From monoscale to multiscale modeling of fatigue crack growth: Stress and energy density factor

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Received April 24, 2013; accepted October 12, 2013; published online December 10, 2013

The formalism of the earlier fatigue crack growth models is retained to account for multiscaling of the fatigue process that involves the creation of macrocracks from the accumulation of micro damage. The effects of at least two scales, say micro to macro, must be accounted for. The same data can thus be reinterpreted by the invariancy of the transitional stress intensity factors such that the microcracking and macrocracking data would lie on a straight line. The threshold associated with the sigmoid curve disappears. Scale segmentation is shown to be a necessity for addressing multiscale energy dissipative processes such as fatigue and creep. Path independency and energy release rate are monoscale criteria that can lead to unphysical results, violating the first principles. Application of monoscale failure or fracture criteria to nanomaterials is taking toll at the expense of manufacturing super strength and light materials and structural components. This brief view is offered in the spirit of much needed additional research for the reinforcement of materials by creating nanoscale interfaces with sustainable time in service. The step by step consideration at the different scales may offer a better understanding of the test data and their limitations with reference to space and time.

multiscale, fatigue, monoscale, dualscale, stress intensity, energy density, macro, micro, nano, spatial-temporal, crack, stability, sustainable time

PACS number(s): 46.50.+a, 62.20.Mk


1 Introduction

The advent of cyberinfrastructure advocated in the 2003 Adkin report [1] and nanotechnology report [2] of the 1990s have exerted enormous impact on the ways with which science and technology will develop in the 21st century. This impact will affect all disciplines from fundamental physics to engineering manufacturing. A real concern as pointed out by Feynman is that the “physical laws” for large bodies are not the same as those for small bodies [3], the advantage of which has yet to be fully realized. Notwithstanding the long-term need to up-date science and engineering on a more fundamental foundation, there is the short-term demand to implement modern technology. This dilemma has been a challenge to those planning for the future well being of research and education [4]. In view of what has been said, the proposed work will attempt to circumvent the aforementioned discontinuity in multiscaling [5] and develop a material damage scheme that can retain the general frame work of the traditional approach of failure control while taking advantage of the knowledge gained on material behavior at
the nanoscale. This entails shortening the validation time of new materials and structures. Safety issues concerning aircraft and nuclear reactor operations should lean toward decisions based on hard core technology rather than policy. For the well-being and safety of the public, the FAA (Federal Aviation Agency) and NRA (Nuclear Regulatory Agency) must be aware of recent developments in research connected with material and structure integrity. It is therefore pertinent to know how the present codes and standards can be enhanced by including the effects of micro- and/or nano-defects, which have been the state-of-the-art, rather than the exception. Even more upsetting are disparities [6–8] on the use of fatigue crack growth models when applying the fracture control methodology, particularly when the scale range of defects had been extended to include micro- and nano-cracks. These are the concerns of the US Air Force, Navy, NASA and US National Laboratories.

2 Dual scale damage model for micro-/macro-cracking

The line segment crack configuration has had much success to model macrofracture of material even though the actual damage is not a perfectly straight line. Equal effectiveness can be obtained at the micro- and nano-scale level if the appropriate size and time scale of the physical process are observed. The chemical decomposition reaction of RDX and HMX used as ingredients in propellant and explosive formulation can be cited [9,10]. Identifying and measuring the intermediate products of chemical decomposition [11] is difficult due to the small size of the gas phase reaction zone is smaller than $10^2 \text{m}$. This is accomplished by using a small solid/crystal sample about 10 mg which is placed in an alumina cell under vacuum and heated by radiation to the gaseous state. The time scale of the reactive processes can be $10^3$ to $10^9 \text{m}$. The energy in excess to that needed for decomposition can be converted to the creation of mechanical defects regardless of whether it takes in the form of a straight line, multiple line cracks, imperfections or the like. In general, the distance from the tip of the leading crack to the site where damage initiated is critical. The line configuration can therefore be used figuratively for assessing mechanical damage in the development of the multiscale model. An equivalent or fictitious crack length may be defined to represent damage. It is the interaction of time and size that determine scale of damage involving macro-, micro- and nano-defects. In what follows, cracking and damage will be used interchangeably.

2.1 State-of-the-art in fracture control concerning fatigue crack growth

By in large, design criteria have shifted from life prediction to failure control exercising inspection and maintenance. Health monitoring has been advocated [12] to provide constant surveillance of the structural integrity although effectiveness of the methodology still relies on a knowledge of the potential site and mode of failure. Crack growth at the different scale has to be unambiguously defined and modeled before reliable detection techniques can be developed.

In the field of fatigue fracture, three groups of distinct interest can be identified according to size and time scale. For large structures, prevention of through macrocracks to run rapidly can be a concern while fatigue crack initiations frequently entail the study of microcracks starting near the free surface. Movement of intergranular atoms can be greatly increased by elevated temperature or radiation to enhance corrosion. Attention is therefore focused on completely engulfed nano-cracks. The available data from these groups are associated with different size, say $a_{macro}$, $a_{micro}$ and $a_{nano}$ which are not generated in sequence from the same specimen geometry, material and environment. However, development of multiscale damage models is needed in general so that data from one scale can be translated to another. Virtual testing may be a way to fill in the gaps where actual data do not exist. Despite this lack of continuity in multiscale fatigue data, this research proposes to develop a method that would connect the three groups below:

$$\frac{da}{dN} = C(\Delta K)$$

(1)

Reg. II for $a \approx 8$–$80 \text{mm}$ (macromechanical),

$$\frac{da}{dN} = f(a, \sigma,\ldots)$$

(2)

Reg. I for $a \approx 10^{-3}$ to $10^{-1} \text{mm}$ (microstructural),

$$\frac{da}{dt} = f(t)$$

(3)

Reg. below I with $a \approx 10^{-4} \text{mm}$ (nanochemical).

There is no general agreement with regard to the choice of how crack size should be grouped although the difference arose naturally by practice. Real cracks do not grow in a self-similar manner; they do not obey geometric similarity. That is the ratio of crack opening to length is not the same for micro- and macro-cracks. Because the discontinuities of the three groups are artificial; any made models will necessarily overlap. Their connection cannot avoid certain degree of artifacts. Crack length $a$ in Region II of Figure 1(a) is usually monitored as a function of time $t$ or number of load cycle $N$. The data are then expressed by the two parameter relation in eq. (1) for determining the parameters $C$ and $n$ which are not constants as they depend on specimen, geometry, material and fatigue load. Eq. (1) corresponds to the black dots in Figure 1(b). The form $da/dN = C(\Delta K)^n$ is assumed to remain unchanged as an apriori. Validation requires checking $\Delta K$ for the “microstructural” segment displayed by the open circles in Figure 1(b). Pre