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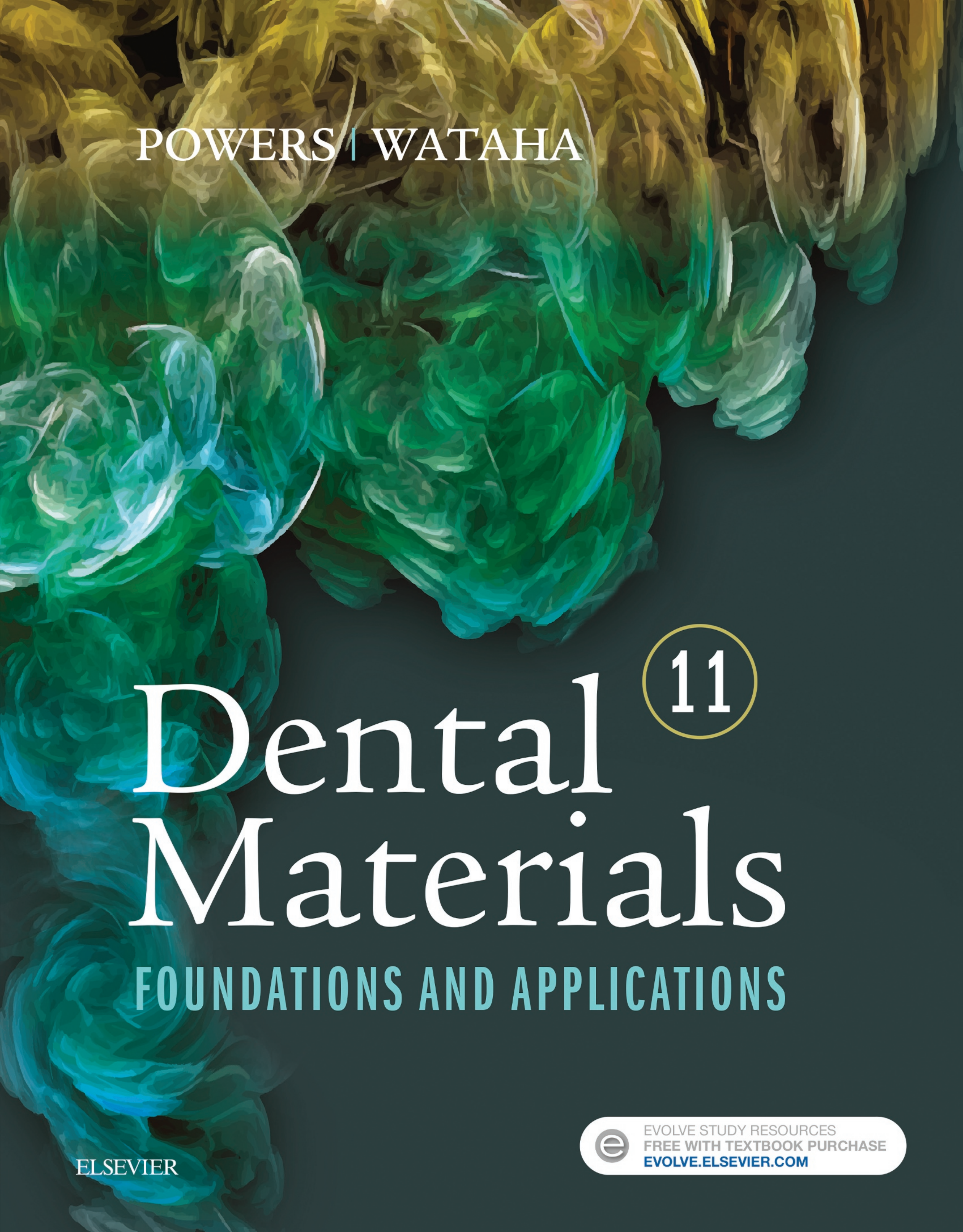

# Dental Materials

11

## FOUNDATIONS AND APPLICATIONS

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# PREFACE

*Dental Materials: Foundations and Applications* presents contemporary information about clinical and laboratory dental materials used throughout all dimensions of dental care.

## BACKGROUND

Now in its eleventh edition, this textbook was edited for over 30 years until 2003 by Dr. Robert G. Craig. Dr. Craig contributed to the education of literally thousands of health profession students, using his research knowledge and inherent teaching skills to promote an understanding of dental materials. This text continues to honor Dr. Craig's commitment to the dissemination of accurate, current knowledge about dental materials in clinical practice. We continue to follow his philosophy of teaching students and clinicians the "hows & whys" of the materials they use to treat their patients.

## AUDIENCE

This textbook is intended for students in dental, dental assisting, and dental hygiene programs. It also is an excellent resource for dental technology programs or programs training midlevel providers and will serve as a comprehensive, contemporary reference for any practicing dentist or dental professional. Finally, it is a good resource for those in need of a thorough review of dental materials for general or specialty board examinations.

## ORGANIZATION

Our goal with *Dental Materials: Foundations and Applications,* 11th Edition, is to provide a comprehensive source of information about dental materials. Following a discussion of the nature of materials, the book provides an overview about how materials are used to treat or prevent disease and trauma. The book then covers important properties of materials, followed by all preventive and direct restorative materials used in contemporary dental practice. Later chapters focus on materials used to fabricate indirect restorations that are critically important to the restoration of a patient's oral health and are important to the dentist or dental professional because of the need to communicate expectations accurately to the patient or laboratory technician.

In this edition, all chapters have been revised, but chapters on ceramics, implants, impression materials, and polymers have been completely redone to present up-to-date information at an appropriate level. We have added over 60 new clinical photos to help students understand the applications of materials in dental practice and help teachers convey the same. We have added information throughout about the rapidly emerging area of "digital dentistry." We have also added an introductory section on the nature of materials to give readers a solid foundation to understand how different materials are, or are not, related.

Key terminology is set in bold type, critical statements are italicized, unusual words are defined in brief text boxes, and quick review or summary statements are placed at the ends of chapters or major sections. Finally, a glossary of terms is placed at the end of the textbook. In addition, a companion website created just for this book (http://evolve.elsevier.com/Powers/dentalmaterials) contains a variety of resources designed to enhance both education and study (see listing below).

## KEY FEATURES

- *Comprehensive, Focused Coverage:* Fifteen chapters plus an introductory section present detailed information about dental materials used in the dental office and laboratory and all the materials relevant to day-to-day practice for dentists, dental hygienists, and dental assistants.
- *Cutting-Edge Content:* The latest materials used in dental practice are discussed, including those used in esthetic dentistry, digital dentistry, and preventive dentistry, and new advanced technologies in laboratory practice.
- *Art Program:* More than 500 full-color illustrations and photographs liberally supplement the text descriptions to help students learn to recognize the differences among the many types of dental materials and thoroughly comprehend their appropriate clinical manipulation. Dozens of intraoral photos show how materials are used, step-by-step, in many cases.
- *Consistent Presentation:* Each material presentation begins with a study of the properties and uses of that material before moving on to the specific manipulations and applications in dentistry, providing a logical framework for comparison among materials.
- *Review Questions:* Each chapter ends with 20 to 30 self-test questions, the answers to which are provided in the online instructor's materials, as a student study and assessment tool.
- *Quick Review Boxes:* Each chapter wraps up with a brief narrative summarizing the content to recap key concepts and help students assess their readiness to progress onto the next topic.
- *Note Boxes:* Interspersed throughout the text, these notes highlight key points and important terminology to help students build the foundational information necessary for clinical competence.
- *Summary Tables and Boxes:* Chapters summarize concepts and procedures within boxes and tables throughout the text for easy-to-read summaries of text discussions for reference and study.
- *Vocabulary Resources:* Bolded upon their initial text mention within the chapter, and defined in a back-of-book

glossary to help students master the language of dental materials.
- *Learning Objectives:* Each chapter begins with a detailed list of student outcomes that serve as study tools and checkpoints for student comprehension.
- *Supplemental Readings:* Chapters include listings of contemporary texts and journal articles that supply further information on the topic at hand to promote evidence-based practice and provide students with sources of in-depth study on specific topics.
- *Conversion Factors:* The inside back cover includes listings of common metric conversions as a handy reference for students.
- *Evolve Website:* A companion site provides resources to ease both instruction and learning.

## NEW TO THIS EDITION

- *New Content:* Expanded and updated discussions are included for particularly dynamic areas such as esthetics, CAD/CAM technology, cements, ceramics, dental implants, and impressions (including digital impressions) to keep up with changes and advances in dental materials and associated technology.
- *Full Color:* This text is in full color, improving the clarity of images and helping students understand complex processes and sequences, and differentiate among the numerous types of dental materials, particularly.
- *New Artwork:* More than 70 new illustrations and photographs have been added, including images that show materials being mixed and used, making this often-difficult subject matter easier to grasp. Many intraoral photos are included to give the reader a sense of how the materials are used in sometimes complex sequences.
- *Appendices:* Several chapters include appendices that set apart from the text discussion and describe dental materials (e.g., agar impression material and zinc phosphate cement) that are less commonly used in modern dental practices.
- *New Ancillary Materials:* A color image collection, expanded test bank, and the addition of case studies are added to the instructor materials, whereas students benefit from access to instant-feedback assessment questions and interactive exercises to reinforce glossary terms.

## COMPANION WEBSITE

An Evolve website has been created specifically for this text and is accessible via http://evolve.elsevier.com/Powers/dentalmaterials. Assets on this site include the following:

## STUDENT RESOURCES

- Self-Assessment Practice Quizzes
- Instructional Videos
- Vocabulary Flashcards

## INSTRUCTOR RESOURCES

- Test Bank (approximately 650 questions)
- Case Studies (including critical thinking questions)
- PowerPoint Presentations
- Image Collection
- Answers to Textbook Self-Test Questions
- Performance Skills Checklists

**John M. Powers**
**John C. Wataha**

# Introduction: The Building Blocks of Restorative Dental Materials

## OBJECTIVES

*After reading this chapter, the student should be able to:*

1. Describe the importance of the atomic number and the periodic table of the elements.
2. Compare and contrast ionic, covalent, and metallic bonds and their role in restorative dental materials.
3. Describe the differences between molecules and lattices and cite which restorative materials occur in which arrangement along with examples of materials using each arrangement.
4. List the four major classes of restorative dental materials and explain how each is unique and how the atomic structure of each leads to its macroscopic and clinical properties.

What makes up the materials in the world around us? What makes materials different from one another in color, strength, flexibility, conductivity, or weight? And why can we use some materials to restore teeth but not others? Why are some materials best suited for oral impressions, others for fillings, still others for implants? The answers to these questions are based on the way the most basic units of matter are arranged and interact. In the current preview, we will briefly explore the world of matter and materials as an introduction to restorative dental materials.

The oral environment is harsh and diverse, and the materials we use in that environment must survive many challenges. This environment experiences remarkable changes in temperature, substantial mechanical forces, adhesion of communities of microorganisms on every exposed surface, and chemical attacks from foods and from the body, with all these occurring over years to decades. Is it any wonder, then, that the materials needed to function in this environment are themselves diverse and complicated? Even more remarkable is that the roles we ask these materials to play. We have asked materials to act as surrogates for missing oral structures for thousands of years. But today, we increasingly ask materials to also serve as therapeutics or to adapt automatically to changing oral conditions.

The world of restorative dental materials is complex, exciting, and evolving. In this preview, we will introduce materials from the most basic perspective of the atom and explore how atoms interact to form the classes of materials we use every day in the treatment of oral disease. In the end, understanding these basic ideas is the key to understanding and predicting whether our everyday clinical treatments with dental materials will succeed or fail.

## ATOMS: THE BUILDING BLOCKS OF DENTAL MATERIALS

The basic building block of all restorative dental materials is the **atom**. Atoms combine various ways via **bonding**; the bonding between atoms is a key feature of what makes dental materials behave the way they do. Beyond atom-to-atom bonding, atoms are arranged at a higher level into **molecules** or **crystals** that ultimately give dental materials their familiar clinical properties. It is these arrangements of atoms and the nature of the bonds among them that allows metals to conduct electricity, ceramics to have translucence, and elastomers to stretch. We will briefly discuss these ideas further in the following sections.

