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Anomalies concerned with interpreting fatigue data from two-parameter crack growth rate relation in fracture mechanics

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ABSTRACT

Early studies on metal fatigue have concerned primarily with testing the bulk properties of smooth or notch specimens. The fine line crack configuration became a standard ASTM specimen when local effects were recognized to play a decisive role in failure initiation. The size of the failure initiation crack can range from a few cm to a few mm or smaller depending on the application that can involve through cracks in metal sheets, surface cracks extruding grain boundaries and embedded cracks interior to the material microstructure. The state-of-the-art in fracture control for the most part is to monitor the length of an equivalent crack, say "a", such that the corresponding rate $\mathrm{d}a/\mathrm{d}N$ can be related to the integrity of the system depending on the geometry, load and material.

Consistent data interpretation has been a concern because of the enormous range of physical defect size that the design must cover to assure the effective application of the failure criterion from nano to structural scale size. The design may have to demonstrate that nanocracks are controlled in miniature devices as macrocracks are kept in the sub-critical state for larger structures, As more nanostructures are being used, consideration of small cracks in the damage evolution process is becoming the rule rather than the exception. Whether the ordinary two-parameter $\mathrm{d}a/\mathrm{d}N$ versus ΔK representation referred to Regions I–III would still accommodate microcrack and/or nanocrack behavior is an issue that deserves attention. Because of the empirical nature of the current $\mathrm{d}a/\mathrm{d}N$ approach, different physical meanings can be attached to the same crack growth rate data. The final decision will invariably favor the best fit of the data to certain pre-conceived condition. Non-uniqueness of the physical interpretation must therefore be kept in mind. Often, it is the a priori assumption based on physics that determines the outcome. Some of the possible differences are discussed with emphases placed on using an equivalent crack length and a corresponding energy density state such that the segmented state of affairs at the different scales can be connected.

The time history of material damage including the degradation of the microstructure should be the primary concern in determining the system integrity. Scale segmentation avoids over stretching the ability of theories, most of which are short ranged. The dual scale approach will be offered as the basis for developing multiscale models. Advent of the modern electronic computer offers the opportunity for optimizing several unknown variables at the same time to arrive at the desired solution that can correspond to the design specification.

1. Introduction

The fracture mechanics technology of the 1900s was developed to control the catastrophic fracture of large structures. Costly lessons in the loss of human lives and properties were learned from the 800 and more explosive like fracture of the T2-Tanker SS Schenectady Liberty ships in 1943; the five accidents of the Comet G-ALYY of South African Airways in 1954 [1]; and fast fracture initiating from the welds of long gas pipe lines became a real concern in the 1960s. Chronologically speaking, failure can be categorized from large-size/small-time to small-size/large time. In retrospect, three distinct periods of advancement in material science and structural mechanics can be identified. They stand out as *large structure design*, *microstructure processing* and *multiscale reinforcement*, the third of which is the challenge of the 21st century. Avoidance of the quick release of localized energy had to be recognized and eliminated by the design of crack arresters for the comet and steel pipe lines. Stress-controlled in contrast to displacement-controlled states had to be recognized to remedy the failure of the Schenectady. Premature global instability in

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catastrophic proportion can also arise from the inability to optimize the combine effect of geometry, loading and material. Extensive research in material of the 1900s were spent to tailor make the polycrystalline metal microstructures for balancing the strength with toughness at the appropriate temperature. These refinements entered into the fracture mechanics arena under the discipline of plastic deformation and ductile fracture, both of which were short lived as nanotechnology took precedent. Even though the holy grail of the fracture mechanics control methodology based on the use of the two-parameter [2] had shortcomings, social/economical/political constrains preserved its existence up to this date. These constrains are present and cannot be ignored in view of the added pressure from the global emphases on sustainable development of science and technology [3]. The comprise entails the practical application of a well entrenched fracture control technology as the frame work within which the two-parameter crack growth relation has to be extended to address crack sizes that are microscopic and nanoscopic in size. This has led to the development of an assortment of material specific crack growth models [4–8] for defects one millimeter or smaller. However, comparison of data from the different sources is nearly impossible on account of inconsistencies encountered in the interpretation of crack growth data that were brought up in [9,10]. Anomalies associated with scaling of defects would naturally arise. They have also caught the attention by the series of annual meetings organized by the Fracture Mechanics Group in China [11] that was established in 2003.

