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Edited by

Alrick L. Smith

Butterworths

Reliability of Engineering Materials

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Butterworths
London Boston Durban Singapore Sydney Toronto Wellington

First published 1984

British Library Cataloguing in Publication Data

Reliability of engineering materials.
1. Strength of materials
I. Smith, Alrick L.
620.1'12 TA405

ISBN 0-408-01507-1

Library of Congress Cataloging in Publication Data

Main entry under title:

Reliability of engineering materials.

Papers from the First European Symposium on Materials Reliability held in Baden, Switzerland, Oct. 26, 1983, sponsored by EUREDATA (the European Reliability Data Banking Association)
Includes bibliographies.
1. Materials – Reliability – Congresses. I. Smith, Alrick L. II. European Symposium on Materials Reliability (1st : 1983 : Baden, Switzerland)
III. European Reliability Data Banking Association.
TA401.3.R45 1984 620.1'1 84-17618
ISBN 0-408-01507-1

Printed in England by Page Bros Ltd., Norwich, Norfolk

Reliability of Engineering Materials

Preface

Engineering materials encompass a vast spectrum of characteristic types destined for performance in an equally vast spectrum of operating environments. Programmes aimed at new materials development, materials characterization and materials lifetime assessment are gaining impetus in the three geographic "units" of North America, Japan and Europe. A new discipline of "materials reliability", spawned from the application of reliability engineering techniques to materials science, is rapidly developing. In order to promote this discipline within Europe where, all too often, geographical barriers are compounded by language barriers, Motor-Columbus Consulting Engineers Inc., with headquarters in Switzerland, proposed hosting the "First European Symposium on Materials Reliability".

EUREDATA (the European Reliability Data Banking Association), an organisation of reliability data bank operators within Europe has, for some time, had an active working group investigating aspects of materials reliability data collection, storage and application. It was, therefore, agreed that EUREDATA would sponsor the Symposium with the objectives of bringing together a limited number of scientists and engineers, working in Europe on materials problems, to review and synthesize various fields of materials applications and thereby lay the foundations for the definition, assessment and applications of materials reliability in order to assist the furtherance of this discipline within Europe.

The chapters of this book represent the papers (some detailing work for the first time in the English language) presented at the First European Symposium on Materials Reliability, held in Baden, Switzerland, on 26 October 1983. The papers have been edited and arranged so as to constitute a logical and self-consistent presentation of the subject "Reliability of Engineering Materials". The comments expressed herein do not necessarily reflect the official policy of either Motor-Columbus or EUREDATA and any textual and related errors are the sole responsibility of the editor.

A.L. Smith
(Editor)

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1 THE RELIABILITY OF ENGINEERING MATERIALS - INTRODUCTION AND OVERVIEW

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1.1 BACKGROUND

Engineering materials encompass a vast spectrum of characteristic types destined for applications in an equally vast spectrum of operating environments. It is useful, therefore, to categorize these materials into generic types, or classes, since reliability considerations regarding engineering materials are presently usually class-related.

Three broad classes of materials may be defined:

- Metals and metallic alloys
- Amorphous alloys (metallic glasses) and metallic composites
- Nonmetallics.

The latter class may be further subdivided, as follows:
. natural and synthetic rubbers
. plastics
. ceramics
. carbon and graphite
. natural composite materials.

The following comments are worth making in connection with some of these subdivisions:

Plastics

Plastics are that subclass of nonmetallics comprising thermoplastics and thermosetters. Thermoplastics (e.g. fluorocarbons, nylon, polyethylene, polypropylene, polystyrene, vinyls) all soften with increasing temperature and return to their original hardness when cooled. Most are meltable. Thermosetters (e.g. epoxy, polyesters, ureas) all harden when heated and retain their hardness when cooled. They "set" into permanent shape when heated under pressure.

Ceramics

Ceramic materials include brick, stoneware, porcelain, fused silica, glass, clay tile, concrete, abrasives, mortars and high-temperature refractories. In general, compared with metals, ceramics resist higher temperatures, have better corrosion and abrasion resistance (including erosion-corrosion resistance) and are better insulators. On the other hand, ceramics are brittle, weak in tension and subject to thermal shock.

