FATIGUE CRACK PROPAGATION RESPONSE IN EXTRUDED AND CAST ALUMINUM ALLOYS

R. W. Hertzberg,[1] G. Miller,[2] K. Donald,[2] R. Stofanak,[1]
and R. Jaccard[3]

1. Lehigh University, Bethlehem, Pa. 18015
2. Del Research Corp., 427 Main St., Hellertown, Pa. 18055
3. Swiss Aluminium Ltd., Buckhauserstrasse,POBox 390, CH-8048 Zurich, Switzerland

ABSTRACT

This study involved an examination of macroscopic and microscopic fatigue crack propagation (FCP) in an extruded and a cast aluminum alloy. Crack growth rates from ΔK threshold to 10^{-3} mm/cyc were determined at stress ratio levels from 0.1 to 0.8 under computer-controlled conditions. These data were analyzed as a function of both ΔK applied and ΔK effective.

KEYWORDS

Fatigue crack propagation, aluminum extrusion, aluminum casting, fracture mechanics, crack closure, fatigue striations, mean stress, threshold.

INTRODUCTION

In recent years it has become well established that the rate of fatigue crack advance in metals and polymers is strongly dependent on the magnitude of the prevailing crack tip stress intensity factor (Paris, 1964)

$$da/dN = A\,\Delta K^{m} \qquad (1)$$

where da/dN is the fatigue crack growth rate, ΔK the stress intensity factor range, and A, m are experimentally determined material properties which depend on environment and stress factors as well. Since ΔK is given in terms of the stress range $\Delta\sigma$ and crack length a, Eq. 1 may be integrated to determine fatigue life. Over a very broad range of crack growth rates, however, it is often found that the da/dN - ΔK plot for a given material takes on a sigmoidal shape with crack growth rates decreasing to a vanishingly small value at ΔK_{th} and increasing to very high levels as K_{max} approaches K_c for the material. Therefore, without characterizing FCP threshold behavior, significant errors can occur in fatigue life prediction.

To date, very few fracture mechanics-type fatigue experiments have been performed on cast and extruded aluminum alloys. Based on prior studies of wrought allcys, one would not expect to find very significant differences in FCP rates among these materials at intermediate da/dN values. However, differences in crack growth behavior among various alloy systems are expected in the threshold and terminal FCP regimes. For example, recent studies have shown that ΔK_{th} values in ferrous and non-ferrous alloys are strongly dependent on alloy strength and grain size (Ritchie, 1977; Robinson and Beevers, 1973; Masounave and Baflon, 1976). Pertinent to the present study of cast alloys, Saxena and co-workers (1978) noted that the cast aluminum alloy A356 exhibited vastly superior threshold behavior to that shown by wrought alloy 2219-T851. To further complicate the problem, it is known that ΔK_{th} decreases rapidly with increasing stress ratio $R(=\sigma_{min}/\sigma_{max})$(Ritchie, 1977). Since extruded and cast components may well possess significant residual stresses, additional information regarding the FCP response (particularly ΔK_{th} regime) of these materials at high mean stress levels is clearly indicated.

Recently, attempts have been made to rationalize mean stress effects on FCP rates in terms of crack closure. As proposed by Elber (1971), the rate of crack extension is believed to depend on ΔK_{eff}, defined by $K_{max}-K_{op}$, where K_{op} represents the K level where the opposing crack surfaces are no longer in contact. Since K_{op} varies with K_{max} and hence with changing R values at a given ΔK level (Vazquez, Morrone and Ernst, 1979), ΔK_{eff} would be expected to account for mean stress effects on FCP rates (Katcher and Kaplan, 1974; Chu, 1974). However, Clerivet and Bathias (1979) and Brown and Weertman (1979) have published results which question the general applicability of the Elber crack closure approach in the analysis of FCP data. It appears that part of the problem lies in the measurement technique for the determination of K_{op} (Clerivet and Bathias, 1979) and in the overall accuracy of the techniques employed.

