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Boris F. Shorr

Thermal Integrity in Mechanics and Engineering

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To memory of my teachers:
Sergey D. Ponomarev, Jacob B. Fridman,
Yury N. Rabotnov, and Isaac A. Birger

Preface

The design and analysis of high-temperature behavior of engineering structures play an important role for aviation and transport gas turbine engines, stationary steam and gas turbine power plants, including gas-transfer stations, and also for aerospace, atomic and chemical engineering, and other branches of industry.

The pioneering work by J. Duhamel in the middle of the nineteenth century inspired investigation of temperature stresses within the framework of solid mechanics. Interest in engineering applications of this phenomenon manifested only in the early twentieth century with the advent of steam and then gas turbines (A. Stodola, R. Bailey, F. Norton, N. Lebedev, and others). Toward the second half of the last century, the theory of thermal integrity (thermal strength) was established as a branch of engineering science studying high-temperature material behavior. It became especially apparent in connection with the invention of aviation gas turbine engines.

In the West, related problems were embodied in publications by A. Freudenthal, R. Larson and J. Miller, L. Coffin, N. Hoff, W. Prager, B. Gatewood, B. Boley and J. Weiner, R. Hill, and other English-speaking authors.

In the USSR, analysis of material strength at high temperatures in application to aviation gas turbines was initiated by V. Uvarov. Beginning from the middle of the twentieth century, this topic was intensively developed at the Moscow Central Institute of Aviation Motors (CIAM) by I. Birger and S. Serensen, and also by their followers B. Shorr, R. Sizova, R. Dul'nev, I. Dem'janushko, Yu. Temis, and some others. This research was carried out in close collaboration with a number of Russian and Ukrainian colleagues, including Yu. Rabotnov, Ya. Fridman, R. Shnejderovich, N. Malinin, and G. Pisarenko. Main results on the subject were delivered at major scientific conferences and widely published.

A relatively complete exposition of the aforementioned problems until the mid-1970s has been presented in the monograph "Thermal Strength of Machine Parts" edited by I. Birger and B. Shorr. Although 12,000 copies were published, the book gained rare status soon after publication in 1975 in USSR.

However, Russian publications in the area of thermal strength remained unknown to researchers from other countries, except for a small number of contributions translated into English.

During the second half of the twentieth century, both in the West and in Russia, numerous papers and books reporting the novel theoretical and experimental results on the strength of materials and structures under elevated temperatures have been published. The range of applications of these developments has been expanded since non-uniform temperature stresses arise not only in mechanical systems, but also in civil structures, road coatings, and even in the Earth's core.

Thermal integrity is a multidisciplinary field combining joint efforts of mechanical engineers, material scientists, and applied mathematicians approaching the problem from their specific viewpoint. This monograph draws on the research of a broad scientific community including the author's contribution.

The scope of thermal strength analysis was considerably extended due to making use of modern computers along with the implementation of FEM codes. However, the author believes that there is a sort of disparity between the power of advanced software, and lack of easy-to-follow books on the theoretical and experimental aspects of thermal integrity. The author endeavors to ensure the rigor of the underlying assumptions along with sufficient simplicity of presentation making the book compelling to a wide audience.

The book is targeted at engineers, university lecturers, postgraduates, and final-year undergraduate students involved in computational modeling and experimental and theoretical analysis of high-temperature behavior of engineering structures. The book is also intended for attention of researchers developing the thermal strength theory as a branch of continuum mechanics.

The author expresses deep gratitude to Prof. V. Babitsky for support of issuing of the present monograph, Dr. V. Arulchandran and Dr. L. Prikazchikova for their contribution to editing of the English text, Dr. Ch. Baumann and the staff of Springer-Verlag for assistance in publication. The author is grateful to Prof. Yu. Kaplunov, Prof. Yu. Temis, Prof. E. Golubovskiy, and colleagues from CIAM, and also from Keele and Brunel Universities for fruitful discussions.

Moscow Boris F. Shorr

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About the Author

Prof. Boris F. Shorr D.Sc. is a renowned expert in the field of thermal strength analysis. He has played a key role in the dynamical and stress analysis of the numerous aviation and stationary gas turbines of different generations. For many years Prof. Boris Shorr presented the advanced courses in solid and applied mechanics at Moscow Institute of Physics and Engineering, Moscow Institute of Physics and Technology, and some other leading technological universities. Since long ago and to this time he has been affiliated with Central Institute of Aviation Engines in Moscow. He is a winner of Zhukovsky Award, Honourable Scientist of Russian Federation and a member of Russian National Committee of Theoretical and Applied Mechanics, an author of several professional books in Russian and English.

Abbreviations and Basic Symbols

Abbreviations

APS	Accumulated plastic strain
CH	Axis of current anisotropic hardening
FEM	Finite element method
FH	Axis of former anisotropic hardening
HCF	High cyclic fatigue
LCF	Low cyclic fatigue
RAPS	Relative accumulated plastic strain
SAH	Stabilized anisotropic hardening
SARH	Stabilized anisotropic-ray hardening
SSS	Stress–strain state

Basic Symbols

$\sigma_{ij},\ i,j = 1,2,3$	Stress tensor and its components
s_{ij}	Deviator of stress tensor
$\boldsymbol{\sigma}_i$ or $\{\sigma\}$	Stress vector
$\lvert\sigma_i\rvert = \sigma_i$	Magnitude of stress vector equal to stress intensity
σ_{ij}^*	Active stresses
r_{ij}	Residual micro-stresses
$r_{\lim}$	Limiting value of micro-stress unsteady part
β_p	Parameter of hardening stabilization in plasticity
$\tau_{\max}$	Maximum tangential stress
$\varepsilon_{ij},\ i,j = 1,2,3$	Strain tensor and its components
e_{ij}	Deviator of strain tensor
$\boldsymbol{\varepsilon}_i$ or $\{\varepsilon\}$	Strain vector
$\lvert\varepsilon_i\rvert = \varepsilon_i$	Magnitude of strain vector equals to strain intensity
ε_{ij}^e	Elastic strains
ε_{ij}^p	Plastic strains

ε_{ij}^c	Creep strains
ε_{st}^c	Steady creep strains
ε_*^c	Stabilized part of unsteady creep
ε_{*0}^c	Transmitting part of unsteady creep
$\varepsilon_{\lim}$	Limiting value of unsteady creep strain
β_c	Parameter of hardening stabilization in creep
v_i^{st}	Intensity of the steady creep rate
$\gamma_{\max}$	Maximum shear
$\Delta\sigma, \Delta\varepsilon$	Stress and strain increments or ranges
$d\boldsymbol{\sigma}_i$	Increment of the stress vector
$\lvert d\boldsymbol{\sigma}_i \rvert = (d\sigma)_i$	Magnitude of the vector $d\boldsymbol{\sigma}_i$ equal to value of stress increments intensity
$d\sigma_i$	Increment of stress intensity
$d\boldsymbol{\varepsilon}_i$	Increment of the strain vector
$\lvert d\boldsymbol{\varepsilon}_i \rvert = (d\varepsilon)_i$	Magnitude of the vector $d\boldsymbol{\varepsilon}_i$ equal to value of strain increments intensity
$d\varepsilon_i$	Increment of the strain vector
E, E_p	Moduli of elasticity and plasticity
G, E_t	Shear and tangential moduli
K	Bulk (voluminal) modulus
μ	Poisson's ratio
$[D]$	Elasticity matrix
E_p''	Modulus of unsteady plasticity
E^*	Modulus of isotropic strain hardening
E_{p0}	Minimum (limiting) value of plasticity modulus
t	Time—physical or formal quantity
T	Temperature
α_T, β_T	Coefficients of linear and volume thermal expansion
ε_T	Thermal expansion (dilatation)
σ_B	Ultimate stress in tension
σ_y	Yield point in tension
N	Number of cycles or half-cycles
D	Damage
f_p or f^p	Parameter referred to plastic yielding
f_c or f^c	Parameter referred to creep
f_d	Parameter referred to damage or failure
$\hat{v}_i$	Projection of any vector $\mathbf{v}_i$ onto the axis CH
ζ	Factor of restitution (recovery) in creep