CHAPTER 1

INTRODUCTION

Accumulated human experience over several millennia in the adaptation of natural materials for useful purposes has caused the notion of materials degradation to be firmly embedded in language and culture. The familiarity of such words as 'fracture', 'wear out', 'burn up' or 'rot' are evidence of the close relationship between human civilization and materials degradation. An instinctive appreciation of surface engineering is present in almost all civilized peoples where the quality of a surface controls much of the value of the object enclosed within. Common examples of this association of value with effective surface engineering are the emphasis given to the polishing or to the painting of mechanical equipment. A single scratch on some new article often causes depreciation in its financial value that is much greater than the cost of mechanical damage caused by the scratch.

Whereas lay persons usually give priority to the subjective significance of materials degradation and surface engineering, it is the task of technologists to evaluate the true costs of materials degradation and balance this against the costs of surface engineering necessary to prevent such materials degradation.

1.1 Definition of materials degradation

Before proceeding into a subject, which depends on an enormous variety of information from many diverse sources, some pertinent questions would have to be asked: What is materials degradation? How does it affect an engineering system? What is the significance of materials degradation in terms of engineering performance?

From the moment that any material is released from the point of production, it is in theory subjected to some form of materials degradation although such degradation may not be readily observed or measured. The rapid rusting of freshly machined steel surfaces is a common example of immediate materials degradation. Such damage continues throughout the lifetime and materials degradation of any component is a limiting factor.

No known service environment provides perfect immunity from materials degradation. Under atmospheric conditions, electrochemical corrosion is the most significant degradation process in economic terms. In outer space, although the absence of atmosphere precludes corrosion, radiation damage can be severe. Corrosion, radiation damage and many other mechanisms all have a shared feature of reducing the performance of engineering materials to cause premature failure of components and devices. A simple definition of materials degradation is that it is the consequence of a wide range of physical processes; it is almost universal in occurrence and is a major engineering problem.

Materials degradation imposes a cost penalty on all engineering systems. For instance, a mechanical structure has to be constructed with extra metal or concrete to allow for corrosion-induced loss of strength. If such corrosion did not occur, the extra metal could be dispensed with and the structure could carry more weight. High-strength alloys may be more prone to corrosion than lower-strength alloys. This would also add to the factor of safety built in while designing the structure. On the other hand, a high strength with good corrosion resistance would add to the cost of the structure. A typical example of this situation is the use of nickel based alloys over conventional alloy systems. Thus the corrosion ensures that a more expensive structure is required for any given load. Wear between pistons and cylinders inside an internal combustion engine causes leakage of combustion gases from inside the cylinders and the engine becomes less efficient. Piston-cylinder wear causes a vehicle to consume more fuel per distance travelled than would otherwise be the case. The risk of sudden fracture of an aluminum structure necessitates frequent and expensive preventive repair of aircraft fuselage. Further examples of loss of performance are discussed below in this chapter.

Materials degradation can be defined in terms of loss of performance of an engineering system. Loss of performance can relate to many parameters, e.g. loss of reflectivity in optical equipment caused by fungal attack. A more common example might be the loss in mechanical strength of a structural component exposed to a corrosive medium. For any item of equipment, there is a critical minimum level of performance, e.g. whether a useful image is obtained from the optical system or whether the mechanical structure will collapse due to corrosion damage. For the engine with worn cylinders, wear can increase the clearance between piston ring and cylinder to such an extent that there is no compression of combustion gases. In this case the engine can be considered to have failed, as it will no longer be able to pull the car or truck up the hill. A mechanical degradation proceeds at a rate that

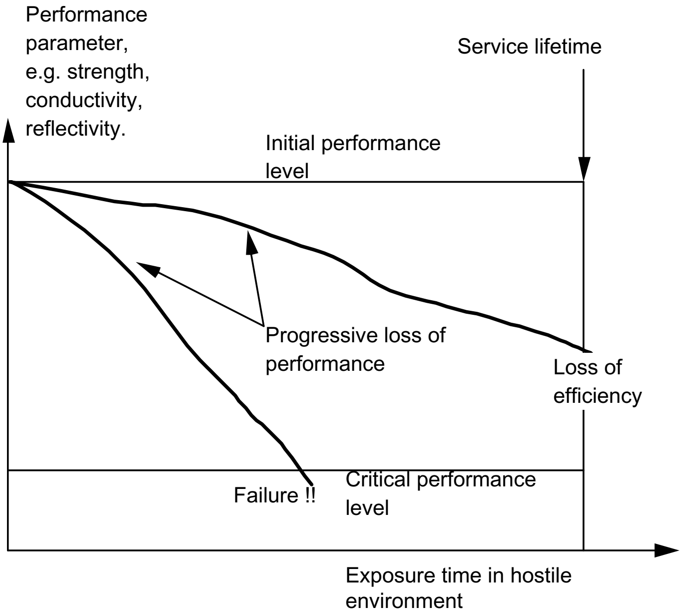

Figure 1.1 Graphical definition of materials degradation as loss of performance of an engineering system.

