ANOMOLOUS FATIGUE CRACK GROWTH PHENOMENA IN HIGH-STRENGTH STEEL

S.C. Forth [1], M.A. James, [2] W.M. Johnston, [3] and J.C. Newman, Jr. [4]
[1] NASA Langley Research Centre, 2 West Reid Street, MS 188E, Hampton, VA 23681 USA
[2] National Institute of Aerospace, 2 West Reid Street, MS 188E, Hampton, VA 23681 USA
[3] Lockheed Martin Corporation, 2 West Reid Street, MS 188E, Hampton, VA 23681 USA
[4] Mississippi State University, Drawer A, 330 Walker Engineering Lab., Hardy Street, Mississippi State, MS 39762 USA

Abstract

The growth of a fatigue crack through a material is the result of a complex interaction between the applied loading, component geometry, three-dimensional constraint, load history, environment, material microstructure and several other factors. Previous studies have developed experimental and computational methods to relate the fatigue crack growth rate to many of the above conditions, with the intent of discovering some fundamental material response, *i.e.* crack growth rate as a function of something. Currently, the technical community uses the stress intensity factor solution as a simplistic means to relate fatigue crack growth rate to loading, geometry and all other variables. The stress intensity factor solution is a very simple linear-elastic representation of the continuum mechanics portion of crack growth. In this paper, the authors present fatigue crack growth rate data for two different high strength steel alloys generated using standard methods. The steels exhibit behaviour that appears unexplainable, compared to an aluminium alloy presented as a baseline for comparison, using the stress intensity factor solution.

1 INTRODUCTION

The growth rate of a fatigue crack through a material is a complex function of the applied loading, component geometry, three-dimensional constraint, load history, environment, material microstructure and several other factors (Paris [1]). Experimental (Bucci [2]) and computational (Blom [3]) methods have been developed to relate the fatigue crack growth rate to all of the above conditions with the intent of discovering some fundamental material response. The technical community uses the stress intensity factor solution (Paris [4]) as a means to relate fatigue crack growth rate to stress, geometry and all other variables described above. The stress intensity factor solution is a very simple linear-elastic representation of the continuum mechanics portion of crack growth. Several researchers have successfully expanded this approach to accommodate elastic-plastic behaviour (Newman [5]), and even micromechanical phenomena (Vasudevan [6]). This simple approach has produced a reasonably accurate representation of the fatigue crack growth response for several metallic materials (Newman [7]).

The fatigue crack growth rate versus stress intensity factor range (da/dN vs. ΔK) has long been deemed a material response curve (FAA [8]) to be used in design, analysis, etc. The development of fatigue crack growth rate data is standardized within organizations such as ISO and ASTM (Bucci [2]). The standards outline experimental procedure, specimen geometry and crack configurations along with tolerances on dimensions and operating parameters. Theoretically, all data developed within these standards will represent the fatigue crack growth response of any metallic material. Recent research in fatigue crack growth has exposed some limitations in the standards that could affect the data in unforeseen ways (Forth [9]). In this paper, the authors present fatigue crack growth rate data from the literature for two different high strength steel alloys that exhibit behaviour that appears unexplainable using the stress intensity factor solution. The objective of this paper is to pose serious questions regarding the confidence of standard test practices to the technical community. A short description of a common aluminium alloy is also presented for comparison purposes.

2 BACKGROUND

The aluminium alloy 7075-T73 has widespread use throughout the aerospace industry for primary and secondary airframe structure. A significant amount of fatigue crack growth rate data exists in the literature [10]. The fatigue crack growth rate versus stress intensity factor range for 7075-T73 is presented in Figure 1 for two stress ratios, R = 0.7 and 0.1. The data was generated in accordance with ASTM E647 (Hudak [11]) using 76 mm wide, 12.7 mm thick compact tension, C(T), specimens. The crack growth rate curves for each of the stress ratios run nearly in parallel over the entire range of ΔK. The R = 0.1 data has lower crack growth rates than the R = 0.7 data for any given ΔK. This relationship between stress ratio, fatigue crack growth rate and stress intensity factor range presented in Figure 1 is considered to be typical. The high load ratio data represents intrinsic material behaviour, and the lower load ratio data is affected by extrinsic effects such as crack closure (plasticity, roughness, environment). The shift in crack growth rate is presumed to be an extrinsic effect that is a function of crack closure (Newman [7]). This is modelled by relating crack growth rate to an effective stress intensity factor range. Crack closure theory purports that there exists a specific point at which a crack will close and that this closure point may not coincide with the minimum load applied to a specimen (Elber [12]). The data presented in Figure 1 is representative of closure theory. The crack growth rate of the R = 0.1 data is lower than the R = 0.7 data for similar ΔK values because the crack is closing prior to minimum load being reached. In other words, the full-range of ΔK is not affecting the crack because of closure. Fatigue crack growth rate data presented in the NASGRO material database [10] and the Metallic Material Properties Development and Standardization (MMPDS) Handbook (the continuation of Mil-Handbook 5) [13] further support this theory.