**! ALERT**

Atoms are the basic building block of all dental materials. The interactions between atoms are the key difference among materials.

### Atoms

Every atom consists of a nucleus of protons and neutrons and **electrons** in cloudlike areas around the nucleus (Figure 0-1). The numbers of protons (the atomic number) determines the identity of the atom—whether it is copper, gold, or carbon, etc. We call atoms with different numbers of protons different **elements**. The components of atoms have a property known as charge: protons are positively charged, neutrons have no charge, and electrons are negatively charged. In their native state, all atoms have equal numbers of protons and electrons and therefore have no net charge.

The number of protons in the nucleus of an atom determines the number and arrangement of the electrons and electron clouds around it. These clouds are technically referred to as atomic orbitals; the complex shapes and properties of these orbitals are well beyond the focus of this chapter. For our purposes, it is sufficient to understand that these clouds of electrons are the basis by which atoms interact with each other and that electron numbers and properties are determined by the number of protons.

The atoms in our universe are arranged into a sophisticated table called the periodic table of the elements (Figure 0-2); this table is arranged in rows (periods) according

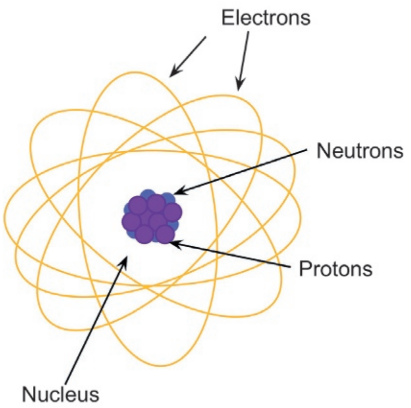

**FIG 0-1** The atom is the basic building block of all restorative dental materials. Every atom consists of a nucleus of protons (positively charged) and neutrons (no charge) surrounded by clouds of electrons (negatively charged). In its native state, every atom is electrically neutral, having an equal number of positive and negative charges. The number of protons determines the identity of the atom in the periodic table of elements (see Figure 0-2) and is known as the atomic number. Thus, the atomic number determines the element. The number of electrons and their configuration around the nucleus largely determines how the element bonds with other elements to form the materials we use in clinical practice.

to the number of protons in the nucleus of the elements. Complex chemical rules dictate the number of elements in each row. Each element has a one- or two-letter symbol; the first letter is always capitalized. If there is a second letter, it is lower case. Remarkably, from this table, we can predict the physical and chemical behavior of an element and general ways of how it will interact with other elements. For example, the periodic table is divided roughly into metals and nonmetals. Metals tend to donate their electrons to other elements; nonmetals tend to accept electrons. There are currently about 109 elements in the periodic table, but the dental materials we use every day are comprised of only about 40 or so of these. Common examples in dental materials are oxygen (O), palladium (Pd), tin (Sn), titanium (Ti), aluminum (Al), silicon (Si), carbon (C), copper (Cu), and gold (Au).

## Bonds between Atoms

Atoms form various types of bonds with one another, and it is these bonds that, in large part, determine the physical and chemical properties of dental materials. It is the electrons of atoms and the configurations of atomic electron clouds that govern bonding between atoms. The electrons of the elements interact in several basic ways (Figure 0-3). In this introductory discussion, we will only touch upon the most basic types of bonds.

**! ALERT**

It is the electrons of atoms and the configurations of atomic electron clouds that govern bonding between atoms and ultimately the clinical behavior of restorative dental materials.

**Ionic bonds** are formed when an electron from one element is given completely to another in return for forming the bond (Figure 0-3, *upper diagram*). In dental materials, ionic bonds are often formed between electron-donating elements and oxygen. Ionic bonds are common in dental ceramics and are among the strongest type of bond. Ionic bonds also are very directional, tolerating little movement of the atoms that they bind. One unique aspect of an ionic bond is that it leaves the

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | H | | | | | | | | | | | | | | | | | He |
| 2 | Li | Be | | | | | | | | | | | B | C | N | O | F | Ne |
| 3 | Na | Mg | | | | | | | | | | | Al | Si | P | S | Cl | Ar |
| 4 | K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr |
| 5 | Rb | Sr | Y | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe |
| 6 | Cs | Ba | La | Hf | Ta | W | Re | Os | Ir | Pt | Au | Hg | Tl | Pb | Bi | Po | At | Rn |

**FIG 0-2** The periodic table of the elements is the tabulation of all elements in the known universe, currently numbering about 109 (not all are shown here). The rows of the table (called periods) determine the nature of the electron configuration of the elements; complex rules dictate the number of elements in each row or period. Each element has a two-letter symbol. For example, gold is "Au." The position of an element in the table is predictive of its electron configuration and its bonding, chemical behavior, and clinical properties. For example, metallic elements (those that tend to release some of their electrons) are generally situated toward the left of the table, whereas nonmetallic elements (those that tend to accept electrons) are toward the right. At the extreme right (column 18) sits the inert elements helium (He) through radon (Rn). These gases do not either release or accept electrons and are often referred to as the inert gases. Restorative dental materials are comprised of about 40 or so of elements, both metals and nonmetals.

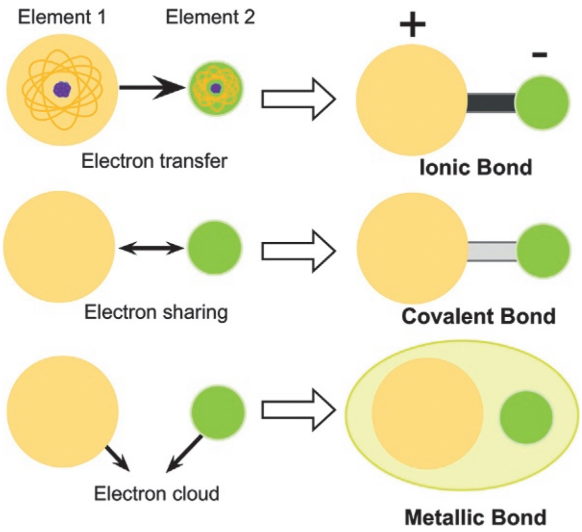

**FIG 0-3** Bonding between elements (atoms) is determined largely by the number and configuration of the electrons of the elements involved. If one element transfers an electron to another *(upper diagram)*, an ionic bond is formed and the donating element assumes a positive charge, with the recipient element becoming negatively charged. If the elements share electrons *(middle diagram)*, a covalent bond is formed with no net transfer of charge. If elements (two or more) donate electrons to an electron cloud *(lower diagram)*, a metallic bond is formed, with the electrons associated with the elements but belonging to neither. The types of bonds formed between atoms are a major determinant of the properties of different restorative dental materials.

donor of the electron positively charged and in a state we call "oxidized." The recipient of the electron becomes negatively charged and is said to be reduced. Furthermore, an atom can form multiple ionic bonds with other atoms; this allows the formation of arrays of atoms (see next sections).

**Covalent bonds** form when atoms share electrons to form a bond (Figure 0-3, *middle diagram*). Direct esthetic materials (Chapter 4) are in part the product of these types of bonds. Similar to ionic bonds, covalent bonds are relatively strong and directional; also atoms may form multiple covalent bonds with other atoms, similar to the atoms forming ionic bonds. But the palette of elements that form covalent bonds is much broader than that which forms ionic bonds. In addition, atoms linked by covalent bonds do not exchange or disrupt charge. Covalent bonds occur in a variety of subtypes not known with ionic bonds. It is these subtypes that give covalently bonded atoms a great diversity in properties, but the reader is referred to an organic chemistry text for more detail.

**Metallic bonds** result when electrons are shared among many atoms (Figure 0-3, *lower diagram*). In the metallic bond, all of the atoms of the material donate electrons to form a "community" electron cloud. The cloud provides a strong bond among the atoms, but unlike covalent and ionic bonds, metallic bonds are not as directional and the electrons in the cloud do not "belong" to any one atom in material. This attribute gives the material unique properties, which will be discussed in the next section.

There are a number of other types of bonds between atoms, but their discussion is beyond the scope of this introduction. Thus, the three most important and strongest bonds between atoms are ionic, covalent, and metallic bonds. It is important to understand that it is primarily the type and number of bonds among the atoms of a material that give it the properties we know and use for our clinical treatment. We will discuss this idea more in the next section.

**! ALERT**

The type of bonding among atoms in restorative dental materials largely determines their physical, chemical, and clinical properties.

## Molecules and Crystals

Atoms bond together into various larger-scale units. It is these larger units that make up dental materials. Two of the most basic and important larger-scale atomic arrangements are molecules and crystals.

**Molecules** are formed when several different elements bond together into a discrete unit, usually via covalent bonds (Figure 0-4). Molecules may contain only two atoms or many thousands, but they are a defined entity with definite spatial boundaries and a specific inventory of atoms (number and type) in each molecule. Therefore, we say that every molecule has a discrete, definable **molecular weight**, which is the sum of the mass of its component atoms. Molecules have other

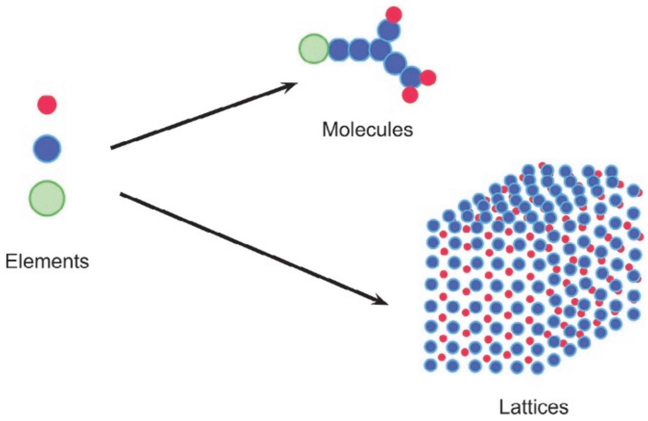

**FIG 0-4** Elements are arranged in fundamentally different ways that have profound effects on the properties of restorative dental materials. Elements may combine into discrete units called molecules; each molecule may contain from only two to over 100,000 atoms and one to a dozen types of elements. Molecules have a defined mass (the molecular weight) and a defined three-dimensional structure, and are generally bonded through covalent bonding. On the other hand, elements may combine to form crystalline lattices, which are vast repeating arrays of elements bonded to one another. Crystals generally contain fewer types of elements than molecules and have no defined boundaries or mass. The atoms in a crystal are generally bonded by ionic or metallic bonds and each element is generally bonded to several others around it.

unique properties that result from a specific three-dimensional structure and the nature of the covalent bonds between the elements. Molecules generally have no net charge. Dental composite resins are comprised partly of long molecular chains called polymers (see next section).

**Crystals** are vast repeating arrays of bonded elements (Figure 0-4). Generally, the arrays of atoms in a crystal involve fewer types of elements than in a molecule, but extend in all directions with a repeated pattern called a unit cell. Unlike molecules, crystalline arrays have no definitive spatial boundaries; the unit cell represents the repeating unit, not a discrete atomic structure. Thus, unlike molecules, crystals have no definable mass or "molecular weight".

Metallic bonds and ionic bonds are most common in crystalline arrays. There are a number of specific types of crystals, each involving differences in angles and lengths of bonds among the components of the crystal; however, a more specific definition is beyond the scope of this book. In dental materials, ceramics and alloys (discussed in the next section) commonly form crystals rather than molecules. Additionally, molecules often arrange themselves into crystalline arrays; in this latter case, the molecule itself is the unit cell of the crystalline array.

## BASIC TYPES OF DENTAL MATERIALS

Through covalent, metallic, or ionic bonding into either molecules or crystalline arrays, elements in the periodic table form the materials we use in restorative dentistry. There are three major classes of materials that result from these combinations of elements: **alloys**, **ceramics**, and **polymers** (Figure 0-5). **Composite** materials result when at least two of these three classes occur together in a material. We will discuss each of these in more detail.