Composite Materials

There is no really adequate definition of a composite material, but there are three main requirements for any acceptable composite material for use in engineering applications. These are /1/:

- It must consist of two or more physically distinct and mechanically separable materials.
- It should be able to be made by mixing the separate materials in such a way that the dispersion of one material in the other can be achieved in a controlled manner to ensure optimum properties.
- Its properties must be superior, and possibly unique in some specific respects, to the properties of the individual components.

Examples of natural composite materials are wood, bamboo, bone, muscle and other living tissue.

Metallic and amorphous alloys, metallic composites and thermoplastics constitute a group of synthetic composite materials termed microcomposite. (Natural composite materials also being microcomposites.) Engineered products such as galvanized steel, reinforced concrete, skis, etc. constitute a group of synthetic composite materials termed macrocomposite.

Most developmental work in engineering materials today is taking place with regard to composites (including plastic-based composites) and ceramics. Nevertheless, metals (and metallic alloys) and ceramics presently constitute over 90 % of world usage of engineering materials and, consequently, the chapters of this book will be primarily concerned with these two classes of materials.

1.2 FAILURE OF ENGINEERING MATERIALS

Engineering materials can be utilized for the construction of passive, active and what will here be referred to as "reactive" components and/or structures. Examples of the former include buildings, dams, storage tanks, containers, pipes (under cetain fluid-flow conditions), flanges, fasteners such as rivets, etc. Examples of the second class include pumps, motors, gears and all working machinery, etc. Examples of the latter class are basically passive components and/or structures which are subjected to continuously variable environmental stresses of a sufficiently large magnitude as to result in large-scale "response" of the structure. Specific examples which can be mentioned are pressure vessels, aircraft bodies, bridges and offshore oil platforms.

Sometimes passive components (e.g. pipes, tubing) can be combined to form a reactive component (e.g. oil platform) or even an active component (e.g. heat exchanger although it could be argued that this is a reactive component). A complete offshore oil-platform system, including topside equipment, actually constitutes a "composite structure" (not to be confused with a composite material) comprising passive (e.g. buildings), reactive (support structure) and active (e.g. pumps and other machinery) constituents. In the case of a heat exchanger (as will be discussed in Chapter 8) the failure of the active component is determined by the failure of its constituent passive components.

Applying the "bathtub", failure rate versus time, characteristic (Fig. 1.1) utilized in failure/reliability considerations on active components to reactive and passive components as well, one may make the following comments:

- In the case of reactive components/structures, design and testing (e.g. pressure tests on pressure vessels) ensure field operation of the component away from the infant mortality regime and design and in-service inspection ensure field operation of the component away from the wear-out regime.

- In the case of passive components, the same comments as made above are generally true, with the main difference being that more emphasis is placed on initial design and materials selection to ensure field operation in the useful life regime.

Whether one is dealing with active, reactive or passive components, engineering considerations strive to ensure that the plateau of the "bathtub" curve is as low and as long as possible. Cost considerations, naturally, limit both the extent and shallowness of the plateau. However, when safety considerations play an important role (such as in the case of a nuclear reactor pressure vessel, as will be discussed in Chapter 3) the shallowness of the plateau should lie in the region of 10^{-7} failures/year (a figure which is, however, still subject to intense international debate).

On the other hand, profit considerations relating to the industrial utilization of components require as long a plateau as possible. Only an optimization analysis can indicate whether the savings in cost (sometimes at the expense of increased risks) by not pushing for too long or too shallow a plateau are indeed not exceeded by expenditure on replacement parts. Broadly speaking, one might say that the subject of this book (the reliability of engineering materials) is concerned with deriving information on materials behaviour which can be used to maximize the useful life/minimize the failure rate of the components/structures fabricated from the material in question.