This paper reports on a study of FCP behavior at various R levels in an extruded aluminum alloy when tested both parallel and perpendicular to the extrusion direction and in a cast aluminum alloy. Preliminary crack closure data are considered in data reduction and the fracture surface morphologies characterized using electron fractographic techniques.

EXPERIMENTAL PROCEDURES

The alloys studied in this investigation were supplied by Swiss Aluminium Ltd. and their chemistries and mechanical properties are given in Tables 1 and 2. Alloy AF42 was cast in a vertical sand mold at a temperature of 740°C and given the following thermal treatment: 515°C/2 hrs. + 530°C/12 hrs. + water quench + 175°C/6-½ hrs. Alloy AC062/61 was extruded with an extrusion exit temperature of 520-580°C. The extruded piece was then water quenched and annealed for 14 hrs. at 760°C.

TABLE 1 Chemical Compositions

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
AC062/61	0.63	0.21	0.17	0.03	0.54	0.11	0.08	0.01	balance
AF42	0.07	0.14	5.0		0.01	-	0.03	0.24	balance

TABLE 2 Mechanical Properties

	Yield Strength MPa	Yield Strength ksi	Tensile Strength MPa	Tensile Strength ksi	% Elongation
AC062/61 (LL,LH)[a]	326	47.3	357	51.8	11.3
AC062/61 (QL,QH)[a]	297	43.1	332	48.2	12.4
AF42	211	30.6	279	40.5	4.6

[a] LL = longitudinal (10 mm); LH = transverse (18 mm)
QL = transverse (10 mm); QH = transverse (18 mm)