### Metals and Alloys

**Metals** are comprised of elements that donate their electrons toward formation of metallic bonds (Figure 0-5). The metal atoms (e.g., copper) form a repeating crystalline array, held together by these metallic bonds. The metallic bonds and resulting electron cloud are in large part responsible for the properties we associate with metals such as ductility, strength, shininess, and conduction of heat or electricity. If the element in a metal has a high number in the periodic table (see Figure 0-2, large atomic number), then the metal will be dense and heavy, as with gold (atomic #79) for example. If the atomic number is lower, then the metal will be lighter and less dense, as with aluminum (atomic #13). One rather unique consequence of the metallic bond is the relative freedom that the atoms in the array have for movement. Because the electrons in the cloud do not belong to any particular atom in the array, movement of the atoms does not disrupt the integrity of the material. This freedom translates to the malleability and ductility of metals to which we are accustomed in everyday life. On the other hand, the tendency of the electron cloud to scatter light makes metals opaque.

When different elements bond together in the same metallic array, we refer to the material as an **alloy**. Alloys may be simple, containing only two elements in the array, or complex, containing over a dozen elements. The crystalline arrays may be simple or complex, forming various types of crystal unit cells that are beyond the scope of the discussion here. Alloys are prevalent in dental restorative materials (Figure 0-5) and are discussed in more detail in Chapters 5, 11, 12, and 15. Dental materials rely on the strength, ductility, conductivity, and hardness of metals and alloys to serve successfully in the oral cavity, particularly when missing teeth must be replaced. It is instructive to remember that all these properties relate back to the nature of the metallic bonds and shared electrons among the atoms in the alloy.

### Ceramics

**Ceramics** are a second major class of dental restorative material (Figure 0-5). Ceramics are collections of metallic elements, such as aluminum, and nonmetallic elements such as oxygen, held together by ionic bonds in crystalline arrays. The strong directional nature of the ionic bonds gives ceramics their strength, brittleness, rigidness, and relatively high melting temperatures. The lack of electron mobility in the ionic bonds gives ceramics their insulating properties. The repeating nature of the unit cell within the crystal allows visible light to be refracted predictably, giving ceramics their optical properties such as transparency or translucency. Similar to alloys, ceramics may be relatively simple, combining one metallic element with oxygen, or may be exceptionally complex, containing several different metallic elements and other nonmetals in addition to oxygen. Also similar to alloys, ceramic crystalline arrays can take on a variety of geometries and unit cells that are beyond the scope of this discussion.

Ceramics play major roles in the restoration of teeth. The optical properties of ceramics are especially useful for mimicking lost tooth structure; thus, ceramics are important to the esthetic aspects of dental restorations (see Chapter 14). However, the strength and hardness of ceramics allows them to play more subtle, if equally important, roles. Ceramics are used to abrade other materials (see Chapter 6), as containers for molten materials during casting or soldering (see Chapter 12), and as fillers to add strength to dental composites (see Chapter 4) and prosthodontic polymers (see Chapter 13). Ceramics play many other roles in dentistry (see Chapters 7 and 9) and are probably the most rapidly growing type of material used for dental restorations.

As with alloys, it is instructive to remember that the nature of the ionic bond between atoms is the fundamental basis for how ceramics behave and the way they are used in restorative dentistry.

**! ALERT**

Polymers are the most diverse class of restorative dental materials.

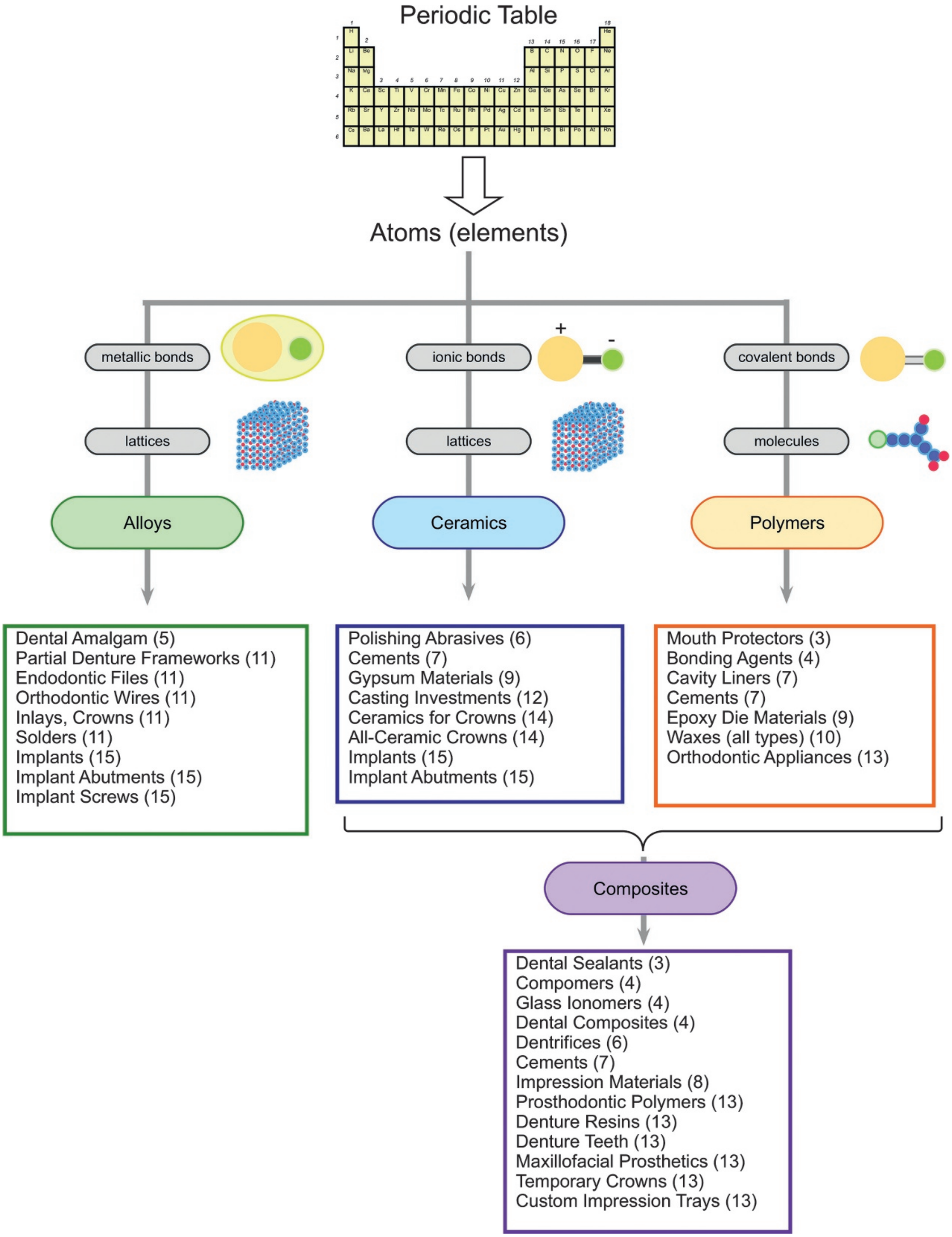

**FIG 0-5** Restorative dental materials may be divided into three major classes: alloys, ceramics, and polymers. Elements in alloys are bonded by metallic bonds into crystalline lattices, and these comprise all the metallic materials of restorative dentistry. In ceramics, ionic bonds form between metallic and nonmetallic elements into lattices; this arrangement is used by a wide variety of dental restorative materials. Polymers are organized into molecules via covalent bonds; molecules interact with each other to produce the diverse properties we see in common polymer restorative materials. Combinations of ceramics and polymers, called composite materials, are among the most familiar of dental restorative materials. The chapter reference to each material is shown parenthetically after the material.

## Polymers

**Polymers** are a third major type of material found in restorative dentistry (Figure 0-5). Polymers are the most diverse class of material because their unit structure is the molecule rather than the crystal. The rich variety of molecules that form via various types of covalent bonds and many possible elements create this diversity. In many polymers, each molecule may have thousands of component atoms, typically with repeating units within them; a molecular weight of a polymer molecule may commonly exceed 100,000. Yet each molecule is discrete, and it is the interactions between polymer molecules that give polymers many of the properties we know: flexibility, moldability, and elastomeric (rubber-like) properties. The ability of the long polymer chains to slide along one another or entangle in each other on an atomic scale translates into the properties we see on a local scale.

Yet, polymer molecules may also be tied together with other small polymers and other types of covalent bonds. In these "crosslinked" polymers, the properties are quite different: more rigid, less moldable, and much harder. Still other types of polymers contain more than one type of parent molecule or more than one type of cross linker. It is thus not hard to understand why this class of materials is so diverse. In spite of the variety of materials that are possible, all stem from the basic covalent bond between atoms and its strength and directionality.

In restorative dental materials, polymers are commonplace. They find use as preventative materials (see Chapter 3), in cements (see Chapter 7), as impression materials (see Chapter 8), and as waxes (see Chapter 10). Polymers also are the basis for many removable prosthodontic restorations such as dentures (see Chapter 13).

## Composite Materials

In addition to the diversity of materials possible among alloys, ceramics, and polymers, still more variety is possible when these classes of materials are combined. **Composite** materials result when classes of materials are mixed together. The most common examples in restorative dentistry are the direct esthetic materials (see Chapter 4) and prosthodontic polymers (see Chapter 13). We will discuss the former briefly here as an example.

In direct esthetic materials, polymers are combined with ceramics. Polymers are used for what is called the matrix of the material, providing the framework and holding the basic material form. In dentistry, these polymers are chemically formed in place ("*in situ*") in the tooth in a matter of seconds! The polymers also are able to bond to the enamel and dentin of the tooth. However, the polymers are not strong or hard enough to resist oral physical and chemical forces over time, and they lack appropriate esthetic properties. For this reason, ceramic particles are added to the polymer matrix, forming the composite material. Ceramics add hardness, and they define the color and optical properties of the material. Ceramic particles also limit the shrinkage of the polymer during its formation *in situ*. Although stronger and harder, the ceramic particles could not be used by themselves; they need the polymer to bind them together, and they cannot bond to the tooth structure by themselves. Furthermore, the ceramics could not be placed *in situ* because they require high temperatures to fuse them together. Thus, the composite material brings the positive attributes of each component material to the overall material. This "material synergy" is common among successful composites in restorative dentistry.

### QUICK REVIEW

It is truly remarkable how atoms can bond together in relatively few ways to form the diverse world of restorative dental materials. The consequences of how the electrons of each atom interact with others are far reaching. Through relatively few simple types of reactions among atoms, matter combines at an atomic level to give us a diverse palette of restorative materials that we often take for granted in the daily practice of dentistry. In this book, we will explore the nuances of that palette and the appropriate use and manipulation to achieve the best clinical outcomes. Yet, as we explore, it is always instructive to remind ourselves of what our materials are at the most fundamental level—simply a collection of bonded atoms.

### SELF-TEST QUESTIONS

*Test your knowledge by answering the following questions. For multiple-choice questions, one or more responses may be correct.*

1. If a material is formed from a specific number and ratio of atoms, it forms what type of structure?
   a. Crystal
   b. Lattice
   c. Crystalline lattice
   d. Metallic lattice
   e. Molecule
2. Ionic bonds involve a transfer of charge.
   a. True
   b. False
3. Polymers are generally formed by atoms that combine via:
   a. Ionic bonds
   b. Covalent bonds
   c. Metallic bonds
   d. All these types of bonds
4. Which structure does not have a charge?
   a. Proton
   b. Neutron
   c. Electron
5. Crystals have a molecular weight.
   a. True
   b. False

1

# Introduction to Restorative Dental Materials

## OBJECTIVES

*After reading this chapter, the student should be able to:*

1. Explain why restorative materials are used in dentistry and why they are important to the patient's total health.
2. Describe the major diseases that lead to tooth damage and how materials may help restore or prevent this damage.
3. Explain the differences between intracoronal and extracoronal restorations, which oral diseases create a need for each, and which restorative materials are used for each.
4. Describe the process of endodontic treatment, when it is needed, and what materials are used for this treatment.
5. Explain which restorative materials and types of restorations are commonly used to restore the function of missing teeth and the advantages and disadvantages of each type of restoration.
6. Describe the role of restorative materials in the prevention of oral disease and trauma.