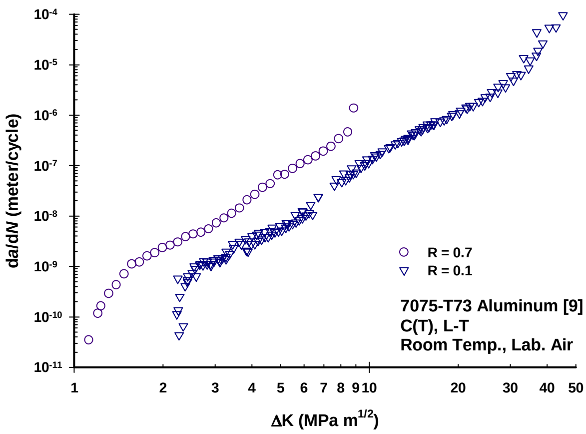

FIGURE 1. Fatigue crack growth rate data for 7075-T73 aluminum [9].

3 4340 STEEL DISCUSSION

The steel alloy 4340 is perhaps the most commonly used low carbon alloy steel in flight-critical aircraft structure and is considered the standard to which other high-strength steels are compared. Therefore, a significant amount of fatigue crack growth rate data exists in the literature (Swain [14]) and material databases [10]. Figure 2 is data from the literature that plots crack growth rate versus stress intensity factor range for R = 0.7, 0.5, 0.3, 0.1 and 0. All data presented is within the specifications defined by ASTM E647. Figure 2 presents data for middle-through crack, M(T) (Swain [14]), and compact tension, C(T) specimens (Forth [15]), with the C(T) specimen data denoted with an asterisk. It is appropriate to plot different specimen configuration data on one plot because the stress intensity solution defined in ASTM E647 accounts for specimen configuration.

It is clear that this data does not exhibit the same trends as the aluminium presented in Figure 1. The 4340 material shows little dependence of crack growth rate on stress ratio, R, in the Paris regime ($10^{-9} < da/dN < 10^{-5}$ meter/cycle) as shown in Figure 3(a). The R = 0 M(T) data propagates at the same rate as the R = 0.7 C(T) data for a wide range of ΔK. Both the M(T) and C(T) R = 0.1 data propagates at the same rate as the R = 0.5 M(T) data. For comparable stress ratios, the C(T) growth rate data is slower than the M(T) at the same ΔK. All of the data converges between a ΔK of 40 and 50 MPa $m^{1/2}$. Based on this data, crack closure phenomenon cannot explain the variation, or lack thereof, in the crack growth rate data presented in Figure 3(a). However, there is a strong dependence of crack growth rate on stress ratio, R, in the near-threshold regime ($10^{-11} < da/dN < 10^{-7}$ meter/cycle) as shown in Figure 3(b). This data also does not follow the crack closure argument. The R = 0.5 data has the lowest threshold, lower than the R = 0.7. If both of these tests are devoid of closure, which crack closure theory suggests, then the difference in threshold could be explained by material variability. However, the R = 0 M(T) data has similar behaviour to the R = 0.7 C(T) data, and there is nearly a factor of two difference in the threshold between the R = 0.1 M(T) and C(T) data. None of these data follow a typical or assumed behaviour.