It is clear that reliability considerations of this nature can have important consequences for safety. Very often, however, the equally important cost consequences are often overlooked. Utilizing data available on the economic impact of materials failure in the USA /2,3/ and converting this to an inflation-adjusted per capita GDP figure, one can estimate that, for the EEC countries alone, the annual cost of materials failure and attendant conventional prevention efforts is in the region of SFr. 300,000 million. This figure is horrifying. (Its plausibility is substantiated by considering that the annual cost for zinc oxide painting to protect against rust, at just one particular European chemical plant, is over SFr. 5 million; also, the indirect cost, in losses due to one day's outage of a 1,000 MW class European nuclear power plant, caused by a failed condenser tube for example, is in the region of SFr. 1 million).

Efforts aimed at increasing existing knowledge about the failure of engineering materials in an effort to utilize this additional knowledge to reduce such failures are, without doubt, justified.

1.3 THE CLASSIFICATION AND SOURCES OF FAILURE IN ENGINEERING MATERIALS

When can an engineering material (or component/ structure fabricated from the material) be considered to have failed? For instance, a support beam, when fractured and without additional struts or ties, can be regarded as having "failed". A waste-disposal storage tank containing highly toxic or radioactive liquid waste can be regarded as having "failed" when it begins to leak (although the consequences of the leak or failure will be dependent upon the magnitude of the failure and its capabilities for imparting damage).

However, with a toothed gear, for example, if the crown of one of the teeth fractures (and provided the broken-off portion is small and is ejected without causing seizure of the gear) the gear can continue functioning and cannot be considered to have "failed". On the other hand, even in the absence of fracture, when the teeth are sufficiently worn to prevent the gear from rotating at all, the gear can be regarded as having "failed". (Note that in both cases the material itself can be regarded as having "failed".) For this reason, one cannot speak of a failure of a component/structure without reference to either its intended function or use to which it is to be put. By including such reference, not only is it possible to talk of failure, but one can then readily define failures of even passive components. A definition of the "reliability" of an engineering material is then feasible (although inherent difficulties in achieving consistency in the use of any such definition in the various fields of materials applications will be highlighted throughout this book).

Generally, an engineering material can be considered to have failed when the component/structure fabricated from the material fails to perform its intended function with the required efficiency. One may, therefore, define the reliability of an engineering material (analogous to the definition of the reliability of an active component) as the probability of non-failure of the engineering material, in a specified use or application, in a specified interval of time in a specified environment. One may then say that the assessment of the reliability of a material is the assessment of the probable lifetime of the material before failure in a specified application. A related aspect, which is of considerable economic significance, is the assessment of the potential residual lifetime (lifetime beyond the assessed probable life) of materials in various applications, for example high-temperature gas turbines, as will be touched upon in Chapter 5.

The following list /4/ provides a useful classification of failures:

- Yielding of the component material under static loading. Yielding causes permanent deformation which could result in misalignment or hindrance to mechanical movement.

- Buckling, which takes place in slender columns when they are subjected to compressive loading, or in thin-walled tubes when subjected to torsional loading.

- Creep failure, which takes place when the creep strain exceeds allowable tolerances and causes interference of parts. In extreme cases failure can take place through rupture of the component subjected to creep. In bolted joints and similar applications, failure can take place when the initial stressing has relaxed below allowable limits, so that the joints become loose or leakage occurs.

- Failure due to excessive wear, which can take place in components where relative motion is involved. Excessive wear can result in unacceptable play in bearings and loss of accuracy of movement. Other types of wear failure are galling and seizure of parts.

- Failure by fracture due to static overload. This type of failure can be considered as an advanced stage of failure by yielding. Fracture can be either ductile or brittle.

- Failure by fatigue fracture due to overstressing, material defects or stress raisers. Fatigue fractures usually take place suddenly without apparent visual signs.

- Fracture due to impact loading, which usually takes place by cleavage in brittle materials for example in steels below brittle-ductile transition temperature.

- Failure due to the combined effect of stresses and corrosion, which usually takes place by fracture due to cracks starting at stress concentration points, for example caustic cracking around rivet holes in boilers.

More detailed considerations of failure by corrosion will be presented in Chapters 7 and 8.