Restorative dental materials are used to prevent or repair damage to teeth caused by oral disease or trauma. The restoration of damage caused by oral disease is critical to the well-being of every individual. Tooth damage, loss, or dysfunction contribute to malnutrition, speech disorders, and deterioration of the temporomandibular joint or alveolar bone, and may inflict significant pain. Furthermore, the teeth dominate an individual's facial appearance, and missing or damaged teeth often compromise social well-being and self-esteem. Emerging data support links between oral health and systemic diseases such as heart disease, diabetes, arthritis, and abnormal pregnancy. Restorative dental materials are among the tools used by the dental team to prevent disease and alleviate pain, inflammation, and infection caused by disease, thereby improving the patient's total health. The dental auxiliary plays an important role in the delivery of care to repair damage to teeth from oral disease and trauma.

**! ALERT**

Damage to teeth may occur from infectious disease, trauma, systemic disease, or congenital disease. The dental auxiliary plays an important role in the delivery of care to repair damaged teeth with restorative dental materials.

## DENTAL DISEASE AND RESTORATIVE MATERIALS

### Caries

In spite of tremendous strides in its prevention, **caries** remains a major global problem in all countries and leads to significant destruction of teeth, pain, systemic infection, and tooth loss (Figure 1-1).

**! ALERT**

Caries remains a problem in all countries, particularly in children. The health costs of tooth damage from caries are staggering.

Caries is caused by a bacterial **biofilm** commonly called plaque, which accumulates on teeth in areas where patients do not remove it (see Figure 1-1). A complex community of bacteria in the biofilm adheres to teeth and secretes acids and enzymes that dissolve the enamel, dentin, and cementum. Carious lesions occur on any tooth surface but are most common in areas where plaque accumulates unchecked—in the pits and fissures, along the gingiva, and interproximally. Caries also is a significant problem on the roots of the teeth of older individuals, where it rapidly destroys the softer cementum and dentin. As caries progresses over a period of months, more and more of the coronal tooth is destroyed, and the bacteria infect the pulp of the tooth and ultimately the periapical tissues as well. If left unchecked, an infection caused by caries can be fatal, but extraction of the tooth is a far more common outcome today. Dental restorative materials are used at every stage of the caries disease process to prevent or repair damage (discussed later).

### Periodontal Disease

Unlike caries, periodontal disease affects the tissues supporting the teeth, including the gingiva, periodontal ligament, cementum, and alveolar bone (Figure 1-2). Periodontal disease also is caused by a bacterial biofilm, although the strains of bacteria in the biofilm are different from those that cause caries, and the progression of the disease occurs over many years rather than months. Initially, toxins secreted by bacteria inflame the gingiva (gingivitis), but the hard tissues

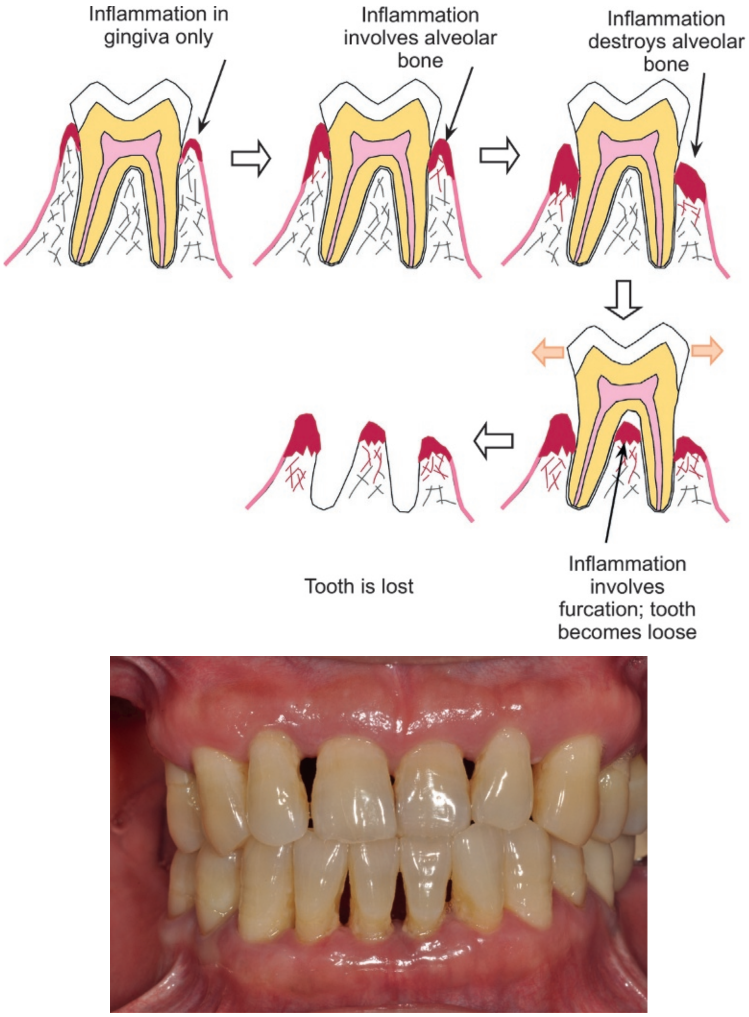

**FIG 1-2** Periodontal disease is a chronic bacterial infection of the bone and soft tissues that retain the tooth (the periodontium). Bacterial biofilms adhere to teeth near the gingival tissues. Bacterial toxins cause inflammation of the periodontal tissues, initially involving only the gingiva (gingivitis). With time, the infection and associated inflammation involve the crestal alveolar bone (periodontitis). Without treatment, the infection causes loss of alveolar bone that eventually involves the furcae and increases tooth mobility *(orange block arrows)*. At this point, the risk of tooth loss is high. Unlike caries, periodontal disease is nearly always painless, although some patients experience dentin sensitivity from exposure of the root surfaces *(photo)*. These exposed surfaces sometimes require restorative procedures to mitigate pain. Advanced periodontal disease increases the risk of root caries and pulpal infection, and it is thought to contribute to systemic inflammation, for example, in the endothelial lining of arteries. Other systemic diseases such as diabetes increase the risks of periodontal disease through high glucose levels in local tissues that trigger oxidative stress. A variety of restorative materials and strategies are used to replace teeth lost to periodontal disease. (Photo courtesy Kanako Nagatomo, private practice, Seattle, WA.)

a major role in repairing trauma-induced damage. Trauma may fracture only the enamel or dentin or may cause a fracture of the tooth that involves the pulp or alveolar bone. Teeth may be completely lost (avulsion) or displaced in any direction. Restorative materials are used to repair teeth, stabilize them until the supporting tissues heal, or replace them.

Systemic disease sometimes destroys teeth and oral tissues, and restorative materials are used to repair this damage. Cancer of the head and neck region may require that a large segment of the maxilla or mandible or associated oral structures be removed for the patient to survive. Dental prostheses restore function or esthetics for these unfortunate patients. Osteoporosis compromises the bony support for teeth, leading to edentulism and the need for major oral restoration. Diabetes accelerates and exacerbates periodontal disease. In older individuals, systemic disease often amplifies oral disease. For example, many older individuals experience decreased salivary production, which limits the body's oral immune response and promotes both caries and periodontal disease. Fluorosis, resulting from natural or iatrogenic excess ingestion of fluoride when the teeth are forming, disfigures and discolors tooth enamel and requires esthetic treatments or restoration. Gastric reflux of acids may lead to destruction of teeth by dissolving enamel.

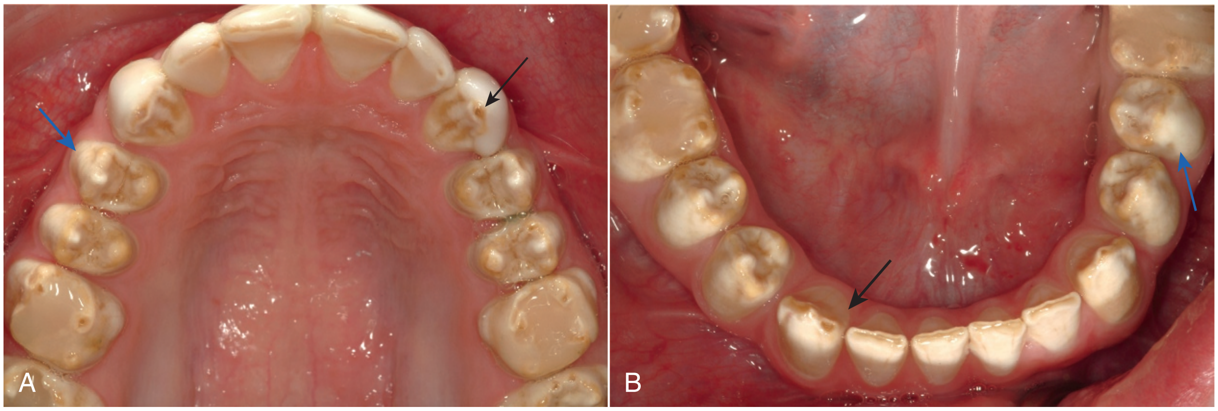

**FIG 1-3** A patient with the genetic condition of amelogenesis imperfecta. In this condition, teeth in both upper **(A)** and lower **(B)** arches are affected by a genetic mutation in the genes that synthesize tooth enamel. The enamel in affected teeth is relatively soft and has numerous malformations, including a mottled, chalky appearance *(blue arrows)* on some surfaces. Premature wear *(black arrows)* occurs, exposing the dentin below. Restorative materials play a substantial role in short-term and long-term treatments of patients like this as nearly every tooth will need reconstruction. (Courtesy Y-W Chen, University of Washington Department of Restorative Dentistry, Seattle, WA.)

Genetic disorders are another significant cause of oral disease that requires the use of restorative dental materials. In several genetic diseases, teeth may be congenitally missing. Other diseases, such as amelogenesis imperfecta (Figure 1-3) or dentinogenesis imperfecta, cause major loss of tooth structure from defective enamel, dentin, or the bonds between enamel and dentin. In these patients, nearly every tooth will require restoration.

## RESTORATION OF DAMAGED TEETH

Regardless of the source of damage, teeth are repaired using two basic types of restorations: intracoronal and extracoronal (Figure 1-4). If the damage to the tooth involves the pulpal or periapical tissues, then endodontic restorative treatments are used in addition to these restorations.

### Intracoronal Restorations

**Intracoronal restorations** are used to repair damage that is restricted to the internal parts of the tooth (see Figure 1-4). Damage of this nature is nearly always caused by caries but is occasionally caused by trauma. For intracoronal restorations, the tooth is first surgically prepared to receive the restoration, a process commonly referred to as cavity preparation (Figure 1-5). Cavity preparation removes diseased or damaged tissue and creates a space that is accessible for restoration and able to stably retain the restoration. Many complex factors govern the surgical cavity preparation, although a thorough discussion of the "principles of cavity preparation" is beyond the scope of this text. Cavity preparations may be restored (Figure 1-6) with materials such as resin composites (Chapter 4), amalgam (Chapter 5), cast alloys (Chapters 11 and 12), ceramics (Chapter 14), or less often by gold foil (Chapter 11).

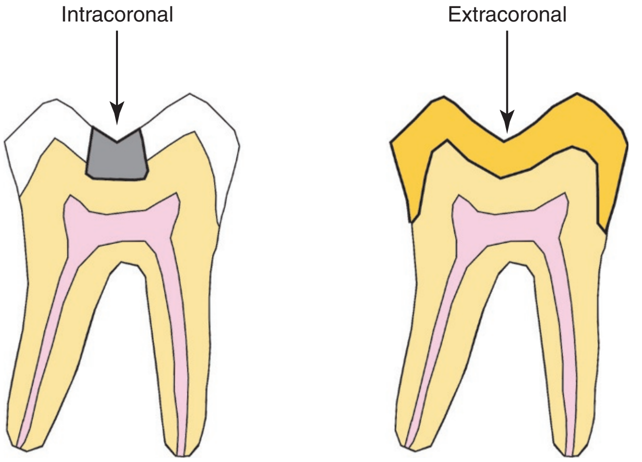

**FIG 1-4** Restorations to repair tooth damage are classified into two broad categories, each requiring different types of materials and different surgical strategies. Intracoronal restorations *(left)* are retained within the body of the tooth primarily by the remaining tooth structure. Extracoronal restorations *(right)* are retained by friction with at least part of the restoration made to fit around the exterior of the tooth. Extracoronal restorations are used when the destruction or loss of tooth structure is extensive. These two categories are not entirely mutually exclusive.

