FATIGUE CRACK GROWTH EQUATIONS FOR TC-128B TANK CAR STEEL

FINAL REPORT
SwRI Project No. 18.12240.01.006
Contract No. DDTS.060183.00.801

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U.S. Department of Transportation
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1.0 Introduction

In an effort to develop relevant data for use in applying damage tolerance analysis concepts to railroad tank cars, the fatigue crack growth (FCG) behavior of TC-128B tank car steel was investigated by SwRI in a previous test program conducted for the Volpe Center [1]. Fatigue crack growth rate data (*da/dN* vs ΔK) for TC-128B tank car steel were obtained in Ref. [1] for two lots of TC-128B steel donated by two tank car manufacturers. In order for these data to be available for use in fatigue crack growth analyses of railroad tank cars, they must be mathematically characterized in terms of crack growth equations or laws. Therefore, the objective of the work reported herein was to obtain empirical constants for crack growth equations that are commonly employed in damage tolerance analyses. These equations are the Paris equation, the Walker equation and the NASGRO® equation.

In the following, a brief review of the previous fatigue crack growth rate test program is first presented, followed by a summary of the crack growth equations that were used to fit the empirical data. The curve fits to the data for each equation are then presented along with recommendations for their use.

2.0 Summary of Previous Test Program

The objective of the TC-128B material test program was to develop a database of fatigue crack growth rate data representative of modern tank car steels. Material samples were donated to the test program by two tank car manufacturers and were from two different steel mills. Each set of material was processed (heat treated) to be consistent and representative of TC-128B material in the current fleet of tank cars. Both material lots met AAR specifications for TC-128B and there was little measurable difference between the two lots of material supplied by the different builders in terms of chemistry, grain size and strength. In addition to material lot differences, variables assessed in the test program included load ratio (R = 0.1, 0.6 and -1.0), orientation (L-T and L-S), crack growth test technique and environment. Tests were performed in accordance with ASTM E-647, the fatigue crack growth testing standard described in Ref. [2].

The two material lots tested produced virtually identical fatigue crack growth properties at both low and high load ratios. The in-plane (L-T) orientation produced crack growth rates approximately two times (2x) faster than the through-thickness (L-S) orientation. Perturbations in environment (temperature and humidity) only had a slight effect on FCG rate behavior, on the order of 1.5x. In general, the data generated for TC-128B in the two orientations tested agreed well with A617-Gr.B data found in the literature and exhibited slightly slower growth rates when compared to other common structural and low alloy steels while showing less environmental influence.

Complete details of the TC-128B test program including material procurement, processing, experimental methods, and material characterization, along with resulting data for all tests, are provided in Ref. [1]. Table 1 lists the FCG tests from that program used to perform curve fits to obtain the crack growth law parameters; it is a subset of the information contained in Table 3-1 of Ref. [1]. Note that it was not possible to develop curve fits for the negative R-ratio data obtained from M(T) specimens in Ref. [1] since those specimens exhibited asymmetrical crack growth that invalidated the measured data per the criteria of ASTM E-647 [2].

Table 1 Summary of FCG Tests Used in Curve Fitting Crack Growth Equations

Specimen ID	Tank Car Manufacturer	Specimen Type	Orientation	*R*-ratio
TC-A-1A	A	C(T)	L-T	0.1
TC-B-1A	B	C(T)	L-T	0.1
TC-A-1B	A	C(T)	L-T	0.1
TC-B-1B	B	C(T)	L-T	0.1
TC-A-2A	A	C(T)	L-T	0.6
TC-B-2A	B	C(T)	L-T	0.6
TC-A-9	A	SE(B)	L-S	0.1
TC-A-10	A	SE(B)	L-S	0.1
TC-A-12	A	SE(B)	L-S	0.1

Notes: C(T) = compact tension specimen
SE(B) = single-edge bend specimen
L-T = in-plane (longitudinal-transverse) direction
L-S = through-thickness (longitudinal-short) direction
R-ratio = $\sigma_{min}/\sigma_{max}$ or K_{min}/K_{max}

3.0 Fatigue Crack Growth Equations

The driving force for fatigue crack growth is described by the range in stress intensity factor ($\Delta K = K_{max} – K_{min}$) and fatigue crack growth data are commonly represented on a log-log plot of crack growth rate (da/dN) versus ΔK as shown in Figure 1. Typically, three different regions of the FCG curve are considered in developing analytical models to represent empirical data as shown in Figure 1 by the roman numerals. Region I is the "near-threshold" region in which very slow crack growth occurs and where no growth occurs below a threshold value of driving force, denoted as ΔK_{th}. Region II is the linear, steady-state region of the crack growth curve. In the higher growth rate portion of the curve, Region III, rapid and unstable crack growth occurs as final fracture is approached when K_{max} equals K_c, the fracture toughness of the material.