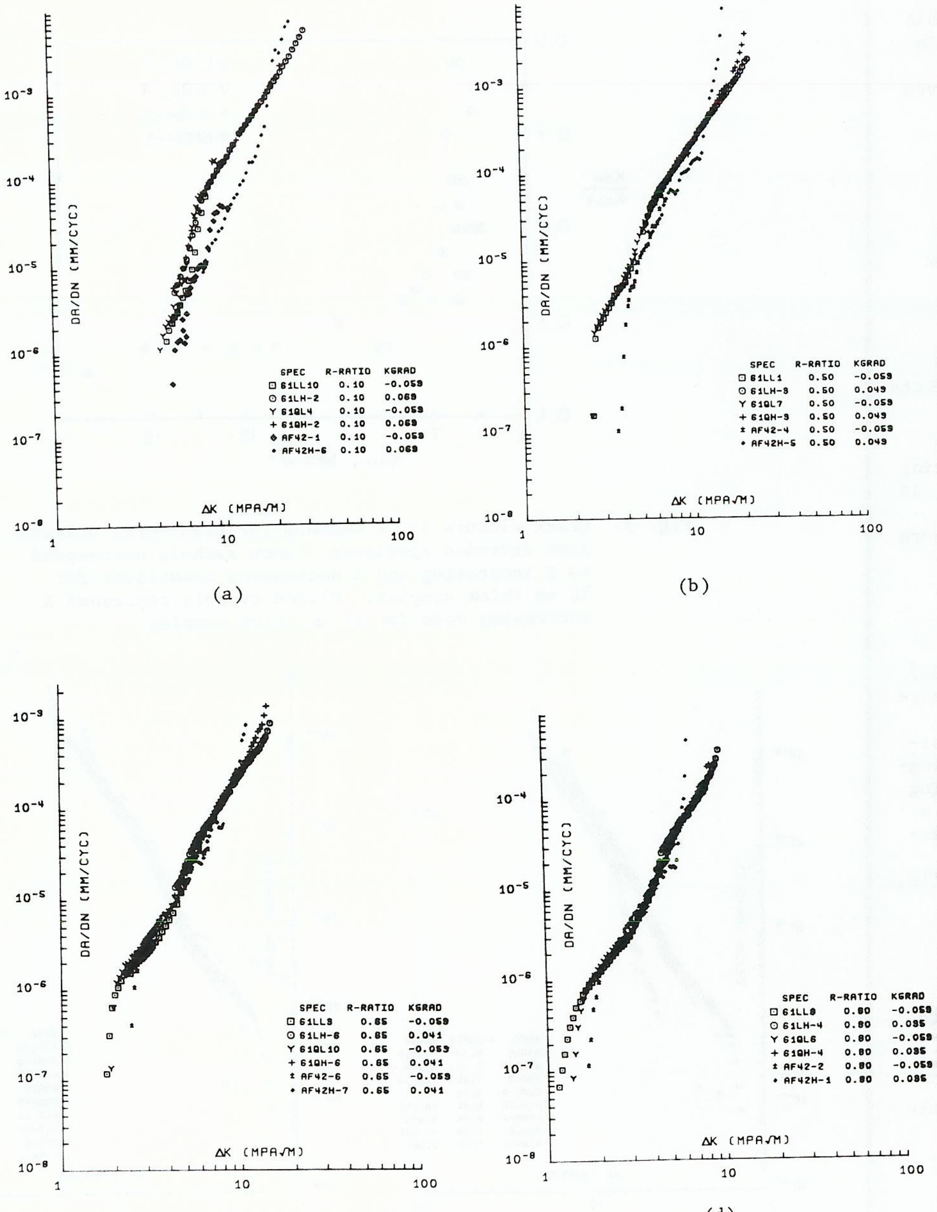
Fatigue crack growth rates from 5×10^{-8} to above 1×10^{-3} mm cycle were obtained. For threshold and low growth experiments, a WOL specimen 10 mm thick was tested at 125 Hz. An automated test system was used to obtain the required crack growth rate data. The crack length was monitored continuously by using the elastic compliance technique, enabling the stress intensity to be controlled according to the equation: $K = K_o \exp[C(a-a_o)]$, where K_o is the initial cyclic stress intensity corresponding to the initial crack length, a_o; $\underline{a}$ is the current crack length, and C is a constant with the dimensions of 1/length (Saxena and co-workers, 1978,1978a). A double cantilever clip-in displacement gage was used for monitoring crack opening displacements along with visual verification via a 10 power microscope. The value of the K-decreasing parameter C was -.059/mm for the first part of these tests. Following either attainment of the desired low growth rates or crack arrest, these specimens were subsequently cycled to failure using constant amplitude loading. This procedure provides an overlap of the growth rate data on a single sample and, hence, serves as a good check on the K-decreasing portion of the test. High growth rate data were obtained using 18 mm thick WOL specimens at a test frequency of 10 Hz. For these tests, a K-increasing parameter value between 0.35 and 0.69 was chosen depending upon the load ratio of the test (Donald and Schmidt, 1980). Fatigue crack growth rates were obtained with a modified secant method. As part of this test program, an oscilloscope display of a "cancelled" load vs. displacement curve was monitored in order to determine at what fraction of maximum load the crack was fully open. This was done by electronically subtracting from the raw load vs. displacement curve a straight line equal in slope to that portion of the load vs. displacement curve above crack closure.

Fractographic examination of all fatigue fracture surfaces were performed using two-stage (cellulose acetate-carbon) chromium shadowed replicas. Microscopic growth rate data were obtained from an average of at least 15 separate striation spacing readings.

