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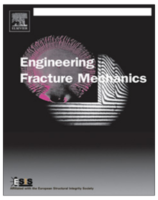

Mechanisms and modeling of subsurface fatigue cracking in metals

A.A. Shanyavskiy

State Centre for Civil Aviation Flight Safety, 141426, Moscow Region, Chimkinskiy State, Airport Sheremetievo-1, PO Box 54, Russia

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ABSTRACT

In terms of a synergetic system at its sequentially increased scale levels, evolution of the fracture-behavior patterns in various cyclically loaded metallic alloys is analyzed together with the alternatives of subsurface initiation of fatigue cracking. When free of the non-homogeneities like lamination sites, inclusions, etc., subsurface cracks arise due to the loss of plastic stability at the micro- or nanometer-scale level, i.e., in the local flat areas up to 500 nm in depth, normal to the load axis. Two mechanisms are controlling the formation of such a region, which is due to the instability of rotational plastic flow and fracture of the material in the state of three-dimensional compression and twisting; thereby, an even facet or a nano-structured zone forms, the latter comprising tiny particles of irregular, ellipsoid and/or spherical shapes. On further cycling, the fracture surface develops on the particle boundaries. The data of numerous investigations are shown to confirm the validity of the above-proposed models on the subsurface nanostructures in metal.

1. Introduction

Currently, the materials science is changing its views on nanotechnologies as a promising ground for creating new generation of materials [1]. Here we mean the ways of creating material structures with grain size as small as 10^{-9} m, i.e., 1 nm. At the micrometric, as well as at the other scale levels of metal structure, metal properties depend on the structure state in the well-known ways. This knowledge favored, for instance, the development of the dislocation theory [2], which considers lattice defects (vacancies or voids) of one or several atomic spaces, that is, distances of 1–10 nm. This range of dimensions is well in the scope of the nano-material science [1].

Concerning metallic materials, one can hardly distinguish between the *micro-* and *nano-* scales dimensionally; yet these do differ critically regards the concepts of metal functions or *designing*. Nano-technology implies the creation of a structure composed of elementary small-scale particles prepared in a special way. Ordinary (traditional) technologies also deal with the macro-scale conglomerates which, once brought into interaction, would terminate at a final product.

Therefore, one cannot avoid taking into account how much material science integrates the new-nano-scale-concepts in designing a product. One can hardly imagine that, in about 10–20 years, a complex structure, whose rupture would endanger hundreds human lives, might be built up based entirely on the nanomaterial-science concepts, that is, as if composed by a multitude of elementary nanoscopic (*atom-scale*) structures into the single full-scale solid. However the *nano-scale* approach to the material behavior already appears an every-day demand; this makes very important for the searchers to develop reliable ways of running safely the structures manufactured of a metallic material processed either traditionally or according to modern technologies.

The powder metallurgy, with its hydrostatic-compression (compaction) techniques to produce density metallic components [3,4], appears a forerunner technology to design new materials. The latter, tested in a wide range of applied stresses, in

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E-mail addresses: shananta@mailfrom.ru, shana@flysafety.msk.ru

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Nomenclature

a	fatigue-crack length
a_0	fatigue-crack length for $(\Delta K_{eff})_{\mathrm{th}}$
a_c	final crack length
a_q	fracture quantum
b	Burgers' vector
C_f	proportional factor for S–N curve
da/dN	crack growth rate
E	Young modulus
FGA	fine-granular area
ODA	optically dark area
k_b	Boltzmann's constant
$F(R)$	the correction function for K_I stress intensity factor at a stress ratio R
GBF	granular bright facet
ΔK_{eff}	range of Mode I effective stress intensity factor
$(\Delta K_{eff})_{\mathrm{th}}$	threshold value of ΔK_{eff}
k_T	stress concentration factor
m_f	slope of S–N curve
N_f	lifetime to failure (durability)
N_p	fatigue crack growth period
P	pressure
T	absolute temperature
T_m	melting temperature
t_0	constant
U_0	starting activation energy
$(\Delta q_\sigma)_i$	bifurcation stress ranges
$\Delta q_{\sigma 2}$	bifurcation stress range, for the transitional S–N curves between *very-high-cycle-* and *high-cycle* fatigue regimes
$(\alpha_{eff})_1$,	effective stress-concentration factors inside material
$(\alpha_{eff})_2$	effective stress-concentration factors at the material surface
γ_n	coefficient controlled by the material state
σ	tensile stress
σ_{wi}	critical tensile stress for transition from one to another scale level
ε	deformation
v	Poisson's ratio
σ_T	theoretical tensile strength
τ_T	theoretical shear strength

general reveal subsurface fatigue cracking with the respective fatigue-lives as different as 10^3–10^{10} loading cycles, at both low (0.1 and 35 Hz) [4] and high (20 kHz) [3] loading frequencies.

The patterns of subsurface fatigue cracking have repeatedly been examined [5–10]. The Authors report on the cracks initiated at non-metal inclusions or at metal discontinuities such as cast defects, as well as on the cracking from a smooth facet formed initially by the well-known dislocation reactions and looking free of an even particular relief. Such a variety of feasible patterns of subsurface crack-initiation called one to look into them only by using the concept of scale hierarchy of strain and fracture events in metals. This approach primarily concerns the range of ultra-high-cycle fatigue (UHCF) in that, at the nanoscopic scale level, the amount of damage is increasing in metal at high loading frequency and low stress amplitude.

Quite naturally, the following questions arise:

- Under certain conditions of cyclic mechanical loading, can a metal organize itself as to form nanoscopic structures.
- How much are the self-organization mechanisms controlled by the cyclic-loading conditions, irrespective of the nature (including crystallographic parameters) of a material.

These questions are here examined related to the effects of subsurface initiation of fatigue cracks when a metal is cyclically loaded in the UHCF range.

2. Bifurcation diagram of fatigue fracture

Commonly, the phenomenon of fatigue failure of metals is discussed in terms of the Wöhler equation [11]:

$$\sigma^{m_f} N_f = C_f, \tag{1}$$

where σ is the stress level and N_f is the number of loading cycles to cause failure of the tests specimen.