varies with local conditions and failure occurs if the performance declines to below the critical level. Loss of efficiency occurs if performance declines but remains above the critical level during the service lifetime. Referring to the previous examples of the optical system and mechanical structure, loss of efficiency could involve a progressive distortion of the image for the optical system and load restrictions for the mechanical structure. This view of mechanical degradation is illustrated schematically in Fig. 1.1.

Some loss of performance is inevitable unless very expensive control measures are implemented, e.g. constructing a car from stainless steel instead of plain steel. The objective of surface engineering is to ensure that performance remains far above the critical level for the entire service lifetime of the system. The scientific study of degradation of engineering materials can be summarized as predicting the rate of decline of performance; this is the gradient on the graph shown in Fig. 1.1. Engineering analysis of materials degradation is directed at finding the factors controlling this gradient and how to reduce it.

The increasing use of composite materials, e.g. fibreglass reinforced plastic, as opposed to monolithic materials, e.g. steel, leads to increased likelihood of materials degradation problems. Not only are two or more materials now involved, but the interface between the materials may also degrade to cause debonding and structural weakening. Another serious concern with use of composite materials is detection of degradation at an earlier stage when such materials are used in weight-critical structures as the failures can be catastrophic if not detected early. Thus techniques need to be developed for predicting such failures before resorting to measures to avoid them. Moreover, additional safety factors needs to be added for designing structures with composites.

1.2 Definition and significance of surface engineering

Surface engineering is a comparatively recent term that refers to control of problems originating from the surface of engineering components. It is generally considered that the surface of a component is much more vulnerable to damage than the interior of the component and that surface-originated damage will eventually destroy the component. Most types of materials degradation such as, wear, corrosion and fracture are usually located at the surface of a component. As a result of this concentration of damage processes at the surface of a component, surface engineering is essential to control them.

A time-honored solution to the problem of materials degradation is to try and shield the material from the hostile agent. For example, painting is a well-established example of this practice and serves to shield a metal (or wood) from water and oxygen. The range of techniques available to prevent materials degradation by shielding has expanded enormously in recent years. The principle of shielding by surface engineering is illustrated schematically in Fig. 1.2. Corrosion damage is illustrated in Fig. 1.2 but the same principle applies to wear and surface-originated fracture.

Shielding is usually achieved by coating the material with another substance or by generating a surface modified layer, which is more durable than the original material. Another form of shielding is to inhibit the chemical processes that directly control degradation. Cathodic protection where an electrical potential is used to suppress electrochemical corrosion of metals is an example of this latter method. The vast majority of materials degradation problems are, however, managed by the former method of coatings and surface modified layers. Most physical phenomena have been applied where possible for the development of coatings and surface modified layers. The power of an explosion has been used to directly clad steel with a corrosion resistant layer of aluminum. Each method of coating

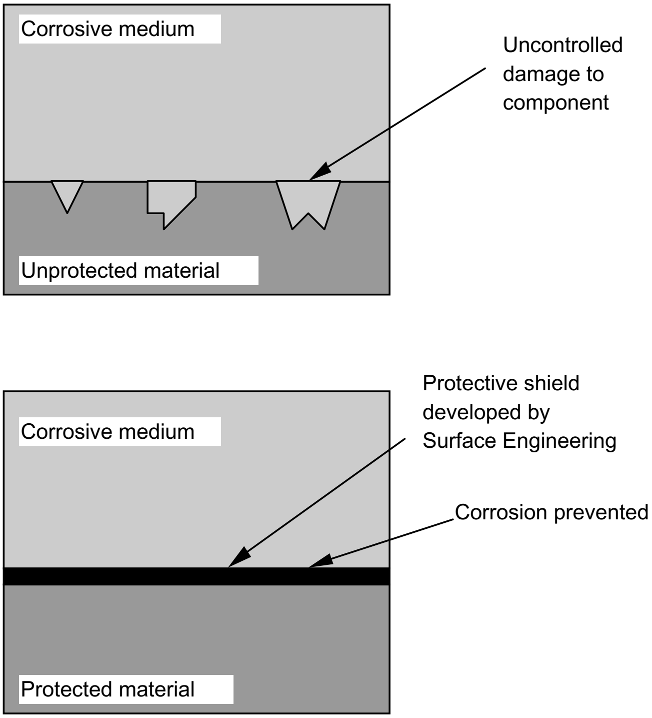

Figure 1.2 Graphical definition of surface engineering to control materials degradation.