### Extracoronal Restorations

**! ALERT**

Extracoronal restorations are used to restore teeth with more extensive damage that cannot be managed with intracoronal restorations.

If damage to a tooth is extensive, then intracoronal restorations are not feasible and **extracoronal restorations** will be necessary

# 2

# Properties of Materials

## OBJECTIVES

*After reading this chapter, the student should be able to:*

1. Define dimensional change and linear coefficient of thermal expansion, and give examples of their importance to clinical dentistry.
2. Give examples of where thermal and electrical properties of restorative materials are important in clinical dentistry.
3. List examples of where solubility and water sorption are important in the success of dental restorative materials.
4. Describe when wettability of tooth structure or dental materials is important clinically.
5. Define stress and strain, and illustrate how they differ.
6. Describe how elastic modulus, proportional limit and yield strength, ultimate strength, and elongation and compression are important in the selection of dental materials, as well as compare the elastic moduli of dentin, enamel, composites, bonding agents, and the hybrid layer of the tooth–composite interface.
7. Describe how resilience and toughness differ from strength properties.
8. Rank the hardness of dentin and enamel with respect to common dental restorative materials, and explain why caution is warranted in the comparison of Knoop and nano-hardness values.
9. Describe why for certain materials a strain–time curve is more informative than a stress–strain curve.

An understanding of the physical, electrical, and mechanical properties of materials used in dentistry is of tremendous importance. First, materials used to replace missing portions of teeth are exposed to attack by the oral environment and subjected to biting forces. Second, the restorative materials are cleansed and polished by various prophylactic procedures. As a result, their properties are the basis for the selection of materials to be used in particular dental procedures and restorations. Clinical experience and research have related clinical success to certain properties of materials, which have been used as guides in the improvement of dental materials. Third, the establishment of critical physical properties for various types of dental materials has led to the development of minimum standards or specifications. The American National Standards Institute (ANSI) and the American Dental Association (ADA), in conjunction with the International Organization for Standardization (ISO) and federal organizations, have established more than 100 standards or specifications for dental materials and maintain lists of materials that satisfy the minimum standards of quality. This information is available from the ADA office in Chicago or on its website (www.ada.org) and is helpful for selecting materials for dental practice and ensuring the quality control of materials.

This chapter emphasizes the dimensional change, electrical properties, solubility and sorption, and mechanical properties of dental materials. Selection of materials should be influenced by their effect on the oral tissues and by possible toxic effects if ingested. The color and optical qualities of materials also are important in the selection of restorative materials.

## DIMENSIONAL CHANGE

**! ALERT**

*Dimensional change* is the percentage of shrinkage or expansion of a material.

Maintaining dimensions during dental procedures such as preparing impressions and models is important in the accuracy of dental restorations. Dimensional changes may occur during setting as a result of a chemical reaction, such as with elastomeric impression materials or resin composite restorative materials or from the cooling of wax patterns or gold restorations during fabrication. To compare materials easily, the **dimensional change** usually is expressed as a percentage of an original length or volume (see an example calculation in Appendix 2-1). Values for other elastomeric impression materials can be used to compare their accuracy.

Volumetric dimensional change is more difficult to measure and is not described here. The volumetric dimensional change is equal to three times the linear dimensional change for a specific material.

### Thermal Dimensional Change

Restorative dental materials are subjected to temperature changes in the mouth. These changes result in dimensional changes in the materials and to the neighboring tooth structure. Because the thermal expansion of the restorative material usually does not match that of the tooth structure, a differential expansion occurs that may result in leakage of oral fluids between the restoration and the tooth.

The linear thermal expansion of materials can be measured by determination of the difference in length of a specimen at two temperatures (see an example calculation in Appendix 2-1). To make a comparison between materials easier, the linear thermal expansion is expressed as a **coefficient of thermal expansion**. Typical values for selected restorative dental materials and human teeth are listed in Table 2-1.

**ALERT**

The linear thermal coefficient of expansion of a material is a measure of how much it expands per unit length if heated 1 degree higher.

The thermal coefficient of expansion is not uniform throughout the entire temperature range and is usually higher for liquids than for solids. The thermal coefficient of expansion for a solid, such as a dental wax, generally increases at some point as the temperature is increased. The linear rather than the volumetric coefficient of thermal expansion usually is reported.

The relationship between the coefficients of thermal expansion of human teeth and restorative materials is important, and Table 2-1 shows that the values for amalgam and composites are about three to five times those of human teeth. The values for unfilled polymers, however, are five to seven times those of teeth, with ceramic being ½ to ⅓ and gold alloys being approximately the same as for human teeth.

A clinical effect of this difference is as follows. If a tooth contained a poorly bonded composite restoration that was cooled by the drinking of a cold liquid, the restoration would contract more than the tooth, and small gaps would result at the junction between the two materials. Oral fluids can penetrate this space. When the temperature returns to normal, this fluid is forced out of the space. This phenomenon is called **percolation** and occurs with some restorative materials, depending on the relationship of the thermal coefficient of expansion of the material and human teeth and the extent of bonding. Percolation is thought to be undesirable because of the possible irritation to the dental pulp and recurrent decay. Dental amalgam is unusual in that percolation decreases with time after insertion, presumably as a result of the space being filled with corrosion products from the amalgam. If the aforementioned composite were bonded adequately to the tooth, the difference in thermal coefficient of expansion could result in stress at the interface, which could lead to failure of the bond over time.

**TABLE 2-1 Range of Linear Thermal Coefficient of Expansion of Dental Materials in the Temperature Range of 20° to 50°C**

| Material | Coefficient ($\times 10^6$/°C) |
|---|---|
| Human teeth | 8–15 |
| Ceramics | 8–14 |
| Glass ionomer base | 10–11 |
| Gold alloys | 12–15 |
| Dental amalgam | 22–28 |
| Composites | 25–68 |
| Unfilled acrylics and sealants | 70–100 |
| Inlay wax | 300–1000 |

## THERMAL CONDUCTIVITY

**ALERT**

Materials with high thermal conductivity values are good conductors of heat and cold.

Qualitatively, materials have different rates of conducting heat; metals have higher values than polymers and ceramics. When a portion of a tooth is replaced by a metal restoration such as amalgam or gold alloy, the tooth may be temporarily sensitive to temperature changes in the mouth. Individuals who wear orthodontic appliances or complete acrylic dentures also notice temperature effects different from those experienced without these appliances.

**Thermal conductivity** has been used as a measure of the heat transferred and is related to the rate of heat flow (see more details in Appendix 2-1). The thermal conductivity of a variety of materials is reported in Table 2-2.

Human enamel and dentin are poor thermal conductors compared with gold alloys and dental amalgam; although amalgam is substantially lower than gold. Glass ionomer cement bases closely replace lost tooth structure with respect to thermal conductivity. The reason for using cements as thermal insulating bases in deep cavity preparations is that, although dentin is a poor thermal conductor, a thin layer of it does not provide enough thermal insulation for the pulp unless a cement base is used under the metal restoration. Composite restorations have thermal conductivities comparable to tooth structure and do not present a problem with this property. Cavity varnishes and liners have low thermal conductivities but are used in layers so thin that they are ineffective as thermal insulators.

**TABLE 2-2 Thermal Conductivity of Dental Materials**

| Material | Thermal conductivity (cal/sec/cm$^2$[°C/cm]) |
|---|---|
| Unfilled acrylics | 0.0005 |
| Zinc oxide–eugenol cement | 0.0011 |
| Human dentin | 0.0015 |
| Human enamel | 0.0022 |
| Composites | 0.0025 |
| Ceramic | 0.0025 |
| Zinc phosphate cement | 0.0028 |
| Dental amalgam | 0.055 |
| Gold alloys | 0.710 |

## ELECTRICAL PROPERTIES

**! ALERT**

*Galvanism* is the generation of electrical currents that the patient can feel.

Two electrical properties of interest are **galvanism** and **corrosion**. Galvanism results from the presence of dissimilar metals in the mouth. Metals placed in an electrolyte (a liquid that contains ions) have various tendencies to go into solution. Aluminum, alloys of which are sometimes used as temporary crowns, has a strong tendency to go into solution and has an electrode potential of +1.33 volts. Gold, on the other hand, has little tendency to go into solution, as indicated by an electrode potential of −1.36 volts. A schematic sketch of two opposing teeth, one with a temporary aluminum alloy crown and the other with a gold crown, is shown in Figure 2-1. The oral fluids function as the electrolyte, and the system is similar to that of an electrical cell. When the two restorations touch, current flows because the potential difference is 2.69 volts, and the patient experiences pain and frequently complains of a metallic taste. The same effect can be experienced if some aluminum foil from a baked potato becomes wedged between two teeth and contacts a gold restoration. Temporary polymer crowns are used to prevent this problem because they are poor electrical conductors.

**! ALERT**

*Corrosion* is the dissolution of metals in the mouth.

**! ALERT**

*Tarnish* is a surface reaction of metals in the mouth from components in saliva or foods.

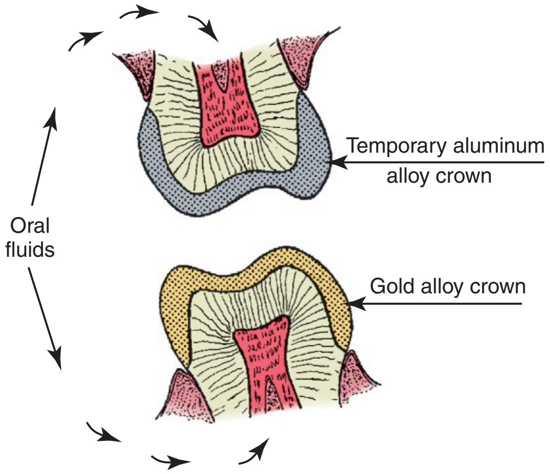

**FIG 2-1** Diagrammatic sketch of opposing teeth with a gold crown and a temporary aluminum alloy crown indicating how galvanism can occur.

Corrosion also can result from this same condition when adjacent restorations are of dissimilar metals. As a result of the galvanic action, material goes into solution, and roughness and pitting occur. This effect also may occur if a gold alloy is contaminated with a metal such as iron during handling in the dental laboratory or because of variations in concentration of elements from one part of the restoration to another. Corrosion also may result from chemical attack of metals by components in food or saliva. Dental amalgam, for example, reacts with sulfides and chlorides in the mouth, as shown by polished amalgams becoming dull and discolored with time. This effect sometimes is referred to as **tarnish**.

## SOLUBILITY AND SORPTION

The solubility of materials in the mouth and the **sorption** (adsorption plus absorption) of oral fluids by the material are important criteria in their selection. Frequently, laboratory studies have evaluated materials in distilled water. At times, these studies gave results that were inconsistent with clinical observations, because materials in the mouth are covered with plaque and therefore are exposed to various acids and organic materials. An example of the inconsistency is that zinc phosphate cements are considerably more soluble in the mouth than in laboratory tests in water indicate. Also, the loss of zinc phosphate cement retaining a gold crown is a result of dissolution followed by and accompanied by disintegration. Nevertheless, laboratory tests usually rank materials correctly, so only the actual magnitude of the numbers should be taken with a grain of salt.

Solubility and sorption are reported in two ways: (1) in weight percentage of soluble or sorbed material and (2) as the weight of dissolved or sorbed material per unit of surface area (e.g., milligrams per $cm^2$).

