Preface

In the current fast pace technological progress and pressing need to constantly innovate, engineering materials selection has become an inseparable part of any engineering design. The right selection of materials ultimately determines the quality, cost, durability and performance of a component or a product. Materials are the keys to the success or failure of a business that deals with engineering products.

With further innovations in the field of engineering materials we can also contribute a great deal to the current global concerns of energy and environment by saving on energy (at the stages of production, handling and operation) and materials (by weight-saving, efficiency and durability). Another field where engineering materials would immensely help is that of healthcare. Special types of engineering materials, known as biomaterials, are finding applications in medical solutions such as in orthopaedics, dental and in other surgeries as implants. Lighter and smarter engineering materials can make big difference to the quality of life of our aging population, both as implants and as external aids. There are many possibilities of new applications and developments of new engineering materials that may perform many medical functions with greater reliability and at much reduced cost.

The above has always motivated this author to work in this fascinating field of engineering, both for my own research and for teaching university students. Teaching students has motivated me even more as I see my students showing very keen interest in learning about engineering materials. Often they challenge me with their very probing questions. These motivations and challenges have definitely kept me in the right mode of learning.

This book has evolved through my last eight years of teaching engineering materials related courses at the National University of Singapore. Therefore, the basic structure and texts presented here resemble my lecture notes and other teaching materials. I feel that students will have easier time learning the subject in a more interesting way using this book because of the narrative type of written style that I have adopted. Also, I have provided my comments and answers to many of the intricate questions that were asked by my past students. Answers to these questions are often difficult to find in a textbook. Questioning-Answering is a very effective way to master a subject than only by reading a textbook. This is because questions can be totally unexpected sometimes, and can become reasons to investigate further that leads to further discoveries. Hence, it is my request to all my students to continue asking questions and let us keep learning!

This book would be very suitable to senior undergraduate and postgraduate students who are studying any topic in mechanical engineering design or those who just want to know about engineering materials. This can be a companion book for industry professionals who are engaged in mechanical designs or engineering failure analyses.

To the teachers: As this book has been written primarily for classroom teaching of engineering materials course, I believe that the book will be very useful if you are teaching a similar course at the university level. Further resource for the teachers who adopt this book in the class as textbook would be available through the publisher of this book.

Finally, though I have spent much time writing and correcting the manuscript, I know some errors might still be there. It is a failure and an inability of mine that I have decided to live with, in the interest of time and because of my desire to bring out the book in published form for the benefit of my current students. However, I would be very grateful to anyone who points out to me any error in the book for future improvements.

I would wish to humbly dedicate this book to all students who are constantly striving hard to learn and contribute to the society through their knowledge.

Sujeet K. Sinha
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Chapter One

Introduction to Engineering Materials

This book will introduce a variety of engineering materials, their common physical and mechanical properties, failure characteristics and mechanisms, and, most importantly, how we can utilize information on materials for their selection in mechanical design. This is an attempt to relate materials to mechanical design with the help of the knowledge about engineering materials, several material selection tools and, our understanding of mechanical design requirements. Such knowledge will eventually help us in making the best use of engineering material properties and innovative design ideas to make high performance and cost-effective mechanical and structural components.

1.1 WHY STUDY ENGINEERING MATERIALS?

Materials are central to every engineering design process. While thinking about any design process, we have to consider materials and design concurrently as both can support each other in achieving the best performance for the designed product. In fact, the third parameter that should also be considered is the processing (or manufacturing) aspect, meaning how that material will be shaped or formed into parts and components. The processing/manufacturing aspect determines materials' properties, quality and the cost of the product. Materials-Design-Processing (Fig. 1.1) should be collectively considered during the design process as they will affect each other and ultimately will

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The above three requirements of design will ultimately determine the final materials selection. As there are many factors that will influence our decision on selecting a material, it is important to adopt a multi-dimensional approach to materials selection rather than a one-way linear approach.

