acrylic resin. Other materials, such as metal restorations, are radiopaque and are evident on radiographs. Some dental restorative materials have been formulated by the manufacturer to match the radiopacity of enamel to facilitate the diagnosis of recurrent decay. Dental materials and their radiographic appearance are discussed further in Chapter 15.

III. Mechanical Properties

Because teeth are used to tear and grind food, they must be strong, and so must the materials that are used to replace missing tooth structure. Luckily, engineers and materials scientists have studied materials and their use for centuries. Dentistry has used this information along with trial and error.

What happens to a tooth or restoration when we bite on it? An external force (biting) is placed on the tooth. A **force** is a weight or **load** applied to an object. Inside the tooth, an internal stress develops to resist the applied external force. This **stress** is the force divided by the area on which the force has been applied. The internal stress that develops in the tooth is equal to the external force applied; however, they are opposite in direction.

Why don't teeth break when we use them to grind our food? Teeth are composed of strong materials with strong atomic bonds. Teeth and their atomic bonds are stronger