*Absorption* refers to the uptake of liquid by the bulk solid; for example, the equilibrium absorption of water by acrylic polymers is in the range of 2%. *Adsorption* indicates the concentration of molecules at the surface of a solid or liquid, an example of which is the adsorption of components of saliva at the surface of tooth structure or of a detergent adsorbed on the surface of a wax pattern.

## WETTABILITY

**! ALERT**

*Wettability* is a measure of the affinity of a liquid for a solid as indicated by spreading of a drop.

The **wettability** of solids by liquids is important in dentistry; for example, the wetting of denture base acrylics by saliva, the wetting of tooth enamel by pit and fissure sealants, the wetting of elastomeric impressions by water mixes of gypsum materials, and the wetting of wax patterns by dental investments.

The wettability of a solid by a liquid can be observed by the shape of a drop of the liquid on the solid surface. Profiles of

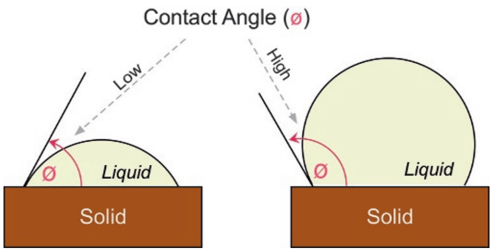

**FIG 2-2** Good wetting of a solid by a liquid with a low contact angle *(left)*; poor wetting by a liquid on a solid forming a high contact angle *(right)*.

drops of liquids on solids are shown in Figure 2-2. The shape of the drops is identified by the contact angle θ, by the angles through the drops bounded by the solid surface, and by a line through the periphery of the drop and tangent to the surface of the liquid.

If a low contact angle occurs, as in the left of Figure 2-2, the solid is wetted readily by the liquid (**hydrophilic** if the liquid is water). If a contact angle is greater than 90°, as in the right of Figure 2-2, poor wetting occurs (**hydrophobic** if the liquid is water).

The degree of wetting depends on the relative surface energies of the solids and the liquids and on their intermolecular attraction. High-energy solids and low-energy liquids encourage good wetting; thus, liquids generally wet higher energy solids well (e.g., water on metals and oxides). On the other hand, liquids bead up on lower-energy solids such as wax, Teflon, and many polymers. The high contact angle of water on these solids can be decreased by adding a wetting agent such as a detergent to the water, thus lowering the surface tension or energy.

## MECHANICAL PROPERTIES

Knowledge of the magnitude of biting forces is essential in understanding the importance of the mechanical properties of dental materials. Maximum biting forces decrease from the molar to the incisor region, and the average biting forces on the first and second molars are about 580 **Newtons** (N), whereas the average forces on bicuspids, cuspids, and incisors are about 310, 220, and 180 N, respectively. To convert Newtons to pounds, Newtons are divided by 4.45.

Patients exert lower biting forces on bridges and dentures than on their normal dentition. For example, when a first molar is replaced by a fixed bridge, the biting force on the restored side is approximately 220 N compared with 580 N when the patient has natural dentition. The average biting force on partial and complete dentures has been measured to be about 111 N; therefore, patients with dentures can apply only approximately 19% of the force of those with normal dentition.

### Stress

**! ALERT**

*Stress* is the force per unit area.

When a force is applied to a material, the material inherently resists the external force. The force is distributed over an area, and the ratio of the force to the area is called the **stress** (see more details in Appendix 2-1).

Thus, for a given force, the smaller the area over which it is applied, the larger the value of the stress. Figure 2-3 illustrates this effect. A distributed force has been applied in Figure 2-3, *A*, and the same force has been applied in a concentrated manner in Figure 2-3, *B*. The number of lines (fringes) in the plastic model of a tooth when examined in polarized light is directly proportional to the stress, and the stress is shown to be inversely proportional to the area of application. This effect can be demonstrated as follows: an unsharpened pencil is placed against the palm of the hand, a force is applied by placing a book on the end with the eraser, and any pain is noted. Then the pencil is sharpened, the procedure is repeated, and the increase in pain is noted as a result of the increase in stress.

The relationship of force, area, and stress is shown also in Table 2-3. A force of 111 N, which can readily be applied in the mouth, can produce a large stress, such as 172 megapascals (or MPa), when the area of application of the force is

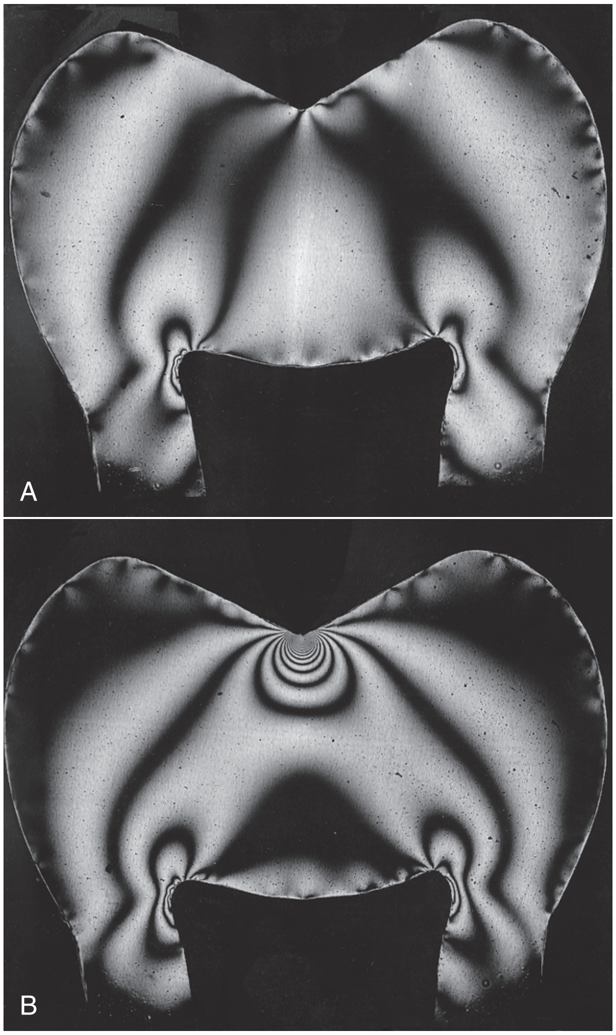

**FIG 2-3** Cross-sectional model of a tooth under distributed force **(A)** and concentrated force **(B).**

### TABLE 2-3 Relationship of Force, Area, and Stress

| Force (N) | Area (mm$^2$) | Stress (MPa) |
|---|---|---|
| 111 | 645 | 0.1724 |
| 111 | 64.5 | 1.724 |
| 111 | 6.45 | 17.24 |
| 111 | 0.645 | 172.4 |
| 111 | 0.0645 | 1724.0 |

small. One megapascal equals approximately 145 lbs/in$^2$. Such conditions readily exist in the mouth, where contact areas of 0.6 mm$^2$ frequently occur.

Several types of stress may result when a force is applied to a material. These **forces** are referred to as **compressive, tensile, shear, twisting moment,** and **bending moment (flexure)** and are shown diagrammatically in Figure 2-4. A material is subjected to compressive stress when the material is squeezed together, or compressed, and to tensile stress when pulled apart. Shear stress occurs when one portion (plane) of the material is forced to slide by another portion. These types of stresses are considered to evaluate the properties of various materials.

## Strain

**! ALERT**

*Strain* is the change in length per unit length of a material produced by stress.

The change in length or deformation per unit length when a material is subjected to a force is defined as **strain**. Strain is easier to visualize than stress because it can be observed directly (see an example calculation in Appendix 2-1). The units of strain are dimensionless. Some dental substances, such as elastomeric impression materials, exhibit considerable strain when a stress is applied; others, such as gold alloys or human enamel, show low strain under stress.

## Stress–Strain Curves

A convenient means of comparing the mechanical properties of materials is to apply various forces to a material and to determine the corresponding values of stress and strain. A plot of the corresponding values of stress and strain is referred to as a stress–strain curve. Such a curve may be obtained in compression, tension, or shear. An example of a stress–strain curve in tension for a dental gold alloy is shown in Figure 2-5. The shape and magnitude of the stress–strain curve are important in the selection of dental materials. Figure 2-5 clearly shows that the curve is a straight line, or linear, up to a stress of about 276 MPa, after which it is concave toward the strain axis. The curve ends at a stress of 590 MPa and a strain of 0.2 because the sample ruptured.

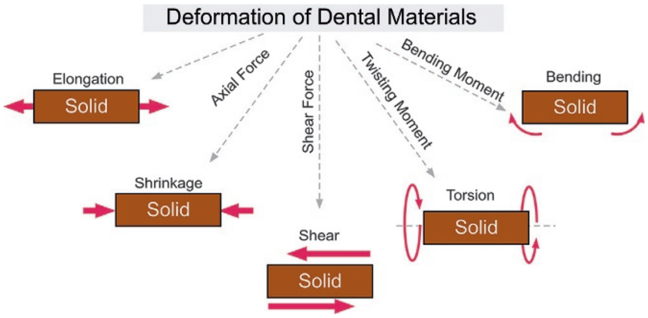

**FIG 2-4** Schematic representation of tensile, compressive, shear, twisting, and bending forces and their corresponding deformations.

## Elastic Modulus

The **elastic modulus** is equal to the ratio of the stress to the strain in the linear or elastic portion of the stress–strain curve (see an example calculation in Appendix 2-1). The elastic modulus is a measure of the stiffness of a material, and high numbers are not unusual for this property. Values for selected materials are listed in Table 2-4, which shows that gold alloys

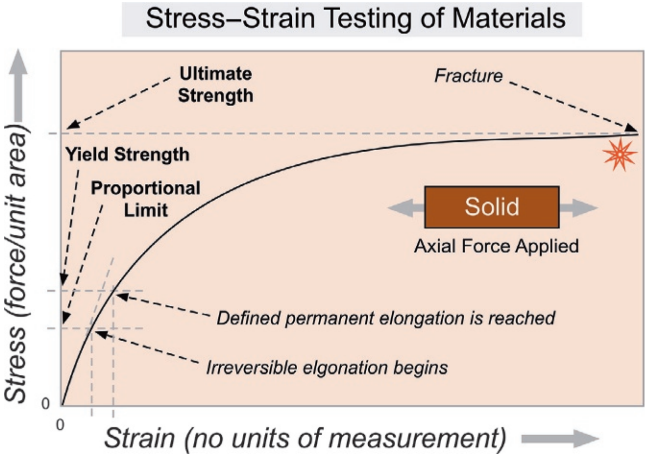

**FIG 2-5** Stress–strain curve in tension for dental gold alloy with fracture point at asterisk (*).

### TABLE 2-4 Elastic Moduli of Selected Dental Materials

| Material | Elastic modulus (GPa)* |
|---|---|
| Silicone impression material | 0.00015–0.001 |
| Unfilled acrylic | 2.8 |
| Zinc oxide–eugenol cement | 2.8 |
| Adhesive resin layer | 3.5–4.8 |
| Zinc polyacrylate cement | 3.9 |
| Glass ionomer cement | 5.5 |
| Low-viscosity resin | 5.8 |
| Hybrid layer (composite/tooth) | 8.0–9.0 |
| Human dentin partially demineralized | 13.0 |
| Zinc phosphate cement | 13.8 |
| Composite | 16.6 |
| Human dentin | 19.3 |
| Dental amalgam | 27.6 |
| Human enamel | 90.0 |
| Gold alloy | 96.6 |

*1 GPa = 1000 MPa.

have approximately the same stiffness as human enamel and that composites and zinc phosphate cement are in the same range as human dentin. Unfilled acrylics are much more flexible, with silicone impression material being the most flexible. Stiffness is important in the selection of restorative materials. Because large deflections under stress are not desired, low values are needed for elastic impression materials so that they can be readily removed from the mouth.

## Proportional Limit and Yield Strength

**! ALERT**

Proportional limit and yield strength are measures of the stress allowed before permanent deformation.