EXPERIMENTAL RESULTS AND DISCUSSION

Fatigue Crack Propagation Data

Fatigue crack propagation data in the form of da/dN - ΔK plots were determined at various R levels and are shown in Fig. 1. It is interesting to note that neither test frequency nor specimen thickness had any significant impact on the test results. Also, the extruded material seems to exhibit no orientation effect. At $R = 0.1$ and 0.5 the cast alloy exhibited lower FCP rates than the extruded alloy at all ΔK levels except near final fracture. Under K-decreasing conditions, cracks arrested sooner at low R-ratios. As a result, it was not possible to determine a meaningful



(a) (b)

(c) (d)

Fig. 1. Comparative fatigue crack propagation response of extruded and cast alloys at different R ratios. a) R = 0.1; b) R = 0.5; c) R = 0.65; d) R = 0.8.

estimate of ΔK_{th} for this test condition; however, suitable values were obtained at higher mean stress levels. In this regard, ΔK_{th} was determined by fitting a best-fit line between at least 5 data points between 5×10^{-8} and 5×10^{-7} mm/cycle and then defining ΔK_{th} as the ΔK level associated with an FCP rate of 10^{-7} mm/cycle from the fitted line. For those tests in which not enough data existed to determine the threshold ΔK in the manner just described, such values were arbitrarily defined by ΔK at crack arrest. As expected, ΔK threshold decreased with increasing R value. When these data are compared with other results from wrought and cast aluminum alloys (Schmidt, 1972; Saxena and co-workers, 1978), it is interesting to note that values for cast materials at any R value are consistently higher than those reported for both wrought and extruded materials (Fig. 2). Referring again to Fig. 1, it is seen that the cast alloy also exhibited superior FCP resistance at intermediate da/dN levels but only when $R \leq 0.5$. At the highest R ratios examined (0.65 and 0.8), both orientations of the extruded alloy and the cast alloy exhibited the same FCP rates.

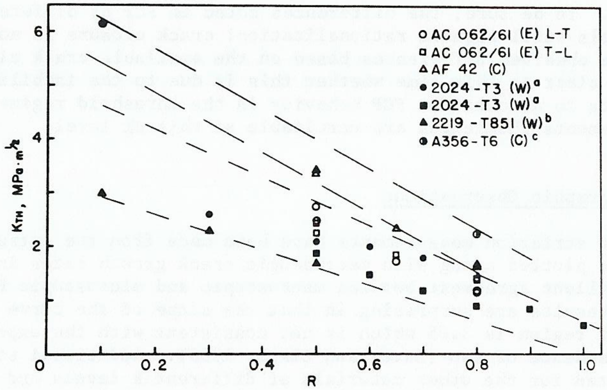


Fig. 2. Dependence of ΔK_{th} on R ratio. E - extruded, W - wrought, C - cast. a - Schmidt, 1973; b - Bucci, 1979; c - Saxena et al. 1978.

At the other end of the growth rate spectrum, it was found that da/dN values increased rapidly in the vicinity of final fracture. This deviation from log-linear behavior (Eq. 1) occurred at progressively lower ΔK levels with increasing R values. Such behavior is believed to be caused by the rapidly approaching condition where the maximum stress intensity level equals the material's fracture toughness. It is interesting to note that the cast alloy, which possesses higher threshold ΔK values, possesses the lowest fracture toughness.

At an R-ratio of 0.1, both orientations of the extruded material as well as the cast material exhibited crack closure. Closure levels in these low R-ratio tests were found generally to increase as the stress intensity was reduced, reaching a level of 75-85% of maximum load when the cracks arrested. This amount of closure and the subsequent crack arrest prevented attainment of the desired low growth rates in the 0.1 R-ratio tests. Following the change to constant amplitude loading, closure levels decreased upon reinitiation of crack growth and continued to decrease to some intermediate level with increasing stress intensity. An example of such data for the transverse extruded aluminum alloy is shown in Fig. 3. Such behavior parallels that reported by Vazquez, Morrone and Ernst (1979) for another aluminum alloy. In the 0.5 R-ratio tests, only the cast material consistently showed a significant amount of crack closure. At higher R-ratios (0.65 and 0.8) no closure was observed for any of the materials either extruded or cast.

