Multiscale approach to micro/macro fatigue crack growth in 2024-T3 aluminum panel

SIH G.C. 1,2*

1 International Center for Sustainability, Accountability and Eco-Affordability of the Large and Small (ICSAELS) Lehigh University, Bethlehem, PA 18015, USA;
2 Key Laboratory of Pressure Systems and Safety, Ministry of Education, School of Mechanical Engineering, East China University of Science and Technology, Shanghai 200237, China

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When two contacting solid surfaces are tightly closed and invisible to the naked eye, the discontinuity is said to be microscopic regardless of whether its length is short or long. By this definition, it is not sufficient to distinguish the difference between a micro- and macro-crack by using the length parameter. Microcracks in high strength metal alloys have been known to be several centimeters or longer. Considered in this work is a dual scale fatigue crack growth model where the main crack can be micro or macro but there prevails an inherent microscopic tip region that is damaged depending on the irregularities of the microstructure. This region is referred to as the “micro-tip” and can be simulated by a sharp wedge with different angles in addition to mixed boundary conditions. The combination is sufficient to model microscopic entities in the form of voids, inclusions, precipitations, interfaces, in addition to subgrain imperfections, or cluster of dislocations. This is accomplished by using the method of “singularity representation” such that closed form asymptotic solutions can be obtained for the development of fatigue crack growth rate relations with three parameters. They include: (1) the crack surface tightness $\sigma^*$ represented by $\sigma_0/\sigma_\infty = 0.3-0.5$ for short cracks in region I, and 0.1-0.2 for long cracks in region II, (2) the micro/macro material properties reflected by the shear modulus ratio $\mu^*$ ($=\mu_{micro}/\mu_{macro}$ varying between 2 and 5) and (3) the most sensitive parameter $d^*$ being the micro-tip characteristic length $d^*$ ($=d/d_0$) whose magnitude decreases in the direction of region I $\rightarrow$ II. The existing fatigue crack growth data for 2024-T3 and 7075-T6 aluminum sheets are used to reinterpret the two-parameter $da/dN=C(\Delta K)^n$ relation where $\Delta K$ has now been re-derived for a microcrack with surfaces tightly in contact. The contact force will depend on the mean stress $\sigma_m$ or mean stress ratio $R$ as the primary parameter and on the stress amplitude $\sigma_\alpha$ as the secondary parameter.

microcrack, macrocrack, microstructure, singularity, multiscaling, scale shift, micro/macro crack growth, 7075-T6 and 2024-T3

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1 Introduction

Metal fatigue became a major concern in the 1900s when catastrophic fracture occurred for aircrafts and ships for reasons that were not apparent at that time. Reliability and safety measures became a concern as maintenance and inspection were developed by adopting the concept of “failure control”. The two-parameter fatigue crack growth relation [1,2] became the center of attention as it provided a convenient way to integrate material effects and design variables. The sigmoid curve in the $da/dN$ versus $\Delta K$ domain remains as the most widely used representation of crack growth data. A revival of interest in the threshold region or
its relevance to the transition of micro/macro cracking has been made in refs. [3,4] which claimed that better correlation can be obtained for cracks in microns and millimeters by means of the pre-ΔK models of Frost-Dugdale [5] in contrast to the fourth power relation [1,2]. In particular, Region I were regarded [4] to consist of non-self similar crack growth that separates self similar growth in Region II. Such an argument is reminiscent of the difference between the second power law [6] in lieu of the fourth power law [7]. Some of the more recent works concerning small cracks [8–10] delve into size scales even lower than the microscopic. In order to relate the results at the different scales, the approach of multiscaling [11,12] has emphasized the obtainment of a straight line relation for Regions I and II such that the data for small and large cracks can be correlated by interpolation. The use of ΔK, however, is a handicap because stress intensity factor is scale sensitive. Although the crack length data provide a smooth transition but non-linearity can prevail. To this end the combined use of ΔK and crack length has also been suggested.

The development of a multiscale material damage model [13–15] has involved using the concept of stress singularity representation. It was essential to obtain closed form asymptotic solutions [16] of a microcrack and/or macrocrack whose tip configuration can accommodate changes due to the effect of material microstructure. This was achieved invoking the uneven constrain of the microcrack tip surfaces. The simulation made use of the stress and/or displacement boundary conditions that are not unique but expedient. The order of the crack-tip stress singularity was found to be different from the familiar 1/ν1 away from the traction free surfa- cies. Even more important is that there might involve a transition region which is referred to as the meso region [13–15]. In general, the boundary conditions on the microcrack are likely to be mixed with tractions and displacements. Hence, a stronger stress singularity of the order, say 1/ν15 or higher could result. Indeed, this is the case of one free surface and one fixed surface in a near incompressible material. Other micro-stress singularities are also possible. This choice will be explored and discussed with the available fatigue data [17] for the 7075-T6 and 2024-T3 aluminum sheets.

There is no intention to demise the correlation of fatigue crack growth rate da/dN data by using empirical models, but the emphasize of this work is to offer a physical representation of multiscaling that can offer a more consistent definition of micro/macro cracking from which da/dN relations can be developed. Keep in mind that large scale numerical approaches should be reserved for theories [18,19] that are not conducive for quick assessment of fatigue data.

2 Problem statement of fatigue crack propagation

There is a fundamental difference between science and en-