METAL FATIGUE

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Edited by

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PREFACE

THIS BOOK derives from a week's residential course on the "Fatigue of Metals" held in the Engineering Department of Nottingham University in September 1955, and attended by 150 members from industry. The object of the course was to present to practising engineers the known facts about metal fatigue and its effects on design, a subject of growing importance in which the University engineering department is carrying out much fundamental research. The course was organized by a committee taken from both industry and the University, under the chairmanship of Mr. G. Forrest. A third of the lectures was given by members of the University, the others by members from industry, research associations and Government departments, each chosen for his expert knowledge in a particular branch of the subject. Each lecture was prepared independently as a self-contained entity. Many of those attending suggested that the lectures should be published in the form of a symposium.

In this book, the substance of the lectures remains unaltered. Each chapter represents one lecture, the whole dividing naturally into three parts:

I. The Fundamentals of Fatigue.
II. The Fatigue Properties of Engineering Materials and Components.
III. Fatigue Testing of Engineering Components.

Inevitably, a symposium of so many independent works involves overlapping. Some aspects are treated over-generously, and some a little sparsely. No effort has been made to prevent this, so that the reader may have a balanced picture of the views of each lecturer. The differences of opinion will be seen to be insignificant, and the vast degree of unanimity really remarkable.

The only features added to the lectures for publication are purely formal. For instance, a standard nomenclature has been used throughout. The work is compiled with the engineering designer in mind, and it has been assumed that, unlike the research worker, the designer will not have a comprehensive library at his elbow. Where reference was made in the lectures to other published works, the salient points have been reproduced in the text. This, of course, does not absolve the reader from referring to the originals if he wishes to "dig deep", and the relevant publications are noted at the end of each chapter.

The Editor believes that this work presents a very clear picture of the present state of knowledge of the fatigue of metals as far as it affects the engineering designer. It is most important that the designer should master Part I if he is to understand fully the implications of the information contained in Part II. Part I should also be of value to the research worker who is coming new to the problem of fatigue. Part III deals with testing and as such should have a special appeal to the development engineer. But again, the designer cannot afford to neglect it. Fatigue of engineering components is so complex that if he is to design up to the limits of his material, he must first test prototypes. In this context, Chapter VI might be taken with Part III.

The Editor's task has been made most enjoyable, thanks to the co-operation and help he has received—from the course committee; his co-authors; numerous workers in this field, who have readily allowed publication of their results; industrial firms, research organizations and Government departments, who have generously helped the authors; and the publishers for their expert assistance. Especially, thanks are due to Mr. G. Forrest for his able guidance in the organization of the course and to my colleague Mr. F. Sherratt who, in addition to checking all proofs, made many helpful suggestions regarding the arrangement of the text.

J. A. P.

LIST OF SYMBOLS

a, b	Measurements of length
d	Diameter
e	Strain
f	Applied stress
f_B	Maximum stress in an inhomogeneity (Orowan)
f_f	Semi-range of direct stress at fatigue limit with mean stress
f_k	Fatigue strength of notched specimen
f_m	Mean tensile stress under fatigue loading
f_n	Average stress when stress raiser is present
f_0	Tensile fatigue (or endurance) limit with zero mean stress
f_u	Ultimate strength in tension
f_y	Yield strength in simple tension
G	Modulus of rigidity
g	Acceleration due to gravity
I	Second moment of area
K_f	Experimental stress concentration factor (or strength reduction factor)
K_t	Theoretical stress concentration factor
M	Bending moment
m	Stress gradient
m_1, m_2	Mass
N	Number of reversals of stress
P	Force
p	Pressure
p_1, p_2, p_3	Principal stresses in the x, y and z directions respectively
p_v	Volumetric stress, $p_1=p_2=p_3$
Q	Notch sensitivity index, $\frac{K_f-1}{K_t-1}$
q	Applied shear stress
q_f	Semi-range of shear stress at fatigue limit with mean stress
q_m	Mean shear stress under fatigue loading
q_0	Shear fatigue or endurance limit with zero mean stress
q_u	Ultimate strength in torsion
q_y	Yield strength in simple shear
R	$\frac{q/q_0}{f/f_0}$
R_1, R_2, R_3, etc.	Principal radii of curvature of curved surfaces
r	Operative radius associated with stress raiser

S	Factor of safety
S_c	Contact stress between curved surfaces
t	Time
w	Angular frequency
x, y, z	Displacements
α, β	Constants used in the ellipse arc relationship
γ	Ratio: $\dfrac{\text{Applied torque}}{\text{Applied bending moment}}$
ψ	Angle plane of maximum shear makes with cross-section of the specimen under combined bending and torsion
ϵ	An electron (with reference to electrolytic action)
U.T.S.	Ultimate tensile strength

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PART ONE

The Fundamentals of Fatigue

CHAPTER I

THEORY OF FATIGUE FAILURE

SYNOPSIS

The nature of the fatigue fracture is described. Metallurgical and X-ray aspects of the fatigue phenomena are discussed. Detailed attention is given to Orowan's theory for fatigue. Finally, attention is given to the effect of mean stress on fatigue strength.

Introduction

With the modern trends of engineering design in which the factor of safety is being continually reduced to the absolute minimum and the speed of operation of machine parts continually increased so that the degree of dynamic loading to be sustained by a component is considerable, it is no exaggeration to claim that the fatigue strength of a metal is probably one of its most important mechanical properties. In all cases of dynamic loading at normal temperatures it is, directly or indirectly, the limiting factor of design. The fatigue strength of metals is, however, a complex subject; it is not apparently a unique property of the metal (although fundamentally it probably is) and is affected by the size of the component, its shape, the type of stress to be applied and the relationship between the dynamic and static stresses it has to withstand. These may be regarded as mechanical variables, and superimposed on these are important metallurgical factors. It is not surprising then that to the uninitiated the fatigue of metals may be regarded as "an enigma wrapped in mystery".

The object of the first five chapters is to deal with the fundamental factors affecting the fatigue of metals and to treat the subject qualitatively rather than quantitatively. At certain points there may be a slight over-simplification for the sake of clarity. The main aim is to underline the more important points and to illuminate the significant trends. In short to provide the "bones" of the subject. My fellow authors, who are dealing with detailed problems, will supply the flesh. It is hoped that by the end of the book the "body" will be complete and will cease to be a corpse but become alive. The success of this volume will be measured not by what information is acquired, but by how much one really believes and trusts this information to the extent of applying it with sound argument and judgement to engineering design. In the battle against metal fatigue there can be no one fixed code of practice. The problem is too complex for that. Success can only come when minds are alert to the fundamental factors affecting the phenomena and each problem tackled on its merits.

The Fatigue Failure

The most characteristic feature of fatigue fracture, and one which greatly worried early engineers, is that even with the most ductile materials failure takes place without revealing any plastic deformation, and generally when the part has been stressed (albeit repeatedly) below the elastic limit. The fractured surfaces show a nucleus, usually at the edge of the fracture, where the crack started. This nucleus is usually smooth and relatively bright where the two surfaces, forming the boundary of the crack, have been rubbing together. The surface immediately around this spot is also relatively smooth indicating the path followed by the crack as it propagated. Eventually the crack spread to such an extent that the remaining metal

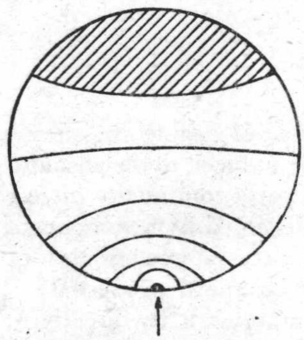

Fig. 1.1. Development of a fatigue crack under repeated bending.

could not support the combination of the applied load and the stress concentration at the head of the crack for even one application and the crack propagated instantaneously and failure was complete. Fig. 1.1 shows diagrammatically the stages in the development of a fatigue fracture. The final path of the crack develops a fractured surface which gives the impression of revealing the grain or crystal structure (this is not actually the case) and hence in the early days there arose the misnomer of "crystalline" fracture or crystallization. This implied a fundamental change in the metallurgical structure of the metal, where in fact this is not the case. Examined on a micro scale the process seems for ferrous materials identical with that of static rupture. It is the mechanical factors which affect the macro behaviour of the metal. The picture given of the development of a fatigue failure is only strictly true for fractures in relatively homogeneous material. It is not applicable to the fractures in materials such as cast iron.

The fact that fatigue failure takes place without previous plastic deformation means that no high stress peaks in the part, due either to design or