To explore the possibility of normalizing the data for the transverse extruded samples with the closure data presented in Fig. 3, plots of da/dN vs. ΔK_{app} and ΔK_{eff} were constructed and are shown in Fig. 4. Since closure was found only in samples tested at $R = 0.1$, only those data should be shifted relative to the other results obtained at higher R values. (Note that the FCP rates above 10^{-6} mm/cyc showed no effect of R in the range $0.5 \leq R \leq 0.8$, consistent with the absence of crack closure.) It is seen that the original spread in the data above about 5 x 10^{-6} mm/cyc (based on ΔK_{app}) is normalized when plotted versus ΔK_{eff}. This reflects the fact that crack closure can account for R ratio effects at intermediate ΔK levels. To be sure, the differences noted in FCP at different R values at lower ΔK levels still require rationalization; crack closure is not capable of accounting for the observed differences based on the available crack closure measurements. It is not clear at this time whether this is due to the inability of crack closure concepts to account for FCP behavior in the threshold regime or whether the closure measurements themselves are unreliable at this ΔK level.

Fractographic Observations

Fatigue striation measurements have been made from the extruded material at $R = 0.1$ and are plotted along with macroscopic crack growth rates in Fig. 5. Overall there is excellent agreement between macroscopic and microscopic FCP rates. In fact, these results are surprising in that the slope of the curve in the striation measurement region is 3.05 which is not consistent with the expected striation spacing-ΔK dependence of two (Bates and Clark, 1969). Additional striation data are being generated for the other materials at different R levels and will be examined as a function of ΔK applied and ΔK effective. At very low FCP rates, the fatigue fracture surfaces took on a highly faceted appearance in the absence of striations which is typical of fracture behavior in the threshold regime (Hertzberg and Mills, 1976).

CONCLUSIONS

Fatigue threshold values were determined in cast AF42 aluminum alloy and found to be superior to those measured in the extruded aluminum alloy AC062/61 at all R ratios examined. FCP rates in the extruded alloy did not vary to any significant degree with test orientation. Preliminary analysis of data from the transverse orientation extruded material has shown that crack closure can account for R ratio effects at intermediate ΔK levels. Fatigue striation spacings agree well with macroscopic crack growth rates in the longitudinal orientation extruded alloy.

ACKNOWLEDGEMENTS

The financial support of Swiss Aluminium Ltd. is gratefully acknowledged.

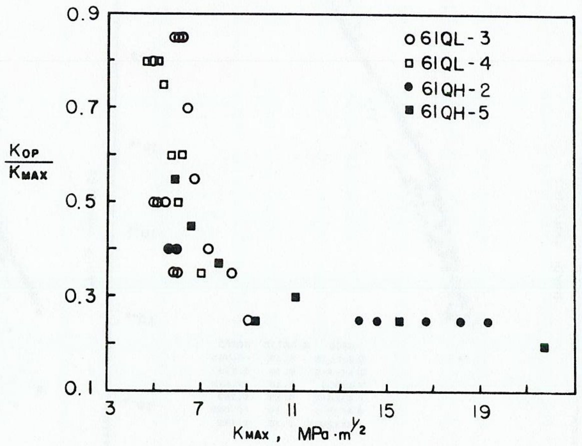


Fig. 3. Crack closure vs. K maximum for transverse orientation extruded specimens. Open symbols correspond to K increasing and K decreasing conditions for 10 mm thick samples. Closed symbols represent K increasing data for 18 mm thick samples.