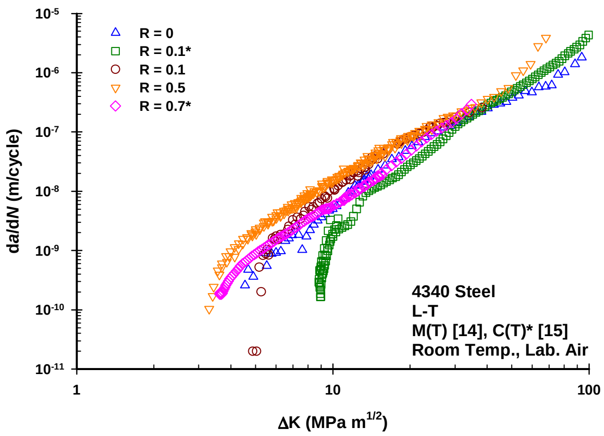

FIGURE 2. Fatigue crack growth rate data for 4340 steel [14, 15].

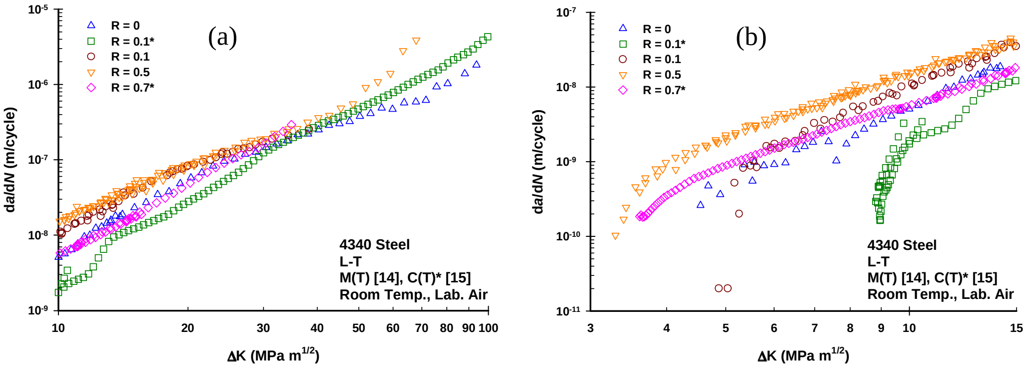

FIGURE 3. Paris (a) and threshold (b) fatigue crack growth rate data for 4340 steel [14, 15].

4 D6AC STEEL DISCUSSION

The steel alloy D6AC is not as prevalent as 4340 steel, but is still used extensively by the aerospace industry. Again, a significant amount of fatigue crack growth rate data exists in the literature (Liaw [16]) and material databases [10]. Figure 4, taken from the literature, is a plot of crack growth rate versus stress intensity factor range for R = 0.7, 0.3, and 0.1 and constant K_{max} = 22 MPa $m^{1/2}$. All data presented is within the specifications defined by ASTM E647. The R = 0.1 data from Liaw, *et al* [16] was generated using 42 mm wide and 6.4 mm thick C(T) specimens (Forth [17]). The R = 0.1 data denoted with an asterisk was generated using a 51 mm wide and 5.1 mm thick C(T) specimen. The remaining data was generated using 76 mm wide and 12.7 mm thick C(T) specimens.

As shown in Figure 5(a), there is no clear crack growth rate dependence on stress ratio in the Paris regime (10^{-9} < d*a*/d*N* < 10^{-5} meter/cycle). Closer investigation of the data shows that the variability between two R = 0.1 tests contains the remaining stress ratio data, supporting the argument that a dependence of crack growth rate on stress ratio does not exist. This would imply that there is very little closure in the Paris regime for this material, assuming the constant K_{max} and R = 0.7 data represent the intrinsic material behaviour, with the lower load ratio data affected by extrinsic effects such as crack closure. However, a strong dependence on stress ratio is seen near the threshold regime (10^{-11} < d*a*/d*N* < 10^{-7} meter/cycle), as shown in Figure 5(b). Focusing first on the 76 mm wide C(T) specimens, the threshold for the K_{max} test is the lowest and the R = 0.1 test the highest. This sequence follows conventional wisdom, as shown in the 7075-T73 data presented previously, where the test data with the least closure has the highest crack growth rate for a ΔK value. However, the extreme "fanning" of the near-threshold data is puzzling, considering the Paris regime data exhibited no crack growth rate dependence on stress ratio. This implies that closure develops at a ΔK of 10 MPa $m^{1/2}$. The large disparity in R = 0.1 near-threshold data based on specimen size remains unexplained. There is no clear trend with respect to specimen width or thickness. The three tests all exhibited the same Paris regime behaviour, yet produced very different thresholds. It is appropriate to plot different specimen configuration data on one plot because the stress intensity solution defined in ASTM E647 accounts for specimen configuration.