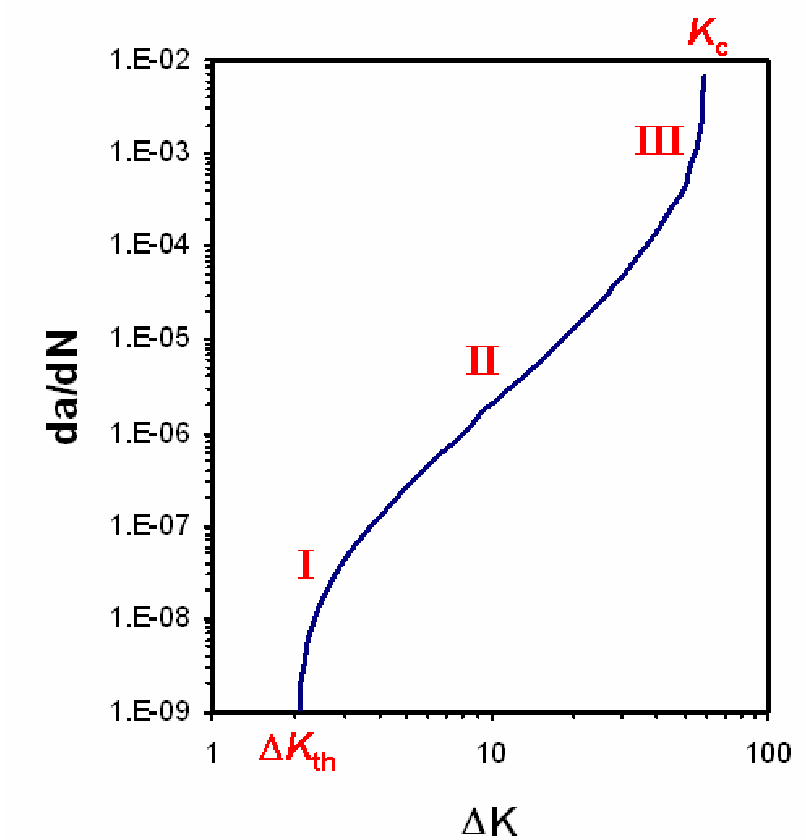

Figure 1 Typical Fatigue Crack Growth Curve Showing Three Regions (I = threshold, II = linear, III = instability)

Over the years, a number of relationships have been developed to represent all or parts of the typical range of FCG data, the simplest being the Paris equation [3] developed in 1963 to represent the linear region of the curve:

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

where C and n are empirical parameters determined from a curve fit to test data. This original model is still in use today for many applications; more advanced models essentially build on the Paris equation by addressing mean stress effects, threshold behavior (Region I), the instability asymptote (Region III), and fatigue crack closure effects.

The Walker equation [4] is a linear model that incorporates mean stress effects through the use of a load ratio, R, where $R = \sigma_{min}/\sigma_{max}$ or K_{min}/K_{max}:

$$\frac{da}{dN} = C\left[\frac{\Delta K}{(1-R)^{1-m}}\right]^n$$

where C, n and m are again empirical parameters determined from a curve fit to a set of FCG test data performed at multiple load ratios. Different values of m are required depending on whether R is greater than or less than zero.

The NASGRO® equation [5] is a full-range model that mathematically represents all three regions of the FCG curve and is given by:

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{max}}{K_c}\right)^q}$$

where C and n are empirical parameters describing the linear region of the curve (similar to the Paris and Walker models) and p and q are empirical constants describing the curvature in the FCG data that occurs near threshold (Region I) and near instability (Region III), respectively. Definitions of the crack opening function, f, the threshold stress intensity factor, ΔK_{th}, and the critical stress intensity factor, K_c, can be found in Reference [5].

4.0 Curve Fits to TC-128B FCG Test Data

4.1. Methodology

As shown in Table 1, fatigue crack growth data were obtained for two crack orientations: in the plane of the plate (L-T) and through the thickness (L-S). However, note that through-thickness data were obtained for only one R value (0.1) while useable in-plane data were obtained for two R values (0.1 and 0.6). Ideally, it would be preferable to have obtained data at more than one or two R values for each orientation; however, within the resource limits of the previous test program, this was all that could be achieved. Therefore, as an expedient, it was decided to initially fit the L-T data for the two R-values of 0.1 and 0.6 and then assume that the stress ratio dependence obtained for the L-T orientation was also applicable for the L-S orientation.