The sources of failure in engineering materials can be generally identified as one (or more) of the following:

- Design deficiencies (e.g. lack of engineering effort to avoid design features known to be conducive to failure, inadequate or erroneous stress analyses, etc.)
- Material selection deficiencies (e.g. specifying materials with inappropriate microstructure or with irremovable imperfections or flaws)
- Processing deficiencies (e.g. improper heat treatment)
- Assembly and installation errors (e.g. unsatisfactory welding, post-fabrication maltreatment - pitting resulting from electrolytic cleaning for instance, etc.)
- Operational and maintenance errors
- Environmental impacts (usually impacts resulting in previously unforeseen stresses or effects that can induce unforeseen failure mechanisms. The effect of the environment is clearly demonstrated in Table 1 which indicates the influence of three different environments on the fatigue strength of four mirror-polished steels of differing ultimate tensile strengths.)

Table 1: Environmental Effects on Fatigue Strength of Mirror-Polished Steels of Differing Ultimate Tensile Strength

Ultimate Tensile Strength (MN/m2)	Maximum Endurance Strength as a Percentage of Maximum Endurance for Steel in:		
	Air	Fresh Water	Salt Water
280	100	72	52
560	100	53	36
1,120	100	25	17
1,540	100	19	14

To reduce the overall impact of materials failure, the above sources (or causes) of failure must be eliminated or reduced through:

- Improved designer/manufacturer/installer/operator reliability
- Improved knowledge concerning materials properties and behaviour (including improved storage of, and access to, relevant data) under different circumstances
- Improved methods for forecasting materials behaviour, and greater accuracy in lifetime assessment, under environmental uncertainties
- Improved materials technology and manufacturing/processing techniques (including the use of "superior" materials, wherever applicable). An example is hot isotatic pressing (HIP). Fig 1.2/5/ depicts the stress-rupture properties of cast, hafnium modified B-1900 alloy at 760 °C and 650 MPa without and with HIP and the improvements as a result of the improved technology are clearly apparent.

1.4 ASPECTS CONSIDERED IN THIS BOOK

An attempt has been made in the chapters which will follow to consider in greater detail the various aspects referred to above. One particular aspect which has not, however, been considered is the impact of the radiation environment on materials, since this has not too long ago received sophisticated treatment elsewhere /6/.

Whilst one may readily appreciate that it is not meaningful to attempt to talk about the reliability of a material without reference to the applicable environment, what is often forgotten is the fact that this implies reference to structural properties since it is these which determine the "contact" between the material and its environment. This can clearly be understood by considering that a solid cube of iron in a corrosive environment will support an object placed on top of it for a longer period of time before failure of the support than will the same mass of iron in the same environment when the iron is a thin-walled hollow cubic structure. Thus, structural aspects should not be forgotten in any considerations on materials reliability.

In this book, structural aspects such as have already been treated in /7/ for example, will not, however, be considered. Instead, in Chapter 2, a novel method for modelling component structural integrity, with the objective of determining failure probability, is presented. Problems relating to data distributions for toughness and defect size are discussed and the fracture mechanics approach is fully employed. These metallic materials fracture mechanics considerations are followed on in Chapter 3 by the development of a mathematical definition of materials reliability and the application of an international benchmark exercise to the assessment of the failure probability of a light-water reactor pressure vessel. The influences of the selection of, and dispersion in, input data are considered in more detail and implications for non-destructive examination (NDE) are assessed. In Chapter 4, fracture mechanics considerations, together with strength distribution and critical flaw size aspects, are applied to non-metallic (cementitious) materials. The role of the microstructure as a factor in reliability considerations is emphasized.

In Chapter 5, high-temperature behaviour of metallic materials is treated, once again emphasizing the importance of microstructure. A novel approach to interpreting the term "reliability" is adopted through a careful consideration of the dispersion in data measurements. Chapter 6 takes the question of data in high-temperature applications a stage further by considering storage, retrieval and interchange of such data using computerized data banks. A specific European high-temperature materials data bank is described. Materials reliability data banking in the chemical industries is discussed in Chapter 7, where corrosion problems are highlighted. The possible use of zirconium as a material in urea reactors is also given attention and it is interesting to note improved component reliability obtained elsewhere /8/ through the utilization of this metal. Teledyne Wah Chang, amongst other interesting results, report that whereas malleable iron flanges for stripper columns and impervious graphite heat-exchanger tubes in a particular chemical process had a lifetime of a few years, replacement by substitutes fabricated from zirconium R60702 resulted in the flanges lasting the life of the column and the heat-exchanger tubes showing no signs of corrosion after even eight years' service.