1.4 MOTIVATIONS FOR MATERIALS SELECTION

From the above discussion, we can see that materials selection is an important aspect in any engineering design. There are many factors that determine why we need to carry out materials selection for an engineering product in the first place. Following are some of the motivations or reasons why we conduct materials selection.

New product development

In many cases, the reason why we have to select a material is because the design of the product is totally new. It can be a totally new product because of a new customer requirement, or, there may be a need for bringing out an innovative, novel product.

Improvement of an existing product

This could be related to making an existing product but with better performance and improvement on safety, or, for making the product cost effective (competitive in terms of price). Often, as an engineer we are engaged in such activities.

Environmental concerns

In the present global scenario, every product designed must bring minimum of environmental damages at the production, service and after-life stages. Thus, making design changes that can accommodate less material or using a more environmental-friendly material would be important. The production process of the product should take less energy and the product should consume less energy (energy-efficient) while in service. Also, by making a product more durable, the environmental damages can be minimized as failure of engineering products is a waste of energy spent in producing it. Another environmental concern is the recyclability design. This method takes geometry of the component into account and comes up with an index that can then be used for determining the performance of the material with respect to stiffness and lightness. To this end, we can now conduct an analysis to find out an index for a simple cantilever design and then we can work out which material might be most suitable for the cantilever if the design requires both high stiffness and light weight.

2.3 EXAMPLES OF MATERIALS SELECTION FOR STIFFNESS-BASED DESIGN

Activity 2.1

Find a suitable method of selecting materials that are stiff and light weight for a cantilever design.

Solution: For the cantilever shown in Fig. 2.3, we first decide the parameter that determines major performance of the design. In the present case, it is the deflection of the free end of the cantilever that determines the performance as far as stiffness of the component is considered. Thus, our objective here is to find an index that can be used to select cantilever material for high stiffness (as a performance indicator) and light weight. Note that, in many of the engineering design and material selection processes, weight is naturally minimized, as light-weight often means low cost (subject to the manufacturing process and service requirements) overall. The performance and the cost have to be ultimately optimized depending upon the application and customer needs.

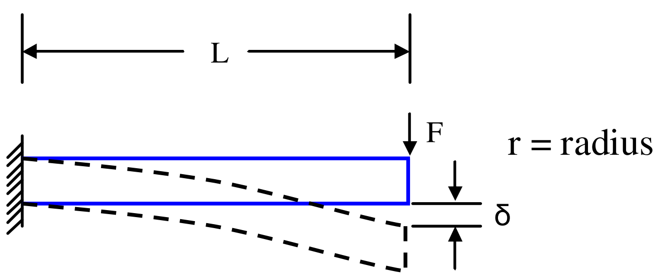

Figure 2.3. A circular cross-sectioned cantilever of radius r, under force, F, at the free end. δ is the elastic deflection under force F.

stiffness-based design, the final goal is to minimize the mass for the same strength performance of the selected material. Based on such calculations, we may come up with a number of materials which can give us excellent strength performance, however, the final choice will depend upon the cost per unit performance and some other considerations (we will discuss this in later chapters).

Activity 3.1

Compute an index for selecting strong and light material for a cantilever design loaded at its free end.

Solution: The geometry is the same as in Activity 2.1 but here we are concerned about the strength of the cantilever beam. Hence, we will first write the equation for maximum stress in a cantilever loaded at free end which is given as,

$$\sigma = (FLr)/I \tag{3.1}$$

where, σ is the stress in the beam, F is the point load, L is the length of the cantilever and r is the radius of the cross-section. 'I' in Eq. (3.1) is the area of moment and for circular cross-section it is given as $\pi r^4/4$. Thus,

$$\sigma = 4FL/\pi r^3 \tag{3.2}$$

We can re-write Eq. (3.2) as,

$$r = (4FL/\pi\sigma)^{1/3} \tag{3.3}$$

Equation of mass for cantilever can be written as,

$$m = \pi r^2 L\rho \tag{3.4}$$

where ρ is the density of the material. Here, as in Activity 2.1, we will eliminate the geometric variable r from Eq. (3.4) by substituting expression for r from Eq. (3.3). The length of the

Chapter Six

Materials for Fatigue-Based Design

6.1 INTRODUCTION

Fatigue is a process of gradual failure of materials by crack initiation and propagation when there is cyclic loading/stress. Cyclic loading means that the stress is continuously varying during service in a regular cyclic or irregular fluctuating manner. The actual magnitude of the maximum tensile stress in a cyclic loading may not be very large compared to the strength of the material, cyclic loading brings about failure by nucleating and growing a crack small-bit at a time. In every cycle, there is a growth of the crack and if the component is subjected to a large number of stress cycles during its operation then the failure can come very soon. There are some materials and design approaches which can ensure that a component has maximum service life despite cyclic stress. Aircraft components, railway car axles, wind mill structures and bridges are most prone to fatigue failure. Others are power transmission shafts, rotating parts, engine parts, heavy lifting devices such as cranes etc.

6.2 METAL FATIGUE MODELS AND LIFE PREDICTIONS

The number of failures of engineering components in industry because of fatigue is very large. There are some critical industrial applications where metal fatigue is a big concern for the design and operation engineers. Aircrafts, gas turbine components,

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where p is the local normal pressure at a point in x direction, $\bar{u}$ is the mean (entrainment) velocity of the two surfaces in x-direction, η is the viscosity of the fluid, h is the fluid film thickness at a given point x, and, h_m is the film thickness when p is maximum. Thus, h_m is the minimum film thickness in the contact. Equation (7.2) is valid for rectangular long channel in steady-state and is a special case of more general and complex equation proposed by Reynolds. Note that the film thickness will be h_m when $dp/dx = 0$. Reynolds solution can be applied to all hydrodynamically lubricated contacts such as inclined plate and journal bearings.

The minimum film thickness, h_m, for a rigid cylinder on a rigid flat plane has been computed numerically by Dowson and Higginson (1966), which, after further analysis, is given as (page 686 in Bhushan, 1999),

$$h_m = 1.66\,(\alpha \eta_o \bar{u})^{\frac{2}{3}}\, R^{1/3} \tag{7.3}$$

where R is the initial radius of the cylinder, α is the viscosity-pressure coefficient and η_o is the viscosity of the fluid at atmospheric pressure. The viscosity is assumed to be a function of the pressure, p, by the relation,

$$\eta = \eta_o \exp(\alpha p) \tag{7.4}$$

The Reynolds equation can be solved for any geometry of contact with very accurate predictions of the pressure inside a lubricant channel. The average pressure can be obtained by integrating the pressure equation over the length of the channel which can then be used for calculating the load carrying capacity of the bearing.

7.5.2 Elastohydrodynamic Lubrication (EHL)

The pressure inside a hydrodynamically lubricated part can rise very high to a level that some elastic deformation of the contacting solids is possible. This happens when the normal pressure is high or when the solids involved are of compliant materials such as polymers and elastomers. Also, in point or line contacts such as in ball or roller bearings, the Hertzian contact pressure is extremely high, enough to cause elastic deformation of the solids and some changes in the viscous property of the fluid confined

Chapter Eight

Materials and Design against Environmental Damage

8.1 INTRODUCTION

There are many types of damages to materials that are related to the environment the material is exposed to. Oxidation, hydrogen damage, aqueous corrosion, radiation damage are examples of environmental damage. Among all types of environmental damage, corrosion affects almost every industry as many metals can corrode in an environment where there is oxygenated water, chloride or other acidic or base chemicals. Cost of corrosion to the industry in USA alone is estimated a few hundred billions of dollars (∼3.1% of US GDP) every year (1998 data). Therefore, materials and design consideration against corrosion is a first priority in almost every industry and country.

8.2 MAN PROPOSES, NATURE DISPOSES

All metals obtained from their ores are destined to return back to their compound forms (primarily oxides, hydroxides, chlorides etc) because of the stable and low energy state of these compounds. The difference between the free energy of the metal and that of the compounds such as oxides is the thermodynamic driving force for a metal to corrode, oxidize or change chemical state. Oxidation and corrosion are two important phenomena that require material and design solutions in any engineering application affected by these issues. The products of oxidation or corrosion are chemically stable states of the metal as compounds and

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corrosion rate than that of the alloy. The aluminium alloy suffers from intergranular corrosion because of the potential difference between the precipitate rich grain boundary and the rest of the structure. Grain boundary is anodic and corrodes preferentially because of galvanic corrosion.

8.10 DESIGNING AGAINST CORROSION

The problem of corrosion in industrial applications can be solved or minimized to an acceptable level by proper design. For uniform corrosion (case of carbon steel corrosion in outdoor applications), a simple additional thickness equivalent to the loss of the material during the entire working life of the structure can be appropriate and cost effective. Use of two dissimilar metals should be avoided, for example, by using welding instead of riveting. One should also ensure that welding is carried out properly as welding itself may introduce metallurgical dissimilarities and internal stresses which will accelerate the rate of corrosion in the welded zone. In the case of possible galvanic coupling, it is recommended that the anodic metal should have surface area much larger than that of the cathodic metal part. If the engineering component involves storage and handling of corrosive liquids then proper drainage would

Figure 8.13. Corrosion inside an insulation due to high temperature and possible intrusion of water inside the insulation. (Courtesy: Balaji.)

high stress in the beginning is gradually replaced by creep strain over time and thus the actual stress is reduced. This type of creep related reduction in the stress happens when the maximum strain is fixed by design, for example in bolts in a mechanical component. This phenomenon is known as stress-relaxation which is a result of creep strain replacing the original elastic strain over time. This is a major problem in the use of materials which are exposed to temperatures in the range of > 0.3 to 0.4 times T_m. Stress relaxation can lead to further problems of fretting, vibration, wear and fatigue as the mechanical system will no longer adhere to the technical specifications due to lower stress and there could be loose joints etc.

The stress-relaxation time is roughly taken as the time in which the stress drops to half of the original stress value. Based on the assumption that the strain is constant and the initial elastic strain is gradually replaced by creep strain over time, it is possible to obtain a relation for the stress-relaxation time, t_r, given as [Ashby and Jones, 1996],

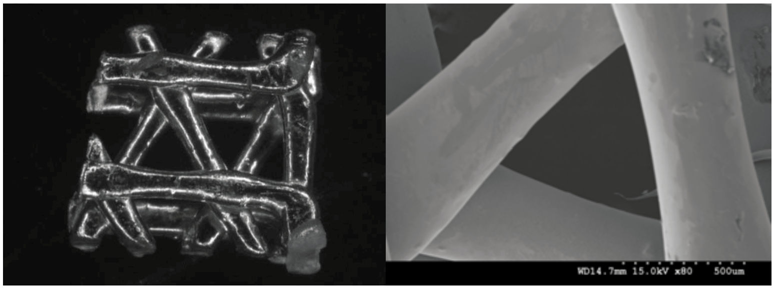
$$t_r = \frac{(2^{n-1} - 1)}{(n-1)AE\sigma_i^{n-1}} \tag{9.6}$$

where A and n are defined in Eq. (9.3), E is the elastic modulus of the material at the prevailing temperature and σ_i is the initial stress applied. A schematic representation of the stress relaxation phenomenon is given in Fig. 9.3.

9.2.3 Creep Fracture

Creep-fracture or creep-rupture is another important aspect in high temperature application of materials. Time to creep fracture is the maximum life of a component at a given temperature and stress and hence, this data would help design engineers in estimating the life of the component with appropriate safety factor. Since creep fracture is a result of creep, the equation for the time to fracture follows the same exponential and power laws as mentioned for creep rate. Since creep rate is given as creep strain over time, the constitutive equation for time to creep fracture takes the inverse form of the equation for creep rate and is given as,

$$t_{CR} = K\sigma^{-m}e^{(Qc/RT)} \tag{9.7}$$



(a) (b)

Figure 10.2. A scaffold for tissue engineering made of PCL. The porous structure is required for the growth of the tissue. (a) optical image at 7.5x magnification, (b) FESEM image. (Sample provided by Prof. S. H. Teoh, National University of Singapore.)

stress environment that is the presence of a biomaterial, which means the grown tissue may be weak as much of the mechanical stress was being taken by the biomaterial during the healing process. This is an important problem with load-bearing orthopaedic implants and it is called stress-shielding. Thus, many polymers are excellent candidates for the above-mentioned implant applications.

10.5.2 Metallic biomaterials

Metals were the earliest biomaterials used as bone plates and they are still used for many applications from hip joints to artificial heart device. The use of metals is limited by their electrochemical activities due to the physiological environment in the body. Many metals would corrode and the metallic ions released due to corrosion could be toxic to the body or may simply migrate and get deposited in other parts of the body that may have long-term harmful effects on the patient's health. Also, some metals (especially the heavy metals) are by nature toxic to our body and should not be used as biomaterials. Very common metals as biomaterial are Ti and Ti-alloys, stainless steels and Co-Cr-Mo alloy. Pt, Ag and Au can also be used, however, they are expensive. Metals are very useful as orthopaedic and artificial heart implants for their good strength and toughness and also as housings for some other implantable devices. Some metals may be ranked from very biocompatible to very toxic as Zr, Ti, Nb, Ta, Pt, Co-Cr, 316L SS, Ag,

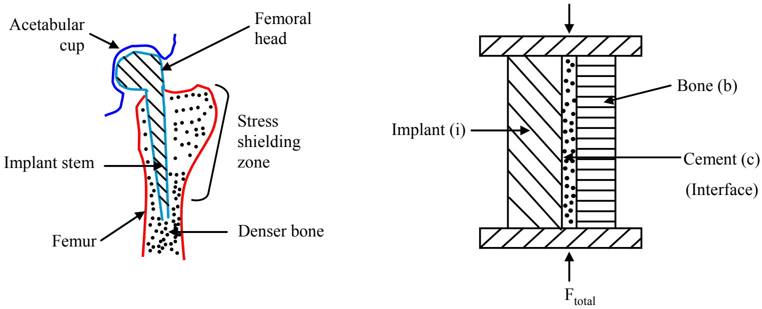


Figure 11.62.

Answer: Stress-shielding is a phenomenon by which part of the bone loses its density (bone mineral density) if a high fraction of the stress is supported by the implant. It is known to occur in femur after hip prostheses as the stem of the femoral implant takes much of the stress which was earlier taken by the bone. A similar problem occurs also in bone fracture fixation by bone plate. Stress-shielding is a result of the nature of bones according to which a bone will respond to extra load or stress at a point by increasing bone density and vice versa. This behaviour of bones is also known as the Wolf's law. Though stress-shielding is a result of lower than normal stress in the bone, this happens because of the high stiffness of the implant in comparison to that of the bone. Once the stem of the femoral implant is fixed in the femur, the implant, the cement and the bone act together as one composite unit (Fig. 11.62). That is, the mechanical load is shared between them because the strain for a given load would be same for each (assuming no loosening of the implant). Let us say ϵ_i, ϵ_c and ϵ_b are the strains in the implant, cement and the bone, respectively, then, $\epsilon_i = \epsilon_c = \epsilon_b$. Using the Hook's law we can say that, $\sigma_i/E_i = \sigma_c/E_c = \sigma_b/E_b$. Thus, since the modulus of the implant material is many times higher than that of the bone (Table 11.2), the stress taken by the implant stem is also high (to maintain the ratio of stress to modulus equal to that for the bone). That is, $\sigma_i \gg \sigma_b$. Therefore, the bone will bear less load or stress and suffer from density loss or osteoporosis. Stress-shielding is one of the main causes of implant loosening.

Theoretical and clinical studies have shown that the problem of stress-shielding is high in femoral stems made of Co-Cr and Ti and the effect tends to decrease if porous or cellular metals with