Curve fits to the Walker and NASGRO equations were obtained using the NASMAT module contained within the NASGRO suite of software [5]. The NASMAT curve fitting algorithms use least-squares error minimization routines in the log-log domain to obtain the corresponding constants. While additional details regarding the curve fitting procedures* can be found in the NASMAT documentation, it should be noted that the initial numerical curve fits were adjusted such that they represented a reasonable upper bound to a majority of the data and also to ensure that there was consistency between the Walker and NASGRO results as much as possible. For

* Note that fitting the NASGRO equation is really a multi-step process involving: (1) fitting or defining the threshold region; (2) fitting or defining the critical stress intensity or toughness to be used at the instability asymptote; (3) making initial assumptions on key parameters such as p and q; (4) performing the least squares fit to obtain C and n; and finally, (5) using engineering judgment to adjust the results for consistency and/or a desired level of conservatism.

example, in the latter case, the Walker and NASGRO parameters were modified such that the resulting fits were nearly identical in the linear region of the FCG curves (Region II).

Since the Paris equation has no ability to represent mean stress effects, it was decided to obtain the Paris constants for the high R-ratio data (0.6). This was done by equating the fitted Walker equation at an R of 0.6 to the Paris equation, and solving for the Paris constant, C, assuming using the Walker slope n applied to each equation for consistency.

4.2. Results

The Walker and NASGRO fits are shown plotted against the experimental data in Figures 2 and 3 for the L-T and L-S data, respectively. For clarity, the Paris equation has not been plotted; it corresponds to the Walker curve at an R of 0.6. Table 2 provides a list of the curve fit parameters for each of the three equations.

It can be seen from Figures 2 and 3 that the NASGRO equation provides a good representation of the knees in the data near the threshold region. Note that in Figure 2, for an R of 0.6, both models fit the lower ΔK region quite well but become conservative at higher ΔK values. There were very few test data points in Region III of the crack growth curves therefore, for the NASGRO equation fits there is some uncertainty as to the fit for the instability region; some conservative judgment was needed in the fitting process in this case.

5.0 Recommendations

The parameters for the fatigue crack growth laws developed herein can be used in the performance of damage tolerance analyses of railroad tank car heads and shells fabricated from modern TC-128B tank car steel. The choice of which FCG equation to use in an analysis depends on the analytical tools that are available to the analyst and the desired level of conservatism and/or accuracy required.

The Paris equation is the simplest to use; the Paris constants were developed at an R of 0.6 as an upper bound to the FCG data generated in the test program. If FCG tests were to be performed at a higher load ratio, for example, 0.8, it is expected that the data would be quite close to the R of 0.6 results already obtained; therefore this Paris fit should provide a conservative analysis. It may, however, be too conservative for accurate crack growth predictions since it does not account for mean stress effects; therefore, in general, it is recommended that the Walker or NASGRO equation be used in tank car damage tolerance analyses.

It is important to note that the NASGRO equation curve fits presented herein were developed using the new form of the NASGRO equation that first appeared in NASGRO v4.0 in 2002. This new NASGRO 4.0 equation contains revisions that model threshold