Proportional limit and yield strength indicate the stress at which the material no longer functions as an elastic solid. The strain recovers below these values if the stress is removed, and permanent deformation of the material occurs above these values. The **proportional limit** is the stress on the stress–strain curve when it ceases to be linear or when the ratio of the stress to the strain is no longer proportional. The **yield strength** is the stress at some arbitrarily selected value of permanent strain, such as 0.001, and thus is always slightly higher than the proportional limit. For example, the proportional limit for the gold alloy in Figure 2-5 is 276 MPa, and the yield strength is 324 MPa. These values indicate that stresses in excess of 276 to 324 MPa in the gold alloy result in permanent deformation after the applied force has been removed.

These two properties are particularly important because a restoration can be classified as a clinical failure when a significant amount of permanent deformation takes place even though the material does not fracture. Materials are said to be elastic in their function below the proportional limit or yield strength and to function in a plastic manner above these stresses.

Typical yield strength values for a variety of materials are listed in Table 2-5, which shows that unfilled acrylic polymers deform permanently at a considerably lower stress than composites, but that both have much lower values than human enamel. It might seem that none of these materials would deform permanently with such high numbers for the yield strength, except that, as shown in the section on stress, biting forces can produce stresses readily that could exceed the yield strength.

**TABLE 2-5 Yield Strength of Selected Dental Materials**

| Material | Yield strength (MPa) |
|---|---|
| Unfilled acrylics | 43–55* |
| Composites | 138–172* |
| Human dentin | 165* |
| Gold alloys | 207–620† |
| Human enamel | 344* |

*Yield strength in compression.
†Yield strength in tension.

## Ultimate Strength

**! ALERT**

The stress at which fracture occurs is called the *ultimate strength*.

If higher and higher forces are applied to a material, a stress eventually will be reached when the material fractures or ruptures. This point on the stress–strain curve, the **ultimate strength**, is denoted with an asterisk in Figure 2-5. If the fracture occurs from tensile stress, the property is called the **tensile strength**; if in compression, the **compressive strength**; and if in shear, the **shear strength**. As Figure 2-5 shows, the tensile strength of the gold alloy was 590 MPa.

The tensile and compressive strength of a material may be significantly different, as illustrated in Table 2-6. Brittle materials, such as human enamel, amalgam, and composites, have large differences and are stronger in compression than in tension.

Limited data are available on the shear strength of dental materials. The shear strength of composites is from 55 to 69 MPa and is about 41 MPa for unfilled acrylics; these values are only slightly higher than and are comparable to the corresponding tensile strengths.

The bond between two materials is usually measured in tension or in shear and is expressed as the stress necessary to cause rupture of the bond. Depending on the system, the bond may be chemical, mechanical, or a combination of the two types. The bond between acrylic denture teeth and acrylic denture bases is essentially chemical and is frequently greater than 34 MPa measured in tension. On the other hand, the bond between composites and acid-etched tooth enamel is essentially mechanical and has a value of approximately 20 to 30 MPa in tension. Adhesives are also available for bonding composites to dentin with reported bond strengths of 15 to 35 MPa. These bonds have been shown to result from the diffusion of the bonding agent into the surface layer of etched dentin.

**TABLE 2-6 Ultimate Strength of Selected Dental Materials**

| Material | Tensile strength (MPa) | Compressive strength (MPa) |
|---|---|---|
| Human enamel | 10 | 400 |
| Unfilled acrylics | 28 | 97 |
| Composites | 34–62 | 200–345 |
| Ceramic (feldspathic) | 40 | 150 |
| Dental amalgam | 48–69 | 310–483 |
| Human dentin | 98 | 297 |
| Gold alloys | 414–828 | – |

## Elongation and Compression

**ALERT**

The amount of deformation that a material can withstand before rupture is reported as the percent elongation when the material is under tensile stress or the percent compression when it is under compressive stress.

The percent elongation at rupture of the gold alloy shown in Figure 2-5 can be determined readily from the strain at rupture simply by multiplying the strain (deformation per unit length) by 100 to convert it to **percent elongation**. In the example in Figure 2-5, the percent elongation is 20% (see an example calculation in Appendix 2-1). Similar calculations can be made for materials in compression and would represent the percent of plastic strain at rupture.

The percents of elongation and compression are important properties in that they are measures of **ductility** and **malleability**, respectively. These two properties indicate the amount of plastic strain, or deformation, that can occur before the material fractures, and, as such, they indicate the brittleness of the material. For example, the gold alloy with 19% elongation can be deformed considerably before fracture, and it would be classed as a ductile alloy. Considerable burnishing and adaptation of the margins of castings from this alloy could be done without fear of fracturing the margin. In general, gold alloys with elongations of less than 5% are considered brittle, and those with values higher than 5% are classed as ductile materials.

Composites are considered brittle materials because the percentage of compression at failure is in the range of 2% to 3%. Clinical observation has been that these materials fail under excessive stress as a result of brittle fracture.

## Resilience and Toughness

Up to this point, properties related only to stress or strain have been discussed. Two properties involve the area under the stress–strain curve and thus involve the energy required to reach specified points on the curve.

**ALERT**

*Resilience* and *toughness* indicate the energy absorbed up to the proportional limit and the ultimate strength, respectively, and relate to the resistance to deformation and fracture under impact.

The energy required to deform a material permanently is a criterion of its **resilience**, whereas the energy necessary to fracture a material is a measure of its **toughness**. These areas are shown as shaded portions of the stress–strain curves in Figure 2-6.

These two properties are more complex than strength or deformation, because their magnitude is a product of stress and strain. Two materials may have the same resilience, with one having high yield strength and low corresponding strain and the other having lower yield strength and higher corresponding strain. Two such materials are composites and unfilled acrylics, both of which have a resilience of approximately 7 cm-kg/cm$^3$, despite considerable differences in yield strength. Toughness also is not a simple quantity; for example, although composites have considerably higher yield strengths than unfilled acrylics, the latter may be deformed so much more before rupture that they are tougher than composites (Figure 2-7).

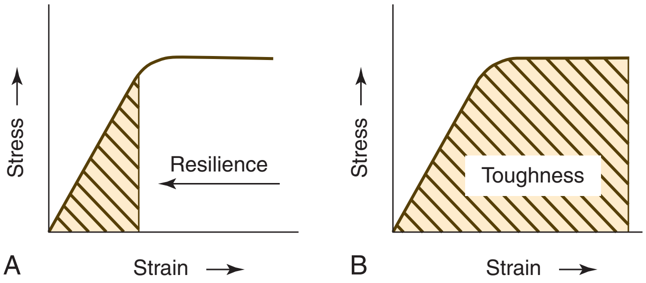

**FIG 2-6** Stress–strain curves illustrating the areas that give a measure of the resilience **(A)** and toughness **(B).**

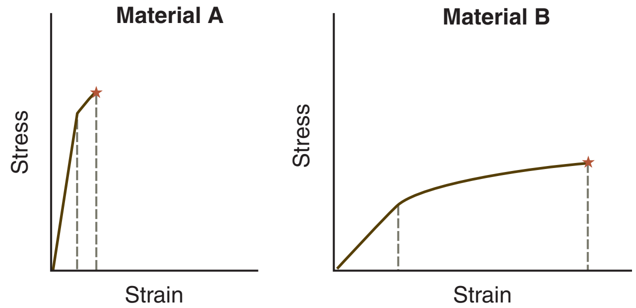

**FIG 2-7** Stress–strain curves for composite (material A) and unfilled acrylic (material B). The two materials have approximately the same resilience, but material B is considerably tougher.

## Hardness

**ALERT**

*Hardness* is the resistance of a material to indentation.

A material is considered hard if it strongly resists indentation by a hard material such as diamond. One would expect that hardness would be related to yield strength and wear resistance; however, the property is complex. In general, no direct relationship exists between hardness and these two properties. The only exception is in the comparison of materials of the same type, such as a series of similar gold alloys.

The hardness of dental materials generally is reported in **Knoop hardness**. The Knoop hardness is obtained by measurement of the length of the long diagonal of an indentation from a diamond indenter and calculating the number of kilograms required to give an indentation of 1 mm$^2$; thus, the larger the indentation, the smaller the hardness value. An example of indentations in dentin and cementum is shown in Figure 2-8; the larger indentations are in cementum,

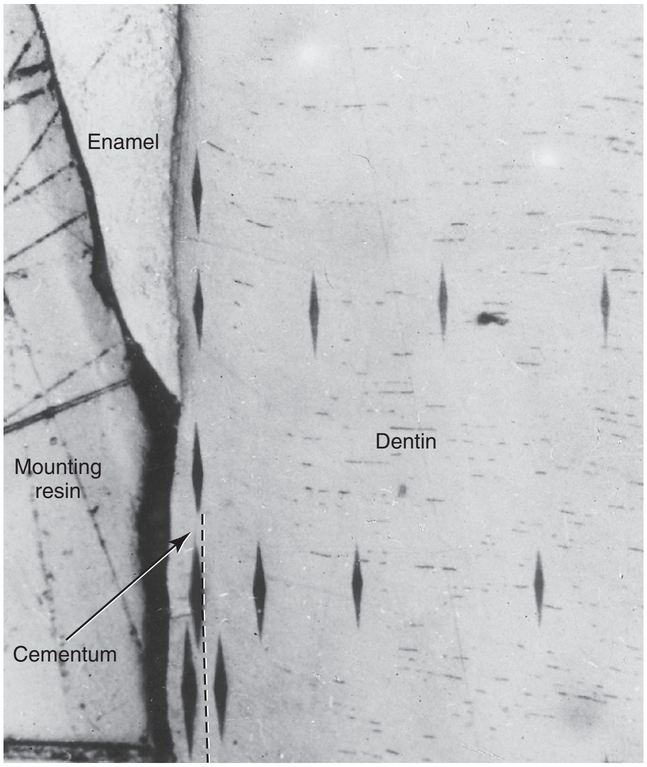

**FIG 2-8** Knoop hardness indentations in dentin and cementum. Longer indentations are in cementum, indicating lower hardness than for dentin.

and the smaller are in dentin. Examples of Knoop hardness values of various materials are listed in Table 2-7. Enamel and ceramic are two of the hardest materials, and unfilled acrylic is the softest of the materials listed.

The Knoop hardness is a satisfactory method for evaluating many restorative materials. Although the indentations are small, they are not small enough to evaluate the hardness of the resin–dentin bonding region of dental composites. Studies of the hardness of this region have used a nano-indentation method. The nano-indentation technique measures much smaller indentations under small loads and allows the hardness of extremely small areas to be determined. However, the nano-indentation values cannot be directly compared with Knoop values, because the Knoop hardness is calculated from the permanent surface deformation after removal of the load and the nano-indentation hardness values are calculated from the penetration while under load. This difference can be seen in the values for enamel and dentin listed in Table 2-7. In spite of this difference, the two methods rank materials in the same order. An additional advantage of the nano-indentation method is that it allows the calculation of the elastic modulus.

## Strain–Time Curves

For materials in which the strain is independent of the length of time that a load is applied, stress–strain curves are important. However, for materials in which the strain is dependent on the time the load is maintained, strain–time curves are more useful than stress–strain curves in explaining their properties. Examples of materials that have strain–time-dependent behavior are alginate and elastomeric impression materials, dental amalgam, and human dentin.

A strain–time curve for an elastomeric impression material is shown in Figure 2-9. A compressive load was applied at $t_0$, and an initial rapid increase in strain occurred from O to A. The load was maintained until $t_1$, with the strain gradually increasing from A to B; this increase resulted from a combination of viscoelastic strain (time dependent but recoverable) and viscous flow (time dependent and not recoverable). The load was removed at $t_1$, which resulted in a rapid decrease in strain from B to C. This recovery took place because of the release of elastic strain. A continued gradual decrease in strain occurred from C to D as a result of the recovery of the viscoelastic strain. At $t_2$, no further decrease in strain took place, and a permanent strain remained, the magnitude of which is represented by DE.