The final chapter extends the corrosion considerations of Chapter 7 to heat exchangers, primarily from the standpoint of large power plant condensers. An expression for the mean time between failures of the condenser, in terms of number of tubes, is established and the modes and causes of tube failure are discussed in detail, together with methods for combatting such failure. This work complements the discussion on heat-exchanger reliability recently presented in /9/.

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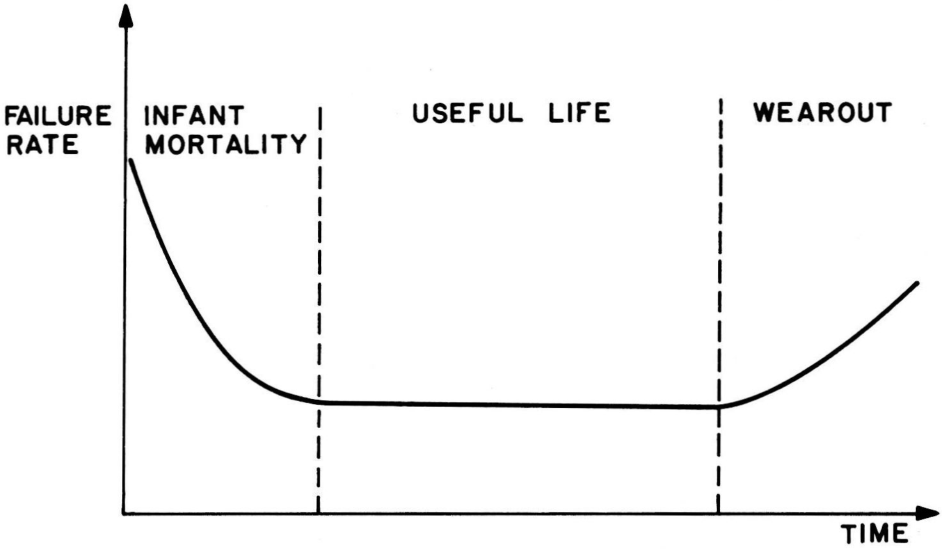

Figure 1.1: The Failure Rate-Age "Bathtub" Curve

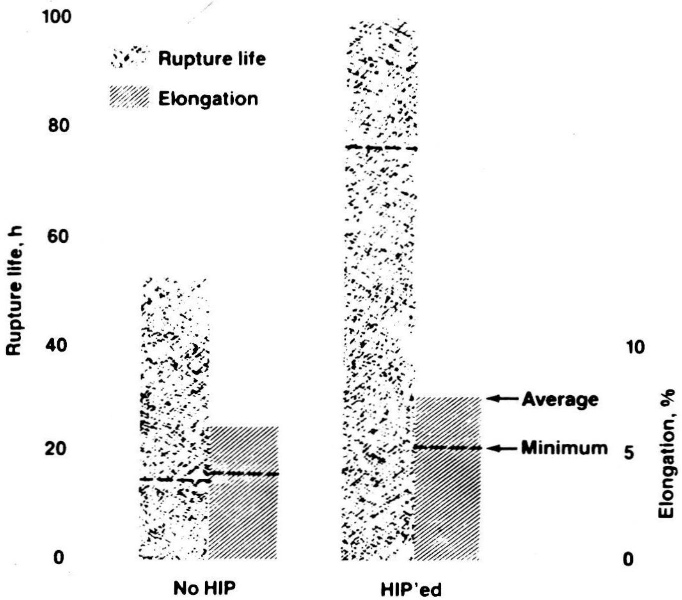

Figure 1.2: Stress-Rupture Properties of Cast, Hafnium Modified B-1900 Alloy /5/