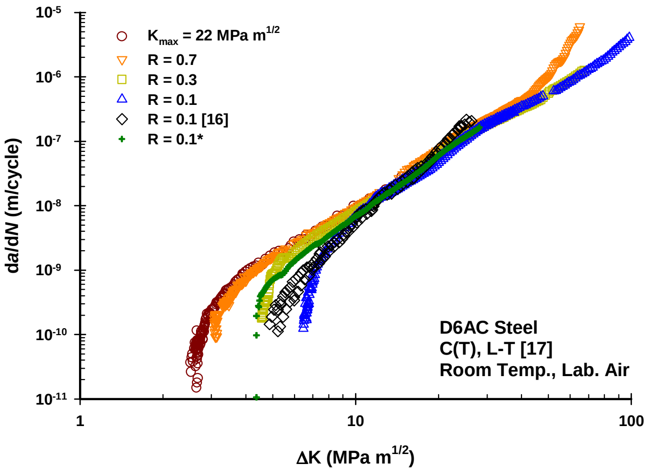

FIGURE 4. Fatigue crack growth rate data for D6AC steel [16, 17].

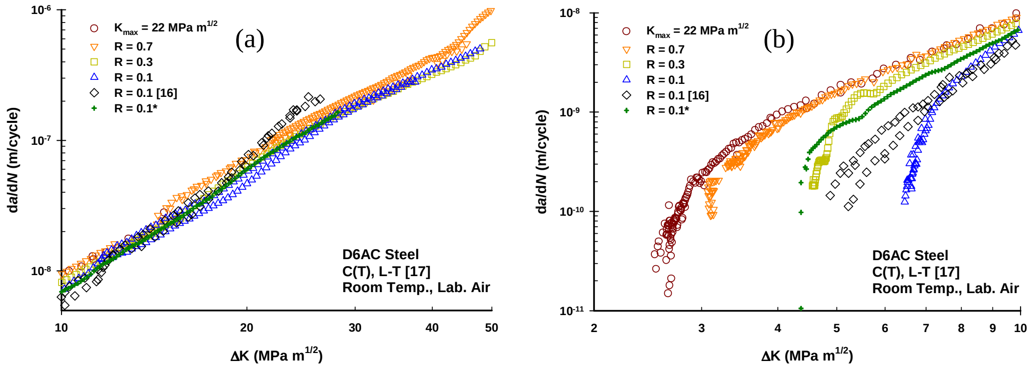

FIGURE 5. Paris (a) and threshold (b) fatigue crack growth rate data for D6AC steel [16, 17].

5 CONCLUSIONS

In this paper the authors have postulated that fatigue crack growth rate is a definable function of the stress intensity factor solution. Furthermore, several studies have shown a distinct relationship between growth rate and stress intensity as a function of the stress ratio. This relationship is a function of crack closure, *i.e.* lower stress ratio data has more closure and subsequently lower crack growth rates. This relationship is visualized in the presentation of 7075-T73 aluminium data (Figure 1) that is intended to be representative of "normal" crack growth rate data. Fatigue crack growth rate data is also presented for two high-strength steel alloys. The 4340 steel data (Figure 2) does not exhibit a clear relationship between crack growth rate and stress ratio for any ΔK. The D6AC steel data presents a material where the crack growth rate is independent of stress ratio in the Paris regime, but displays significant "fanning" near threshold. The lack of a strong dependence of crack growth rate on stress ratio in the Paris regime implies there is little closure in high strength steels. Contrarily, the D6AC steel (Figure 4) near-threshold crack growth rate data shows a considerable dependence on stress ratio. There is no clear explanation to why closure would exist near-threshold and nearly vanish in the Paris regime.

