Fatigue and Durability of Structural Materials

S.S. Manson

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Preface

by S.S. Manson

The past half century has witnessed a virtual revolution in the development of two fields which are the subject of this book: the introduction of advanced materials as structural components in severely loaded machines exposed to high temperatures and temperature gradients, and the development of technology of life computation for such components, of which one of the major failure mechanisms is fatigue. This book is based on the experience of the authors during this period. Although it emphasizes our research both as individuals and as colleagues for half a century, it also includes the work of numerous others who have provided useful results that have moved progress in these fields.

My first report on fatigue appeared in 1953. An intense interest and activity in this rapidly changing field has continued since. Collaboration with Dr. Gary Halford started in 1966 when he joined NASA at its Cleveland center where I served as Chief of the Materials and Structures Division. This cooperation continued after I retired in 1974 to join the faculty of Case Western Reserve University, and even after I retired from CWRU two decades later. We started to write this book well before I left CWRU. Thus, this book has been in the making for a long time, perhaps longer than we care to admit. But to compensate for the slowness of its progress toward publication, it is fair to say that we have been continuously adding content from our own research, and from that developed elsewhere, as warranted.

Initially this book was prepared as a text on fatigue, and its content fashioned after my regular curriculum presentations at Case Western Reserve University, short course presentations at the Pennsylvania State University, and shorter presentations at MIT, The Technion in Israel, and numerous other universities. In later-year presentations it was broadened under the title *Relation of Materials to Design* to include content developed at NASA. Its current context is still largely related to fatigue but includes other subjects representative of the material presented in these courses.

I am grateful to NASA for the support it has rendered me during my employment there, and later in grants provided to continue my activities initiated there. I am also grateful to the Oak Ridge National Laboratory, the Electric Power Research Institute, and the Metals Properties Council for their grants to conduct the research described in this book. My most heartfelt gratitude is expressed toward my co-author, Gary R. Halford. It has been a genuine joy to work with him as a colleague, friend, and co-author.

As always, I express my deep appreciation to the Almighty for the gift of life and long-time participation in the developments contained in this book.

S.S. Manson
December 2005

Preface

by G.R. Halford

This book and a planned second volume dealing with high-temperature durability represent the culmination of many years of collaborative research with my highly respected colleague, S.S. Manson. Few researchers have had the luxury of being able to work together continuously for as long as we have. And few colleagues have been able to work together as amicably as we have. We were fortunate to be involved in numerous advancements to the field through individual and joint publications spread over five decades. Our combined years of experience exceeds a century. This book provides a repository of the most significant of our contributions to the art and science of material and structural durability. Valuable contributions from other researchers are also included as appropriate.

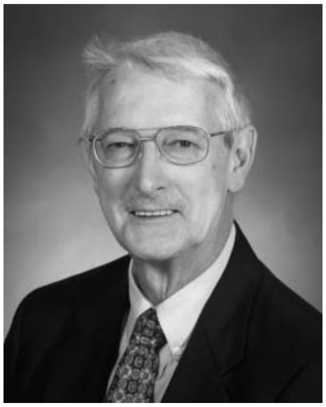
I cannot sufficiently thank NASA for the rare opportunity provided me to have been allowed to work in this field for the duration of my employment. A prime advantage provided by a large government research organization was that we had valuable technical contacts with not only the aerospace industry, but also with many other industries, including electric power generation, off-highway and automotive manufacturing, metals producers, chemical and petroleum producers, and numerous other industries that faced serious material and structural durability issues. We were thus privileged to have exposure to countless durability issues of a diverse nature. From such a vantage point, it was possible to develop generic models having a broad range of applicability.

I would also like to thank the University of Illinois in Urbana-Champaign, its Department of Theoretical and Applied Mechanics, and in particular, Professor JoDean Morrow. I could never have been in a position to participate in this work without their providing me with the appropriate educational background. Finally, my late parents, Herbert C. and Faye S. Halford, brother Donald W. Halford, my wife, Pat M. Halford and our children, Kirk, Gwen, and Shawn must be acknowledged for instilling me with balanced senses of patience, work ethic, responsibility, dedication, and respect—all interspersed with a tinge of humor.

Gary R. Halford
December 2005

About the Authors

S.S. Manson is Professor Emeritus, Case Western Reserve University. Professor Manson joined the National Advisory Committee for Aeronautics (the precursor to NASA) at Langley, VA in 1941 and transferred to Cleveland in 1943. There, he performed cutting-edge theoretical and experimental stress analysis and durability research associated with the materials used in piston engines and the newly evolving gas turbine engines. His research interests drew him into the entirely new area of low-cycle fatigue, particularly thermal fatigue. The basic law of low-cycle fatigue that he developed remains in use 50 years later, i.e., the Manson-Coffin law. His research expanded into the study of creep, creep-rupture and time-temperature parameters, for which he created several of great practical value. He has received numerous awards for his work, including the Gold Medal from the Franklin Institute for development of the Manson-Coffin law of low-cycle fatigue, the NASA Exceptional Scientific Achievement Award, and the Nadai Award bestowed by the American Society of Mechanical Engineers. His book *Thermal Stress and Low-Cycle Fatigue* was published in 1966. He remained at NASA until 1974, serving most of the time as Chief of the Materials and Structures Division. At that time, he moved on to become Professor of Mechanical and Aerospace Engineering at Case Western Reserve University. There he continued to teach on the subject of the mechanical behavior of materials and perform research together with his students and colleagues to develop better durability lifing models. He currently lives in California.



G.R. Halford is a Distinguished Research Associate, NASA Glenn Research Center, Cleveland, Ohio. Following his education in the Department of Theoretical and Applied Mechanics at the University of Illinois under the guidance of Professor JoDean Morrow, he joined the NASA Center in 1966. Dr. Halford, in conjunction with Professor S.S. Manson, has been actively involved in research and development of advanced life prediction methods for low- and high-temperature fatigue analysis of high-performance mechanical systems. Most notable is the total strain version of the method of strain-range partitioning (SRP). That methodology sees use in several industries. Dr. Halford has been involved with durability issues in virtually every propulsion system of interest to NASA. In the aeronautics arena, he has dealt with subsonic, supersonic, and hypersonic propulsion systems. In space propulsion and power, he has dealt with ion engines, solid propellant rockets, liquid rockets of all sizes and description, as well as solar and nuclear energy conversion and storage systems. The severe durability limitations of these systems have spawned much of the research into advanced life prediction methods that are the subject of the planned second volume of this book. Dr. Halford has authored or co-authored over 200 technical papers, coordinated over 60 grant/contractor reports, edited several technical conference volumes, and delivered over 70 invited technical lectures.

Abbreviations and Symbols

a	Crack length
A	Cross-sectional area; creep coefficient; ratio of amplitude to mean
b	Maximum possible crack length; Basquin exponent; thickness where t is time
B	Bulk modulus; Bridgman correction factor; number of repetitions of a cyclic loading sequence
HB	Brinell hardness number
c	Half-depth of beam; radius of shaft; plastic strain vs. life (Manson-Coffin) exponent
C	Fatigue crack growth coefficient
d	Diameter; derivative
e	Engineering strain; base of natural logarithms ($e = 2.718\ldots$)
E	Modulus of elasticity
F	Force; finite width factor of fracture mechanics
G	Shear modulus; strain energy release rate
h	Height; half-height of cracked bodies
I	Area moment of inertia about an in-plane axis
J	Polar moment of inertia; J-integral; damping coefficient
k	Stress or strain concentration factor; spring constant
ksi	Thousand psi
K	Stress or strain concentration factor; fatigue-strength reduction factor; stress-intensity factor of fracture mechanics; strength coefficient for stress-strain curves
L	Length
m	Fatigue limit reduction factor; fatigue crack growth exponent; creep exponent
M	Bending moment
n	Strain hardening exponent, number of applied cycles
N	Number of cycles
p	Pressure
psi	Pounds per square inch
P	Force (load)
q	Notch-sensitivity factor
Q	Activation energy
Q^{-1}	Loss coefficient in damping
r	Radius
R	Ratio for cyclic loading (min/max); plastic-zone size; Rockwell hardness
RA	Reduction of area
S	Nominal, average, or engineering stress
SWT	Smith-Watson-Topper parameter
t	Time; thickness
T	Temperature; torque
u	Energy per unit volume, displacement
U	Energy
v	Displacement
V	Volume
w	Width, displacement
W	Hysteresis energy; work
x, y, z	Spatial coordinates
X	Safety factor

Greek Letters

α	Coefficient of thermal expansion; angle; relative crack length ($a = a/b$)
β	Neuber constant
γ	Shear strain; Walker exponent; surface energy
δ	Slope reduction factor; crack-tip opening displacement; phase angle
ε	Normal strain; true strain
η	Tensile viscosity

θ	Angle
λ	Stress biaxiality ratio $\varepsilon_2/\varepsilon_1$
ν	Poisson's ratio
ν	Notch-tip radius
Σ	Summation
	Normal stress at a point; true stress
τ	Shear stress
ω	Angular velocity

Subscripts: Meaning (Example)

a	Amplitude (σ_a); axial (ε_a)
A, B, C, D	Rockwell Hardness Scales (R_A); general coefficients
c	Creep (ε_c); critical (K_c); value at $y = c$ location (σ_c)
d	Diametral (ε_d)
e	Elastic (ε_e); fatigue endurance limit (σ_e)
eq	Equivalent (σ_{eq})
f	Final (A_f); failure (N_f); true fracture strength (σ_f); or fatigue-strength reduction factor (K_f)
fp	Fully-plastic value (M_{fp})
g	Gross section (S_g)
i	Initial (A_i); summation index, *i*th level of loading
I	Mode one
II	Mode two
III	Mode three
Ic	Critical plane strain (K_{Ic})
j	Summation index where *i* means *initial*
m	Mean (σ_m); melting (T_m)
max	Maximum (σ_{max})
min	Minimum (σ_{min})
n	Nominal stress (σ_n)
oct	Value for octahedral planes (τ_{oct})
p	Plastic strain (ε_p); proportional limit (σ_p)
r	Residual (σ_r); rupture (t_r)
ss	Steady-state creep (ε_{ss})
t	Total (ε_t); theoretical (K_t)
tc	Transient creep (ε_{tc})
tr	Tertiary creep (ε_{tr})
T	Transition life (N_T)
u	Ultimate (σ_u)
x, y, z	Direction (σ_x); axis (I_z)
xy, yz, zx	Plane (σ_{xy})
y	Yield (σ_y)
1, 2, 3	Principal direction (σ_1)
ε	Strain (R_ε)
σ	Stress (R_σ)

Modifiers: Meaning (Example)

δ	Increment or interval ($\delta\sigma$)
$\Delta\sigma$	Deflection; range of variable ($\Delta\sigma$)
dot	Time rate ($\dot{\varepsilon}$)
prime	Value for cyclic loading (n'); other special values
$\bar{x}$	Overbar used to denote composite material variables and properties
$\lvert x \rvert$	Vertical bars denote composited *matrix material* variables and properties

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