If the load had been applied for a longer time than $t_1$ or the magnitude of the load had been greater, the amount of permanent strain would have been more. Clinically, this means the shorter the time and the less force applied to the

**TABLE 2-7 Hardness of Selected Dental Surfaces**

| Material | Knoop hardness (kg/mm$^2$) | Knoop hardness (GPa) | Nano-indentation hardness (GPa) |
|---|---|---|---|
| Unfilled acrylic resin | 20 | 0.20 | |
| Zinc phosphate cement | 40 | 0.39 | |
| Human cementum | 43 | 0.42 | |
| Human dentin | 68 | 0.67 | 0.49* |
| 22-Karat gold alloy | 85 | 0.83 | |
| Dental amalgam | 110 | 1.08 | |
| Human enamel | 343 | 3.36 | 3.39* |
| Ceramic | 460 | 4.51 | |
| Adhesive resin | | | 0.10* |
| Hybrid layer (composite/tooth) | | | 0.15–0.19* |
| Microfilled low-viscosity resin | | | 0.19* |
| Fillers in composites | | | 2.9–8.8* |

*Values determined by nano-indentation are not directly comparable to Knoop hardness values.

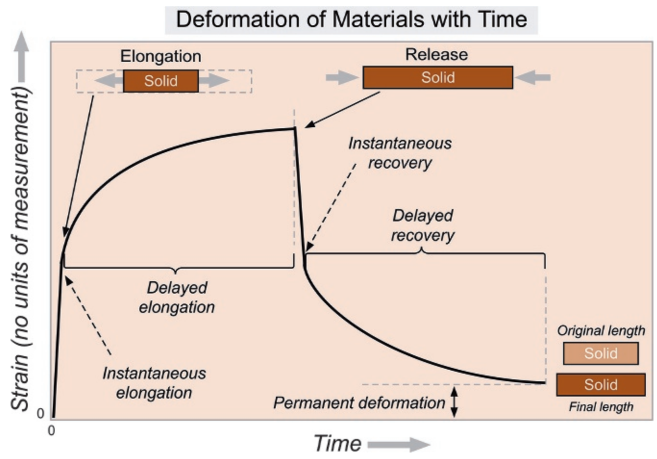

**FIG 2-9** Strain–time curve for elastomeric impression material.

impression material, the lower the permanent strain and the more accurate the impression.

The strengths of such materials are also dependent on the rate of application of the load. Higher tensile strengths result at more rapid rates of applying the load. As a result, it is recommended that alginate impressions be removed from the mouth in a rapid motion.

Dental amalgam is stronger the more rapidly the force is applied. However, values for the compressive strength obtained at low rates of load application have been shown to correlate better with rankings of clinical service than higher rates of loading. As a result, the testing of amalgam usually is conducted at low rates of application of force.

## Dynamic Properties

The properties described so far are classified as static properties because of the relatively slow rate of application of the load. The properties at extremely high rates of loading, such as from an impact, are also important in dentistry. They are classified as dynamic properties and are important in the evaluation of materials such as athletic mouth protectors.

Properties of particular importance are the dynamic modulus and dynamic resilience. The dynamic modulus is a measure of the stiffness of the material at a high rate of strain and is important for mouth protector materials for which the mechanical properties are strain–rate dependent. The dynamic resilience measures the energy absorbed at high rates of strain such as from a blow to an athletic mouth protector.

### QUICK REVIEW

The properties of materials are major criteria for the performance of dental materials in service. Dimensional stability is an important property requirement of impression and restorative materials. Thermal conductivity is important as a measure of how much heat and cold are transmitted to pulpal and soft tissues under restorations. Electrical properties are important in terms of galvanic currents generated by dissimilar metals and the discomfort they cause patients. Solubility is especially important in regard to cements that hold restorations in place. Wetting of dental materials by liquids is important in the processing of dental materials and in their relation to saliva in the mouth. Hardness is a measure of the resistance of a material to indentation and scratching. Elastic modulus indicates the stiffness of a material, yield strength the stress it can withstand before permanent deformation, ultimate strength the stress required to fracture a material, and elongation its ductility. Toughness measures the energy needed to fracture a material, and it is important for materials such as denture resins to withstand the shock of being accidentally dropped without breaking.

### SELF-TEST QUESTIONS

*In the following multiple-choice questions, one or more of the responses may be correct.*

1. Which of the following statements describe(s) the purpose of the American National Standards Institute and the American Dental Association specifications?
   a. The specifications measure clinical properties of materials to establish minimum standards.
   b. The specifications measure critical physical and mechanical properties of materials to establish minimum standards.
   c. Knowledge of materials that meet minimum requirements ensures clinical success.
   d. Knowledge of materials that meet minimum requirements ensures quality control and is helpful in the selection of materials for dental practice.
2. An impression of the vertical dimension of a cavity preparation 8 mm in length shows a linear contraction of 0.5%. Compute the actual dimensional change in micrometers (µm).
   a. −4 µm
   b. −40 µm
   c. +40 µm
   d. +0.04 µm
3. A pattern 8 mm in length made from a wax with a linear coefficient of thermal expansion of $380 \times 10^{-6}$/°C cools from 37° to 22° C. Compute the actual dimensional change in micrometers (µm).
   a. −45.6 µm
   b. −0.0456 µm
   c. −4.56 µm
   d. +4.56 µm
4. Rank the following dental materials in order of increasing values of their coefficient of thermal expansion: dental amalgam, human teeth, ceramic, and unfilled acrylics.
   a. Human teeth, ceramic, dental amalgam, and unfilled acrylic
   b. Ceramic, human teeth, unfilled acrylic, and dental amalgam
   c. Ceramic, human teeth, dental amalgam, and unfilled acrylic
   d. Human teeth, ceramic, unfilled acrylic, and dental amalgam
5. Which of the following statements describe(s) percolation?
   a. Percolation usually decreases with time after insertion of dental amalgam.
   b. Percolation is caused by differences in the coefficient of thermal expansion between the tooth and the restorative material when heated or cooled.

c. Percolation is thought to be undesirable because of possible irritation to the dental pulp and recurrent decay.
d. Percolation is not likely to occur with unfilled acrylic restorations.

6. Which of the following restorative materials has/have values of thermal conductivity similar to human enamel and dentin?
   a. Dental amalgam
   b. Composites
   c. Zinc phosphate cements
   d. Gold alloys
7. Which of the following is/are examples of galvanism in restorative dentistry?
   a. Aluminum foil from a baked potato becomes wedged between two teeth and contacts a gold restoration.
   b. A temporary acrylic crown contacts a gold restoration.
   c. A temporary aluminum crown contacts a gold restoration.
   d. Patient complains of a metallic taste.
8. Which of the following conditions could lead to corrosion in restorative dentistry?
   a. A gold alloy contaminated with iron during handling in the dental laboratory
   b. A chemical attack of a metal by components in food or saliva
   c. Polished amalgams that have become dull and discolored with time
   d. Adjacent restorations constructed of dissimilar metals
9. The contact angle of water on a dental wax is 105°. Which of the following terms describe(s) the wettability of the wax?
   a. Hydrophobic
   b. Hydrophilic
   c. Hydroscopic
   d. Hygroscopic
10. Which of the following factors increase(s) the wetting of a solid by a liquid?
   a. High surface energy of the solid
   b. Low surface energy of the liquid
11. Which of the following statements is/are true?
   a. The average biting force on an incisor is about 180 N.
   b. The average biting force on a first molar is about 1110 N.
   c. The average biting force on complete dentures is about 111 N.
   d. When a first molar is replaced by a fixed bridge, the biting force on the restored side is about 220 N.
12. An amalgam has a force of 111 N applied over a contact area of 0.645 $\text{mm}^2$. Which of the following is the stress applied to the amalgam? Would you expect the amalgam to fracture?
   a. 17.2 MPa
   b. 1720 MPa
   c. 172 MPa
   d. 1.72 MPa
13. An alginate impression can withstand a strain of 10% without significant permanent deformation. If the impression must be deformed 0.5 mm to pass over an undercut, how thick should the material be between the tray and the tooth?
   a. 10 mm
   b. 5 mm
   c. 0.5 mm
   d. 0.05 mm
14. Which of the following dental materials has/have an elastic modulus value that is similar to human enamel?
   a. Zinc phosphate cement
   b. Human dentin
   c. Dental amalgam
   d. Gold alloy
15. Which of the following statements is/are true?
   a. The yield strength is always slightly higher than the proportional limit.
   b. Above the stress associated with the yield strength, a material no longer functions as an elastic solid.
   c. Above the stress associated with the yield strength, a material will be permanently deformed, even after the applied force is removed.
   d. Most restorations are not classified as clinical failures until fracture has occurred.
16. Rank the following dental materials in order of increasing tensile strength: dental amalgam, gold alloy, human dentin, and human enamel.
   a. Dental amalgam, human dentin, human enamel, and gold alloy
   b. Human enamel, dental amalgam, human dentin, and gold alloy
   c. Human dentin, human enamel, dental amalgam, and gold alloy
   d. Human dentin, human enamel, gold alloy, and dental amalgam
17. Rank the following dental materials in order of increasing compressive strength: unfilled acrylic, dental amalgam, human dentin, and human enamel.
   a. Human enamel, human dentin, dental amalgam, and unfilled acrylic
   b. Unfilled acrylic, human enamel, human dentin, and dental amalgam
   c. Unfilled acrylic, human dentin, human enamel, and dental amalgam
   d. Dental amalgam, unfilled acrylic, human dentin, and human enamel
18. Which of the following is/are test(s) for measuring hardness?
   a. Knoop
   b. Toughness
   c. Yield strength
   d. Resilience
19. Which of the following dental materials has/have mechanical properties that are time dependent?
   a. Human dentin
   b. Gold alloy
   c. Dental amalgam
   d. Alginate hydrocolloid
   e. Elastomeric impression materials
20. What happens if a load is applied to an elastomeric impression for a long rather than a short time?
   a. The permanent strain will be greater.
   b. The permanent strain will be less.
   c. The elastic strain will be greater.
   d. The viscoelastic strain will be less.

*Use short answers to fill in the following blanks.*

21. The property that measures the expansion of a material per unit length for every degree of temperature change is called the ______________.

22. If the contact angle of a water droplet on the surface of a dental material is greater than 90 degrees, the material is classified as _______________.
23. When the deformation of a material is divided by the length of the material, the quotient is called the_______________.
24. When the force applied to a material at fracture is divided by the area over which the force was applied, the quotient is called the _______________.

*For the following statement, answer true or false.*

25. An alginate impression material gave two different stress–strain curves (shown in the following figure) when tested rapidly and slowly. As a result, the properties (i.e., plastic and elastic) are better evaluated using a strain–time test than a stress–strain test.
    a. True
    b. False

*Provide an answer for each section (a–e).*

26. A dental material gave the following stress–strain curve when tested in tension. Which portions of the curve (e.g., points O, A, or B, sections OA, OAB, AB, or ab) represent the following properties?
    a. Elastic
    b. Plastic
    c. Initial permanent deformation
    d. Ultimate tensile strength
    e. Stiffness

*Calculate the correct answers for each section (a–c).*

27. A dental material yielded the following stress–strain curve in tension. What are the values of the following properties?
    a. Elastic modulus
    b. Proportional limit
    c. Tensile strength

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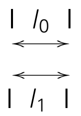
## APPENDIX 2-1 EQUATIONS

### Dimensional Change During Setting

A typical example is the linear dimensional change of an addition silicone impression material from a time just after setting until 24 hours after setting. An impression is taken of two marks on a metal plate approximately 51 mm apart; then the distance between the two marks transferred to the impression is measured with a measuring microscope just after the impression sets, $l_0$, and, again, 24 hours later, $l_1$. The percentage is calculated as indicated by the following formula:



$$\frac{l_1 - l_0}{l_0} \times 100 = \%$$

$$\frac{50.876 - 50.985}{50.985} \times 100 = -0.21\%$$

The result of −0.21% indicates that a linear shrinkage took place within 24 hours after setting.

### Thermal Dimensional Change

To make a comparison between materials easier, the linear thermal expansion is expressed as a coefficient of thermal expansion, which is calculated according to the following formula:

$$\frac{l_{t2} - l_{t1}}{l_{t1}} \div (t_2 - t_1) = \text{Linear coefficient of thermal expansion}$$

The first term converts the change to unit length and the second to unit temperature. The value represents the change in length per unit length for each degree of temperature change. Following is a typical calculation for an unfilled dental polymer: