Materials Science, Testing, and Properties for Technicians

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Symbols Used in This Book

A - Area, initial impact angle set
B - Final impact angle set
°C - Degrees Celsius
D - Depth, diameter
d - Depth, diameter
E - Modulus of elasticity, voltage, energy
e - Strain
F - Force
°F - Degrees Fahrenheit
G - Shear modules
h - Height
I - Electric current (amperes)
K - Kelvins
K - Coefficient of thermal expansion
L - Length, load
m - Mass
N - Number of grains in 0.0645 mm^2
n - Grain sizes number, index of refraction
P - Pressure, load
Q - Heat
°R - Degrees Rankine
S - Stress
T - Time, torque, thickness
t_1 - Cold face temperature
t_2 - Hot face temperature
V - Volume
W - Width, work
BHN - Brinell hardness number
Btu - British thermal unit
cal - Calorie
CF - Cement factor
DPH - Diamond Pyramid hardness
e_t - Torsion Strain
H_c - Heat capacity
HRa,b,c, . . Rockwell hardness number
Pa - Pascal
R - Resistance, radius
r - Radius
SG - Specific gravity
SH - Specific heat
α - Shear angle
γ - Shear strain
η - Poisson's ratio
ρ - Density
θ - Torsion angle, angle of refraction
τ - Shear stress

Equations Used in This Book

$A = s^2$ Area of a square
$A = L \times W$ Area of a rectangle
$A = \pi r^2$ Area of a circle
$V = s^3$ Volume of a cube
$V = L \times D \times W$ Volume of a rectangular solid
$V = \pi r^2 h$ Volume of a right circular cylinder
$P = F / A$ Pressure
$F = m \times a$ Force
$S = 4 \pi r^2$ Surface of a sphere
$V = 4 \pi r^3 / 3$ Volume of a sphere
°C = (°F − 32)/ 1.8 Conversion of degrees Fahrenheit to degrees Celsius
°F = 1.8 x °C + 32 Conversion of degrees Celsius to degrees Fahrenheit
K = °C + 273 Conversion of degrees Celsius to kelvin
°R = °F + 460 Conversion of degrees Fahrenheit to degrees Rankine
Btu = cal / 252 Conversion of calories to Btu
$\rho = m/V$ Density
$SG = \rho_{material} / \rho_{water}$ Specify Gravity
$SH = Hc_{material} / Hc_{water}$ Specify Heat
Therms = Btu/100,000 Conversion of Btu to therms
$Q = K(t_2 - t_1)\, aT / d$ Heat loss through a wall
$P = EI$ Electrical power
$E = IR$ Electrical resistance
$S = 4P / \pi d^2$ Stress on cylindrical specimen
$S = P / W \times D$ Stress on rectangular specimen
$e = (L - L_0) / L_0$ Strain
$E = S / e$ Modulus of elasticity
$\eta = -e_{cross\ section} / e_{longitudinal}$ Poisson's ratio
$G = \tau / \gamma$ Shear modulus
$E = 2G(1 + \eta)$ Conversion of shear modulus to modulus of elasticity
$S = 16T / \pi d^3$ Torsion stress
$S = 16Td_{(outside)} / (\pi d^4_{outside} - d^4_{inside})$ Torsion stress on pipe
$e_t = \theta d \pi / 360L$ Torsion strain
$BHN = 2L / \pi D(D - \sqrt{D^2 - d^2})$ Brinell hardness number
$DPH = 1.8544P / d^2$ Vickers diamond pyramid hardness number
$KHN = 1.43\, P / L^2$ Knoop hardness number
$BHN = 1.42 \times 10^6 / (100 - HRc^2)$ Conversion from HRc to BHN
$BHN = 2.5 \times 10^4 / (100 - HRc)$ Conversion from HRc to BHN
$BHN = 7.3 \times 10^3 / (130 - HRb)$ Conversion from HRb to BHN
$W = F \times D$ Work
$E = W \times h$ Energy of a falling body
$E = W \times R \times (\cos B - \cos A)$ Impact energy for Izod or Charpy test
$N = 2^{n-1}$ Grain size number
$n = \sin \theta i / \sin \theta r$ Index of refraction
CF = 27/yield Conversion of yield to cement factor
$BF = L \times W \times D/12$ Board feet

PERIODIC TABLE OF THE ELEMENTS

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh												

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

Preface

You are embarked on the study of engineering technology. Congratulations! Everything an engineer, engineering technician, or drafter designs must be made from materials. To make intelligent designs and decisions about materials, it is imperative that you gain some knowledge of materials and the way in which they are tested. This book is designed to help you achieve that end. The book, by itself, is not going to make you learn about materials. You must do that yourself. There are a few suggestions that might help you in this course.

1. Read the book *carefully*. Have a pencil or highliner in your writing hand. Underline the important concepts as you read them. In cases of mathematical presentations, do the calculations yourself as they are presented in the book. Refer to the figures as you read about them. Remember, this is not a novel; you cannot "speed read" this book and understand it.
2. In learning a science such as materials science, you must learn an entirely new vocabulary. You will have to learn as many new words in studying a science as you would in taking a foreign language. In this book the important words are italicized. Learn the definitions of these words before you go on. Look up immediately the meaning of any words that you do not understand. There is a glossary of these terms in the back of the book. For words not in the glossary, you may have to refer to physics, chemistry, or other handbooks and manuals. Do not wait until later, or try to guess at their meanings. Remember, many words in the English language have several meanings. Different academic disciplines apply different meanings to the same word. You must learn the meanings of these words as they are applied to materials science.
3. The problems in this book are designed to help you understand what you have just read. Work them! If you truly understand the problems, they will become easy, yes, even boring. When *you can demonstrate the solution to others with ease*, you have mastered them.
4. Periodically, throughout this book, there are some questions called Think-

ers. These are problems or questions without specific answers. There may be many correct answers to them. They are designed to make you stretch your brain a bit. In answering these, be prepared to defend your answers and give reasons for them as well as coming up with answers. Your reasoning and method of getting the answers is just as important as the answer itself.

5. Show an interest in materials. Ask questions when necessary. Your instructor is there to help you learn but cannot learn for you. Interested and inquiring minds have more questions than there are answers.

6. It would be impossible to cover every material in any book. If you have an interest in a particular material, look it up or research the literature on that material. Do not wait for the instructor to get around to your favorite material—he or she may never get to it.

7. Remember, materials science and technology is a subject in which new discoveries are being made faster than anyone can learn about them. The study of science and technology is not a static "learn it once and you are set forever" type of subject. Once you have started learning about materials, it will be necessary to keep on learning about them. Supplement this book with articles from current journals, such as *Scientific American*, *Nature*, *Science*, *Science Digest*, *Discover*, and even *Popular Science* and *Popular Mechanics*.

Every effort has been taken to try to make this book engaging and readable. However, it is up to you to supply the interest and the drive to learn the subject. Remember also that learning is not a spectator sport. It is hoped that you will have an interesting and profitable course in your study of materials testing and properties. Good learning to you.

William O. Fellers

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1 Tests of Materials

INTRODUCTION

The progress of civilization has closely followed the development of materials. Early humans used stones, wood, and other materials which they found in the sizes and shapes that they needed. It was a major technological achievement to discover that flint or chert could be chipped and sharpened to provide a cutting edge. The first metals to be used were those found in their natural state: gold, copper, and meteoritic iron. Entire civilizations developed around the use of copper and its alloys (bronzes).

Probably among the oldest manufactured materials were ceramics in the form of pottery. Archeological finds have produced ceramic objects dating from as early as 3000 B.C. Glass objects dating from 2000 B.C. are known. Closely paralleling ceramic and glass development was that of iron. Although natural iron from meteorites had been known for centuries and was even worshipped by some as being "heaven sent," it was not sufficiently abundant to be in wide use. Around 1500 B.C. (200 years before Moses) the Hittites found a method of extracting iron from its ore. The Hittites lived in the upper Euphrates valley of Mesopotamia (now Iraq and Syria). This new material, much harder and stronger than copper and bronze, was soon used in armament. Soldiers equipped with iron swords and shields enjoyed a definite advantage over opponents outfitted with bronze equipment. The first "ultimate weapon" had been invented. By the middle of the thirteenth century B.C. the manufacture of iron products had spread throughout the Mediterranean world. The Old Testament of the Bible has nearly 90 references to iron, and by the time of Christ, iron was in common use.

As time elapsed, materials were improved and new ones developed. The Romans were known to have used lead for water pipes. As chemistry and other sciences gradually produced new materials, the variety of products increased. The technical skills needed to work with these new products expanded, with a resultant elevation in the standard of living. The most modest household today displays far more luxurious furnishings than those of most of the royalty of ancient times.

The late nineteenth century brought many new materials into commercial use. Aluminum, Bakelite, magnesium, portland cement, and celluloid are examples of a few of these materials. After World War II scientific discoveries increased greatly. Whereas only a few plastics were known prior to the 1940s, they now number in the thousands. Semiconductors, adhesives (epoxies, superglues), composite materials (fiberglass, graphite–epoxies, etc.), synthetic fibers (Dacron, nylon, etc.), and new building materials have all been discovered and produced in the twentieth century.

Very often throughout history, the development of new technologies has been hampered because materials were not available to keep pace with the theory. The rotary calculator was designed by Pascal and Leibniz in the mid-seventeenth century, but the manufacturing tolerances and materials at hand were not sufficiently precise to make the calculator work properly until the mid-nineteenth century. Similarly, the development of the powered heavier-than-air airplane was delayed because the engines available were too heavy per horsepower produced to get the planes into the air. Early internal combustion engines had limited power output because the materials available to early engineers would not withstand the high temperatures produced at the high compression ratios required to build high-horsepower engines. This problem still exists to a certain extent. Development of the thermonuclear (fusion reaction) reactor is delayed because no material known can withstand the extremely high temperatures produced in the fusion reaction.

Thinker 1-1:

List at least 10 materials that have been developed or have become available commercially within the last 10 to 15 years.

Thinker 1-2:

List five items (i.e., machines, electrical items, etc.) that have depended on the development of new materials.

Thinker 1-3:

List five items that have been replaced by newer materials or that have been improved by the introduction of new materials.

THE NEED FOR MATERIALS TESTING

Since the industrial revolution in the late eighteenth century, the reliability of machinery has improved steadily. A major factor in this better reliability is growth in the knowledge of materials. Until the early twentieth century, the treatment of metals and other materials of construction and manufacture was primarily an art. Metalsmiths were trained to gauge the temperature of heated metals by the color of the metals in the fire. They forged their shapes by hand and judged their hardness by "feel." Most of the design work was at best an educated guess based on previous experience. If a 16-ft span in a building was well supported by a 6 by 12 in. wooden beam spaced every 4 ft, a 20-ft span would probably need an 8 × 12. In reality the same 16-ft span would have been adequately supported by a 4 × 12.

For engineers to design buildings or machinery efficiently, they had to understand the properties of the materials with which they worked. Ways had to be developed to test these materials. Materials are tested for at least four reasons:

1. Research
2. Quality assurance and quality control
3. Fracture or failure analysis
4. Engineering design analysis

Research on materials is done to determine the properties of materials. When a new material is developed, engineers must know all the properties of that material before they can use it in design work. Research testing will determine the tensile strength, hardness, density, thermal conductivity, electrical conductivity, and many other properties of the new materials. (Each of these tests is discussed later in the chapter.) Armed with this information, engineers can intelligently design new products using the newly developed materials. As an example, if research indicates that a steel bar of 1-in^2 cross-sectional area can support a load of 40,000 lb in tension, an engineer can calculate that a cross-sectional area of 4-in^2 is needed to support a load of 160,000 lb.

Other examples of the need for materials research can be found in the history of science. When Thomas A. Edison was developing the electric light bulb, it is said that he tested over 600 different materials to find a suitable filament. He was using the old "cut and try" technique of research. Modern techniques would have guided Edison to rule out over 90% of the materials he tried as being theoretically unworkable for light-bulb filaments and would have allowed him to concentrate on the other 10% to determine the most suitable material.

Quality assurance comprises tests performed by a company receiving new supplies to make certain that the shipment meets the standards called for in the order. *Quality control* involves tests done by a company on their own products prior to shipment to ensure that the product meets the manufacturer's standards. Large companies will test almost every product they purchase before accepting shipment or paying for it. It is, for example, better to determine that ball bearings that a company buys to put in their electric motors are of the proper size, within tolerance, and have the specified hardness before they are installed rather than to find later that these parts did not fit, or wear out prematurely, and thus jeopardize the quality of their product. Similarly, a reliable company will test its own products before marketing them.

Fracture or failure analysis involves tests performed on parts that have failed, or on new parts which are similar to parts that have failed, to determine why the failure occurred. We are all familiar with the widespread publicity that follows the crash of a commercial airplane. Politicians belatedly call for new laws to prevent future disasters. Public outcry against aircraft manufacturers is whipped to a frenzy. The metal is hardly cool at the site of the accident before inspectors are on the scene collecting every scrap of the fallen plane. Very often fracture tests are performed on critical parts of an aircraft to determine if failure of these parts could have caused the accident. Such tests can help to determine if the crash was due to a flaw in material used in vital parts of the aircraft, an improperly designed component, a poorly manufactured part, an improperly installed part, or was due to human error. The results of such testing are made available to concerned companies and governmental agencies. Rarely is the public, which soon loses interest, informed of the months of study involved in trying to prevent similar tragedies. Often, study of structural failures involves fracture analysis of materials. Materials do not "just break"—they are broken—and we now know how to determine what causes such breaks.

There are always many ways to design and manufacture an item. The engineer's job is to determine the "best" design and the "best" manufacturing techniques. Engineering design testing involves testing an experimental product to determine such things as the product's reliability, how long it will last, how well it will perform, how safe it is, and how cheaply it can be produced. (Yes, economics is an engineering function, too.) In engineering design analysis, either models or full-scale replicas of new products are tested, often to failure, to determine their performance characteristics. Many new tires are run to failure on test machines to determine their reliability and safety prior to marketing. Before the government will buy a component for a satellite, for instance, the part must be proved, by testing, to meet all the design criteria established by the space agency. Often, many designs of the same component, sometimes made by competing companies, are tested. Other areas in which products must be tested to ensure absolute infallibility occur in a number of the health fields. Heart valves, pacemakers, artificial joints, and synthetic arterial implants, for example, must all function perfectly, or the results could be fatal. In all the instances noted above, it is materials technicians who do the actual testing.

Very few students know where they will be working or the situations in which they may find themselves once they are in industry. It is therefore imperative that all engineering technicians and engineers have, prior to completing their technical training, a working knowledge of materials of manufacture and construction and the ways by which materials are tested.

> *Thinker 1-4:*
>
> Listen to the radio or watch television for an evening. List 10 advertised products and outline why they should be tested.

QUALITIES OF A GOOD TEST

To be useful, a test must be done exactly the same way every time by every person running the test. This is called standardizing the test. Several organizations have drawn very specific guidelines and details that must be followed in the execution of tests of materials. The American Society for Testing and Materials (ASTM), the American Iron and Steel Institute (AISI), the American Society for Metals (ASM), the American National Standards Institute (ANSI) [formerly and often still referred to as the American Standards Association (ASA)], the Portland Cement Association (PCA), and many others have developed and standardized various types of tests.

A good test must be *reliable* and *valid*. A test is said to have *reliability* when it gives the same results for the same material on repeated tests. It has *validity* if the test measures exactly what it claims to measure and not some other, often unknown property of the material. Weighing a feather on a scale might be considered a reliable test; however, trying to determine the force of gravity by measuring the distance a feather will fall in a given amount of time might not be a valid test since the fall of a feather would be greatly influenced by the air.

Tests should be *objective*, not *subjective*. *Objective tests* are those that will give the same results regardless of who performs the test. *Subjective tests* are often affected by the judgment of the person conducting the test. Multiple-choice tests which can be graded by a machine are much more objective than essay tests which must be read and evaluated by a person. Digital readouts are usually more objective than are dials.

Precision and *accuracy* are terms used with measurements in any test. *Precision* is a measure of how close together values of the same measurement lie. *Accuracy* is a measure of how close to the true value a measurement falls. Weighing a part on a miscalibrated scale may give precise results but be entirely inaccurate. Conversely, soft-boiling an egg using a 3-minute sand (hourglass type) timer may give fairly accurate results but with little precision.

Thinker 1-5:

Evaluate the following types of measurements as to their reliability, validity, objectivity, precision, and accuracy.

a. Measuring 10 gallons of gasoline from a gas pump
b. Measuring the speed of your automobile, using the odometer (speedometer)
c. Measuring the speed of your automobile by finding the time it takes, using your wristwatch, to go a measured mile
d. Measuring the speed of your automobile by finding the time it takes, using a stopwatch, to go a measured mile
e. Laying out a mile track by "pacing it off"

There is a difference between *mistakes* and *errors*. *Mistakes* are "goof-ups," "boo-boos," "wrong moves," and so on, and can usually be corrected and eliminated if given a chance. Simply "do it over and do it right." *Errors* are inaccuracies in measurements and can be minimized but never eliminated entirely. No measurement can be made exactly. If one measures the length of a table using a standard "yardstick," the table can only be measured to the nearest $\frac{1}{8}$ in. There is a possible error due to the instrument of $\pm \frac{1}{16}$ in. If greater accuracy is desired, a better-calibrated instrument must be used. If the table is measured with an instrument calibrated to the nearest thousandth of an inch, the error could still be five ten-thousandths of an inch either way. Even finer measurements will still have an error. Remember, the more accurate and finer the calibration of test instruments, the more expensive they become.

There are several terms associated with materials that must be understood prior to discussing the methods by which materials are tested. These terms are often misunderstood since they can have other meanings when applied to different disciplines.

Brittleness: A characteristic of a material that causes it to break prior to undergoing plastic deformation. *Plastic deformation* is a permanent change in material caused by a load being applied. If material will not stretch or bend, it is brittle. A brittle material is one for which the tensile strength and the breaking strength are the same.

Ductility: The ability of a material to be drawn into a wire. It is considered the opposite of brittleness. It is one type of plasticity.

Elasticity: The ability of a material to return to its original size and shape once a load has been removed. Most but not all materials have some degree of elasticity.

Malleability: The ability of a material to withstand rolling or pounding into sheets. It is another form of plasticity.

Plasticity: The ability of a material to withstand permanent deformation without tearing or rupturing.

Resilience: The ability of a material to absorb energy without being permanently deformed. The *modulus of resilience* of a material is the amount of energy in foot-pounds per cubic inch or newtons per cubic meter that can be elastically recovered by deforming the material.

Toughness: A measure of the ability of the material to absorb energy without breaking. The *modulus of toughness* of a material is the energy in foot-pounds per cubic inch or newtons per cubic meter required to break the material.

TYPES OF TESTS

Materials are usually tested by techniques that closely approximate their use. Structural members that are being pulled on are said to be in *tension*. Figure 1-1 shows cables in a suspension bridge which are in tension. Conversely, components that are being pushed together are under *compression*. In Figure 1-2, the chair legs are an example of structural members in compression.

If a rod or bar is being twisted, it is in *torsion*. Motor shafts and drive shafts in automobiles are subject to torsion. Figure 1-3 shows a rod in torsion.

Beams and other parts that are being bent are said to be in *flexure*. A load applied to the middle of a board while it is supported at both ends will put the board into flexure. Similarly, diving boards at swimming pools are supported as a cantilever beam and are in flexure. Figure 1-4 shows a bookshelf that must resist flexure.

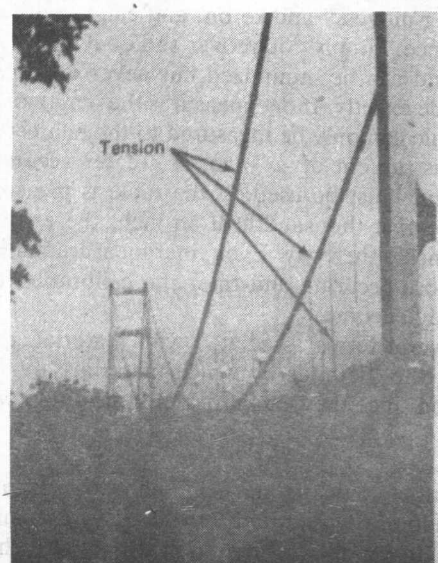

FIGURE 1-1 Tension members.

FIGURE 1-2 Compression members.