The reliability of microelectronics has also called for a set of new rules for the design of miniature parts and devices μm or smaller. More efficient use of micro- and nano-materials have been made even though their application to large structures is still dubious [12]. This implies that cracks smaller than 1 mm would have to be dealt with for modeling possible damage at the early stage. Use of the two-parameter fatigue crack growth relation [2] for micro- and nanocracks would require scrutiny, in particular for the transition of small to large cracks. To be accounted is the life of a component that is expended by defects differing in size and time. *Evolution of the local stress and strain states have to be synchronized with the damage rates of the material nanostructure, microstructure and macrostructure*. Multiscale material needs to be use specific, if efficiency is a concern. A knowledge of the load spectrum for each component in a structure becomes mandatory such that the use specificity of a particular part can be defined. Such a requirement might be crucial for the performance of a high performance engine in the future. The evaluation of the life of a turbine blade [13] using the traditional da/dN approach is a case in point. Tailor-made materials require the specification of the time degradation of the nano-, micro- and macro-structure to be implemented in fabrication. In other words, energy dissipation depends on the time and size scales dictated by the load spectrum. Although current composite material fabrication accounts for different scale and type of microstructures and/or nanostructure, they still fail to enforce the evolutionary character of energy dissipation process of the successive scales such as nano, micro and macro. Stringent design requirements of recent decades with due consideration for environmental effects and energy efficiency [14,15] demand more intricate interpretation of fatigue growth data that entail a much wider range of the defect size and time. Inconsistencies of the traditional approach [2] are apparent unless fundamental modifications are made beyond the mere adjustment of empirical data. Modifications need to be translated into analytical terms that can be used by the designers and/or fabricators of the material. To this end, efforts have been made to device dual scale models starting with micro-/macro-cracks [16–18] such that the same approach can be used for the model with nano-/micro-cracks. In this way, dual scale models can be connected for the multiscale case. Consistency will be of primary concern in the development of analytical models. The main features of the material structure at each scale are to be captured by average-value parameters. This does not imply that microstructure or nanostructure effects are left out. The relative comparison of material behavior for at least two scales is required to reflect the so called inherent size effect. In what follows, an attempt will be made to discuss the fracture mechanics aspects of data interpretation involving fatigue crack growth and material specificity.

2. Fracture control: cracks initiation, growth and termination

It would be unthinkable to talk about "rectangular strength" and "circular strength" just because the breaking stress for a rectangular bar and circular cylinder is different. Tests, however, will show this difference even for the same material microstructure, chemical composition and mass. The strength criterion considers the separation of the cross-sectional area as the terminal point. It is an improvement over the load criterion because it is the first recognition that specimen size makes a difference. However, it still falls short of the distinction between load and material. Tensile strength and compressive strength imply that the strength of material would change according to load type. This would no doubt invoke conceptual difficulties to the design of structures where the stress/strain states can vary with location and load. This would also disqualify the strength criterion since it is inconceivable to invoke multiple design criteria for changing multi-axial stress states. The implication is that load and material effects need to separated. The three entities load, geometry and material must therefore be conceptually independent and yet their mutual interaction must be recognized in reality. This dilemma is well known to the design and material engineers and can still be a sticky issue in many situations.

Variations arising from mechanical and metallurgical processing are known to affect the outcome of uniaxial tests. They have been regarded as effects due to the material. To be noted is that the traditional strength test considers only the bulk material properties or the global average. Only the terminal stage of material separation were of concern such as the ultimate strength. Reduction of data scatter were made possible by taking the location of failure initiation into account. Reconciliation of the local material properties with the bulk average can be important, particularly in the neighborhood of a mechanical defect or a crack. This prompted the consideration of two separating free surface known as a macrocrack [19] which is physically and mathematically different from a microcrack [20]. The stress free condition for the macrocrack is replaced by the anti-symmetric boundary condition being characteristics of the microcrack. Both models are idealized to capture the basic physics; they need to be effective only for a small segment of the crack tip, macro or micro. When viewed in detail none of them represent the reality where the crack surfaces are highly irregular. The art of mechanics entails the ability to dust off the cosmetics, much like the free-body diagram in statics although it is much less obvious when material microstructure and defects are involved. It follows that a macrocrack would be assigned with a singularity of the order of 0.5 while a microcrack can possess double singularities, a weak one with order of 0.15 and a strong one with order of 0.75 [21]. The corresponding intensities of these singularities are known to be related to the onset of crack growth. For the macrocrack, this factor is being referred to as the stress intensity factor whose critical value has being adopted by ASTM as the K_{IC} fracture toughness value for high and medium strength metal alloys. The use of the stress intensity concept to microcracks and nanocracks cannot be taken for granted and remains to be investigated.

Effectiveness of the linear elastic fracture mechanics technology of the 1960s has been realized only in retrospect by the consistent