or surface modification has its own advantages and disadvantages. For instance, painting may be cheap but will it be effective when the corroding water is substituted by abrasive aqueous slurry? A comprehensive knowledge of the various coating and surface modification techniques is required before an optimum or near-optimum solution to a materials degradation problem can be obtained. A definition of surface engineering is an informed selection of the appropriate coating or surface modification technology and its effective application to prevent or delay one or more forms of materials degradation thereby improving the performance of components and devices.

1.3 Classification of materials degradation by physical mechanism

Almost any known natural phenomenon can cause materials degradation. Heat, light, short-wavelength electromagnetic radiation, radioactive emissions, chemicals, mechanical stress and interactions with bacteria, fungi or other life forms; all these can damage materials. Classification of materials

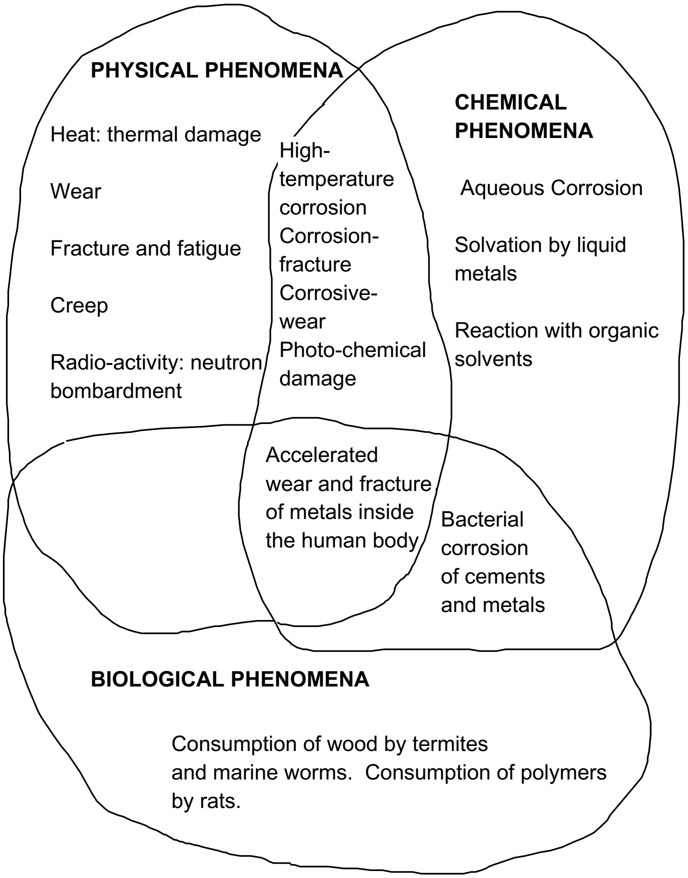

Figure 1.3 Classification of the various types of materials degradation in terms of physical, chemical and biological phenomena.

degradation according to its basic cause is a first step in any plan to protect a specific material in a specific situation. A classification of the known forms of materials degradation as physical, chemical or biological phenomena is illustrated schematically in Fig. 1.3 as a Venn diagram.

There are three basic categories of materials degradation, physical, chemical or biological in origin. Physical origin refers to the effect of force, heat and radiation. Chemical origin relates to destructive reactions between the material and chemicals that contact it. Biological origin includes all interactions between life forms and engineering materials.

Materials degradation such as thermal damage or chemical reactions, which are either entirely physical or chemical in nature, coexists with combined forms of materials degradation such as corrosive-wear.

Materials degradation is an uncontrolled process without restriction on interactions between seemingly unrelated events. Environmental conditions also exert a strong effect on materials degradation with the result that any given materials degradation problem is effectively dependent on locality. As will be shown in later chapters, there is a wide range of possible interactions or synergy between degradation processes and considerable care is needed to predict which of these interactions are significant to any given situation.

An important example of interactions between degradation processes is corrosive-wear, which is mechanical wear that is accelerated by chemical damage to the worn material. Biological phenomena are either found in a pure form, i.e. organisms eating artificial materials or in a complex form such as bacterial corrosion where the waste products of bacteria are destructive to materials. Biological, chemical and physical phenomena all interact in the human body to impose severe stresses on any metal component implanted in the human body.

Damage that depends on just one type of phenomena, e.g. physical, is easier to recognize than multi-phenomena modes of damage such as those occurring inside the human body. Protective measures are usually ineffective when a multi-phenomena mode of damage is mistakenly concluded to be a single-phenomenon mode of damage. In this book, single-phenomena modes of materials degradation are described before more complex forms of degradation are discussed. An example of this approach is the prior discussion of abrasive wear and aqueous corrosion before corrosive-abrasive wear is introduced.

1.4 Economic and technical significance of materials degradation

How much will materials degradation cost the company or project? What are the technical problems caused by materials degradation? Practicing engineers and technologists need to know the answers to these questions to ensure the success of any engineering venture. An idea of the scale of costs incurred by materials degradation can be obtained by trying to estimate the value of all the engineering equipment that is currently in use in the world. A figure reaching perhaps trillions of dollars would not be surprising. Suppose now that materials degradation causes an effective depreciation of 5% a year in capital value, which is a very conservative estimate. The cost of materials degradation would then be in the range of \$100 billion to \$1 trillion a year. Expert studies have pursued this method of estimation of costs in far greater detail and arrived at similarly high cost

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estimates. Friction and wear losses alone cost about 1% of the GNP of Germany or about 10 billion DM per annum in 1975 prices [1]. Corrosion is estimated to impose a similar level of costs on advanced economies with one estimate being 5% of GNP. Admittedly, the idea of a direct cost imposed by materials degradation is simplistic in economic terms as much economic activity is generated by replacement of corroded or otherwise degraded components. However, even with the beneficial effect of extra economic activity, materials degradation represents an undesirable financial burden and it is the task of engineers to try and reduce it as much as possible.

As discussed above, before a component or device must be replaced because of materials degradation, some loss of performance would have already occurred. Rusting and corrosion can reduce the factor of safety in mechanical strength so that a structure or component can fail unexpectedly during severe loading. In 1989, a Boeing 747 aircraft suffered an in-flight structural failure, which is believed to have been due to localized corrosion and metal fatigue. Fortunately, the structural failure was limited to the loss of a door and the plane was able to land safely. Corrosion products of pipe materials can easily become contaminants of the fluid conveyed by the pipe. Dissolved metal emanating from the stirrer blades of a casting system can compromise the metallurgical content of the cast metal. Wear of screw threads and gears causes a progressively increasing backlash in mechanical transmission. This will prevent accurate location of a cutting tool or milling cutter. Wear of cutting tools causes increased roughness and dimensional inaccuracy on the cut material. This corruption of mechanical performance by materials degradation must be considered when devising reliable engineering systems.

Before the reader is persuaded that materials degradation is entirely destructive, it should be noted that the same phenomena, which in uncontrolled form cause damage, could also be controlled to achieve useful results. For example, the interaction between corrosion and abrasive wear by small hard particles is found to polish silicon wafers much more efficiently than pure abrasion by the hard particles alone. In this instance, the acceleration of abrasive wear by corrosion reduces the time required to remove machining marks from a silicon wafer surface and generate an extremely smooth surface on the wafer. The key factor is control, which is very costly to implement and cannot be readily applied on a routine basis to any engineering system. This is a major reason why materials degradation is suppressed instead of being arranged to occur at some pre-set time. It would be economically advantageous if a large metal structure such as a ship could be planned to self-destruct into small manageable lumps of metal at the end of its service life. At present, obsolete ships are often manually dismantled by large teams of workers in countries with low labor costs. It is probable that in the future, all countries will reach similar labor costs with no cheap labor countries. Ship breaking will then become more expensive and impose an extra cost on ship construction unless an alternative method is found.

1.5 Summary

Human culture has recognized the importance of materials degradation since the beginning of civilization. Many methods of protecting materials have been devised based on either traditional practice or more recently on scientific knowledge. There are many forms of materials degradation, which require a specific mode of protection, which may not be applicable to another form of material damage. Materials degradation causes such a high level of costs to industry and individuals that effective countermeasures are essential. Damage to materials can lead to either complete failure of an engineering system or else its loss of performance, efficiency or accuracy.

Recommended Reading

1. Research Report, 1976. (T76-38) Tribologie (Code BMFT-FBT76-38), *Bundesministerium fur Forschung und Technologie* (Federal Ministry for Research and Technology), West Germany.

Study Questions

1. *Why is the total cost of wear and corrosion for any developed national economy so large?*
2. *How does wear and corrosion affect the design of a motor car?*
3. *What are the implications of selecting lightweight materials or composites for structural applications?*