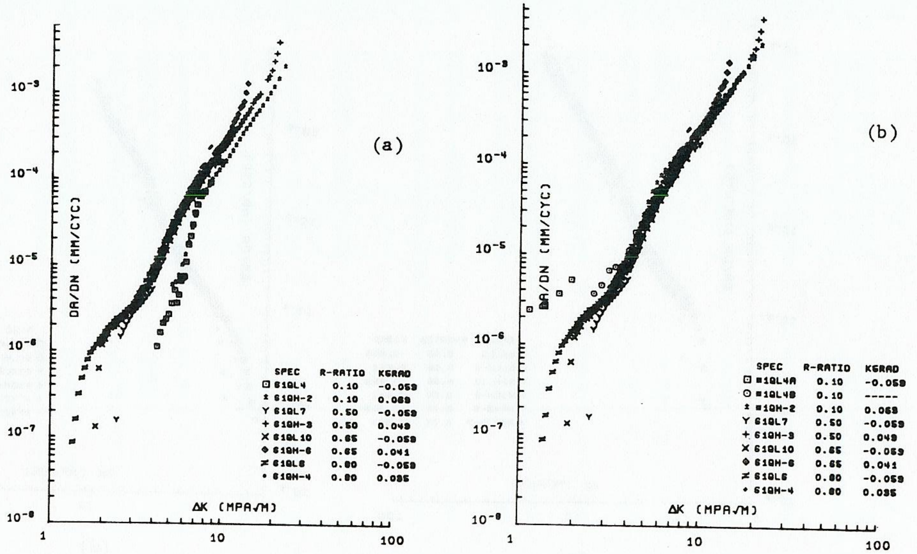


Fig. 4. Fatigue crack propagation data for transverse orientation extruded samples vs. a) ΔK applied and b) ΔK effective.

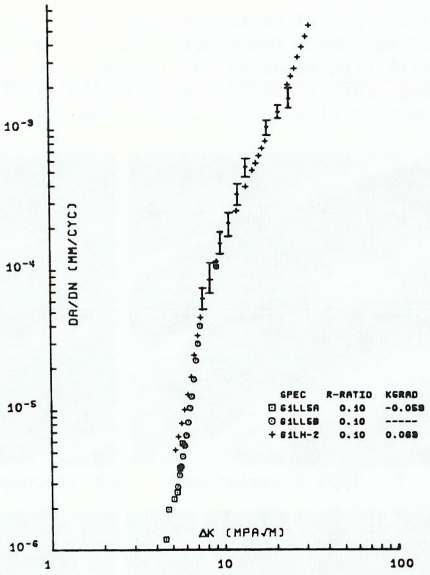


Fig. 5. Agreement between macroscopic and microscopic fatigue crack growth rates in longitudinal orientation extruded alloy. Mean and standard deviation of striation spacing data are indicated.

REFERENCES

Bates, R. C. and W. G. Clark, Jr. (1969). Trans. Quart. ASM 62(2), 380-389.
Brown, R. D. and J. Weertman (1978). Eng. Fract. Mech. 10, 757-771.
Bucci, R. J. (1979). ALCOA Report No. 57-79-14.
Chu, H. P. (1974). Trans. Quart. ASM 62(2), 380-389.
Clerivet, A. and C. Bathias (1979). Eng. Fract. Mech. 12, 599-611.
Donald, J. K. and D. W. Schmidt (1980). J. Testing and Evaluation 8(1), 19-24.
Elber, W. (1971). ASTM STP 486, 230-242.
Hertzberg, R. W. and W. J. Mills (1976). ASTM STP 600, 220-234.
Katcher, M. and M. Kaplin (1974). ASTM STP 559, 264-282.
Masounave, J. and J. P. Baflon (1976). Scripta Metallurgica 10, 165-170.
Paris, P. C. (1964). Fatigue--An Interdisciplinary Approach. Proceedings 10th Sagamore Conf., Syracuse, New York.
Ritchie, R. O. (1977). ASME J. Eng. Mater. Tech. 99, 195-204.
Robinson, J. L. and C. J. Beevers (1973). Metal Science 7, 153-159.
Saxena, A. and S. J. Hudak, Jr. (1978). Int. J. Fract. 14(5), 453-468.
Saxena, A., S. J. Hudak, Jr., J. K. Donald and D. W. Schmidt (1978a). J. Testing and Evaluation 6(3), 167-174.
Schmidt, R. A. and P. C. Paris (1973). ASTM STP 536, 79-94.
Vazquez, J. A., A. Morrone and H. Ernst (1979). Eng. Fract. Mech. 12, 231-240.