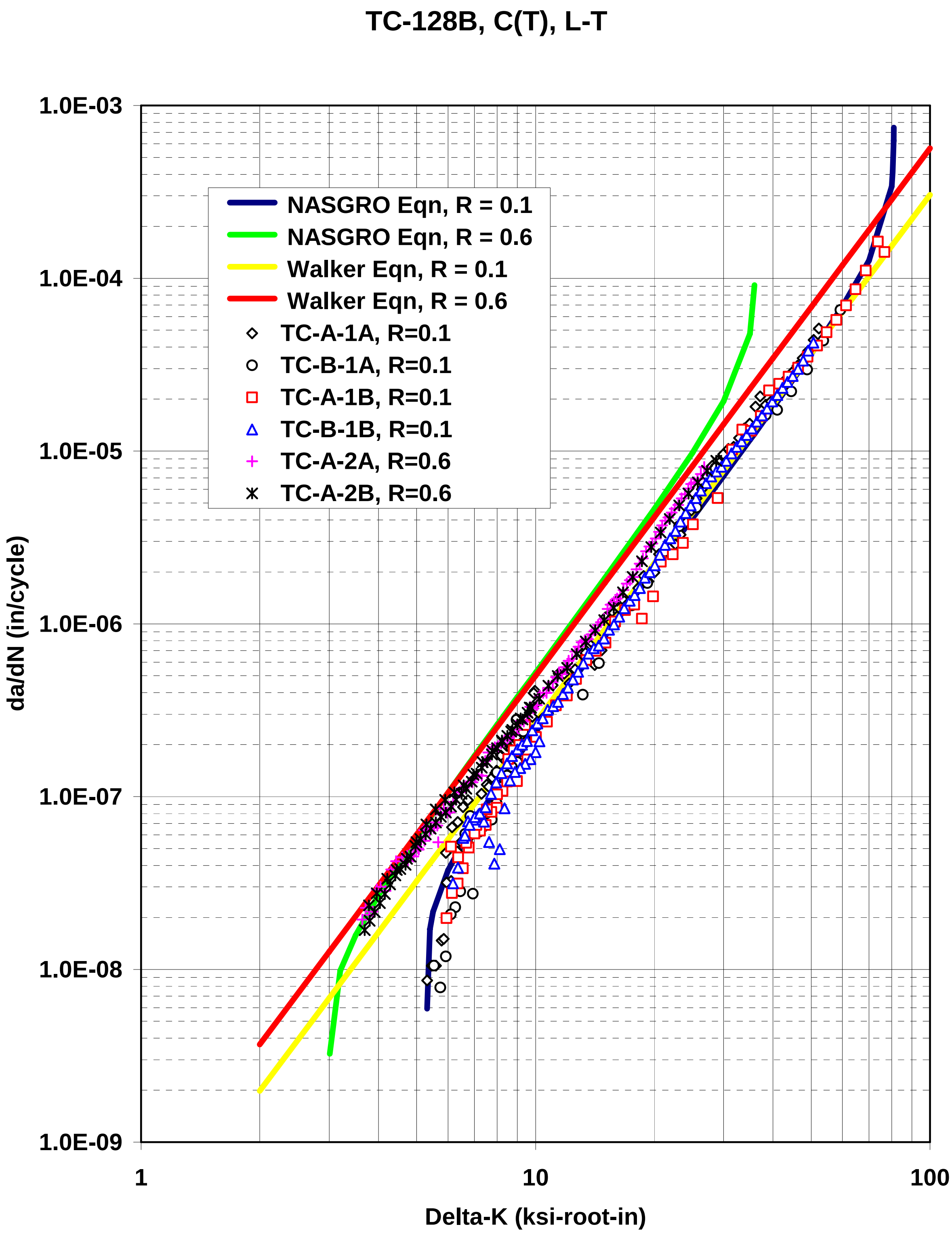

Figure 2 Walker and NASGRO Equation Curve Fits to TC-128B C(T) L-T Data

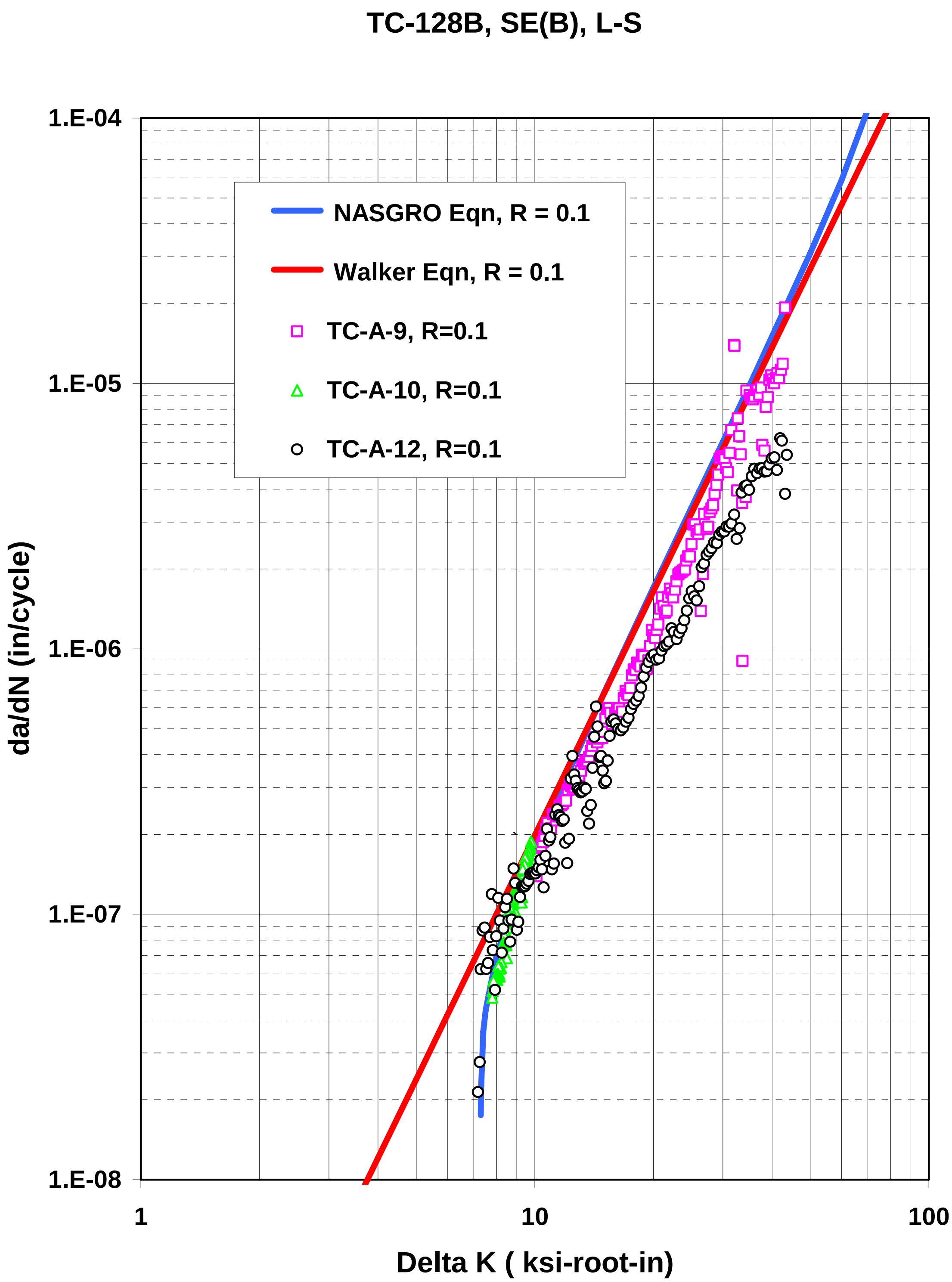

Figure 3 Walker and NASGRO Equation Curve Fits to TC-128B SE(B) L-S Data

behavior in terms of a high-R threshold (ΔK_1 in Table 2) rather than a threshold at a ΔK of zero [5]. Earlier variants of the NASGRO equation (e.g., as used in versions 2.0 and 3.0 of NASGRO) should *not* be used with the NASGRO parameters listed in Table 2. Therefore, it is recommended that the most recent version of NASGRO [5] be used with the parameters listed in Table 2 for the NASGRO equation.

Table 2 Summary of FCG Equation Parameters for TC-128B Tank Car Steel

Equation and Parameters	L-T Orientation (in-plane)	L-S Orientation (through-thickness)	Notes
Paris			
C	4.43E-10	3.26E-10	(1)
n	3.053	3.053	(1)
Walker			
C	2.20E-10	1.62E-10	
n	3.053	3.053	
m	0.75	0.75	
NASGRO			
C	7.00E-10	6.00E-10	
n	2.90	2.90	
p	0.25	0.25	
q	0.25	0.25	
$\sigma_{max}/\sigma_{flow}$	0.30	0.30	(2)
α	2.50	2.50	(2)
K_c	90.0	90.0	
ΔK_1	1.99	2.73	(3)
C_{th}^{+}	1.73	1.73	(3)
C_{th}^{-}	0.10	0.10	(3)

Notes:

(1) The Paris equation parameters were obtained for $R = 0.6$.
(2) The ratio of the maximum stress to flow stress, $\sigma_{max}/\sigma_{flow}$, and the plane stress/strain constraint factor, α, are used along with R to compute the crack opening function, f, in the NASGRO equation [5].
(3) The threshold stress intensity factor range, ΔK_{th}, in the NASGRO equation, is a function of the high-R threshold, ΔK_1, and the C_{th} parameters that control the spread or fanning of the data as a function of R in the threshold region [5].
(4) Units on K and ΔK are ksi√in and da/dN has units of in/cycle.

Lastly, it is well known that the railroad tank car load spectrum contains a significant amount of compressive loading. None of the test data or curve fits discussed above address compressive loads (negative load ratios). Note that in Ref. [1] some FCG tests were performed at a negative load ratio with unsuccessful results due to problems with meeting ASTM validity criteria. Therefore, it is recommended that FCG rate data be obtained for at least one or two negative load ratios for TC-128B steel. In the absence of negative load ratio data, engineering judgment will need to be used in modeling FCG rates for cycles containing a compressive load, regardless of which crack growth law is used in the damage tolerance analysis.

6.0 References

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