Additionally, the 4340 steel data shows significant variability in crack growth rate, for a specific ΔK, for different specimen configurations, M(T) vs. C(T). The Paris regime crack growth rate data for the R = 0.5 M(T) specimens is nearly twice that of the R = 0.7 C(T) specimen. However, near threshold, the data nearly converges for these two test cases. The D6AC steel data also shows significant variability in specimen configuration. In this case, all of the tests were conducted using C(T) specimens, however the width and thickness varied. The R = 0.1, threshold ΔK varied by a factor of two between specimen sizes. Based on the d*a*/d*N* vs. ΔK data presented in this paper, the stress intensity factor solution is not capturing the specimen configuration effects for high strength steels. Finally, the high strength steel data presented in this paper generated using ASTM E647 cannot be considered representative of the material response.

6 REFERENCES

1 Paris, P.C., "The fracture mechanics approach to fatigue," *Fatigue – An Interdisciplinary Approach*, p. 107, 1964.

2. Bucci, R.J., "Development of a Proposed ASTM Standard Test Method for Near-Threshold Fatigue Crack Growth Rate Measurement" *Fatigue Crack Growth Measurement and Data Analysis, ASTM STP 738*, ASTM, pp. 5-28, 1981.

3 Blom, A., Wang, G. and Chermahini, R. G., "Comparison of Crack Closure Results Obtained by 3D Elastic-Plastic FEM and Modified Dugdale Model," *Localized Damage: Computer-Aided Assessment and Control*, Computational Mechanics Publications, pp. 57-68, 1990.

4. Paris, P.C. and Erdogan, F., "A Critical Analysis of Crack Propagation Laws," *Transactions of the ASME, Journal of Basic Engineering*, Series D, *85*, 3, 1963.

5. Newman, J. C., Jr., "A Nonlinear Fracture Mechanics Approach to the Growth of Small Cracks," *Behavior of Short Cracks in Airframe Materials, AGARD CP-328*, 1983, pp. 6.1-6.26.

6. Vasudevan, A. K. and Suresh, S., "Influence of Corrosion Deposits on Near-Threshold Fatigue Crack Growth Behavior in 2XXX and 7XXX Series Aluminum Alloys," *Metallurgical Transactions A*, *13A*, pp. 2271-2280, Dec. 1982.

7. Newman, J. C., Jr., "A Crack-Closure Model for Predicting Fatigue Crack Growth under Aircraft Spectrum Loading," *Methods and Models for Predicting Fatigue Crack Growth under Random Loading, ASTM STP 748*, ASTM, pp. 53-84, 1981.

8. "Damage Tolerance and Fatigue Evaluation of Structure", *Federal Aviation Regulations*, Title 14 Code of Federal Regulations, Part 25, Section 571.

9 Forth, S.C., Newman, J.C., Jr. and Forman, R.G., "On generating fatigue crack growth thresholds," *Int. Journal of Fatigue*, Vol. 25, p. 9-15, 2003.

10 NASGRO Material Database, www.nasgro.swri.org, 2004.

11 Hudak, Jr., S.J., Saxena, S.J., Bucci, A. and Malcolm, R.C., "Development of Standard Methods of Testing and Analyzing Fatigue Crack Growth Rate Data – Final Report," *AFML TR 78-40*, Air Force Materials Laboratory, Wright Patterson Air Force Base, OH, 1978.

12 Elber, W., "The Significance of Fatigue Crack Closure," *Damage Tolerance in Aircraft Structures, ASTM STP 486*, American Society for Testing and Materials, pp. 230-242, 1971.

13 Metallic Properties Development and Standardization, www.mmpds.org.

14 Swain, M. H.; Everett, R. A., Newman, J. C., Jr. and Phillips, E. P. "The Growth of Short Crack in 4340 Steel and Aluminum-Lithium 2090", *AGARD Report No. 767*, pp. 7.1-7.30, 1990.

15 Forth, S.C., James, M.A. and Johnston, W.M., "Mechanical Properties of 4340 Steel," *NASA Technical Memorandum*, 2004.

16 Liaw, P.K., Peck, M.G., and Rudd, G.E., "Fatigue crack growth behavior of D6AC pace shuttle steel," *Engineering Fracture Mechanics*, Vol. 43, pp. 370-400, 1992.

17 Forth, S.C., James, M.A., Newman, J.A., Everett, R.A. and Johnston, W.M., "Mechanical Properties of D6AC Steel," *NASA Technical Memorandum*, 2004.