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PREDICTING THE LIFE OF MILITARY VEHICLE COMPONENTS IN THE PRESENCE OF DEFECTS

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ABSTRACT

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When the components of a military vehicle are designed, consideration is given to long term durability under repeated mission applications. In reality, surface and subsurface defects have always existed in weldments, forgings, and castings. These defects came from the manufacturing process or nucleated during the life of the vehicle. These defects may grow under repeated operations, resulting in ultimate failure of parts well before the design life is achieved. In such situations, a design based on crack initiation alone will not suffice, and a fracture mechanics based fatigue should also be included to predict the design life of a part accurately. In this paper a methodology is given on how to predict the available design life given the presence of defects in different parts of a military vehicle. An example will be provided with the process to demonstrate each step of the process.

INTRODUCTION

Often at manufacturing, a component on a military vehicle might have defects present, or defects may nucleate during the vehicle's service life. A defect is any discontinuity found in the material of the component. To determine the service life of a component with defects a process must be established using available technologies. This process (see Figure 1) must include the definition of requirements for vehicle/component life, the determination of stress/life histories, the determination of a block loading to be used for cycle counting, and the fracture mechanics model that develops the stress intensity factor. The goal with this process is to be able to use Paris' Law [1] to obtain the number of cycles of life available for component life.

To accompany the process description an example will be followed within each subsection. The example component will be a sprocket carrier (see Figure 2) found on military tracked vehicles. It connects the power pack to the vehicle's suspension system. It mounts to the vehicle's final drive output shaft and supports the suspension sprocket gear that drives the suspension track string. It is usually a casting and is subjected to many different loadings from the track string and impact. Because of its complexity, it is usually manufactured with the presence of defects allowed. Figure 3 shows the location of an allowable circular corner crack that occurred during manufacturing.

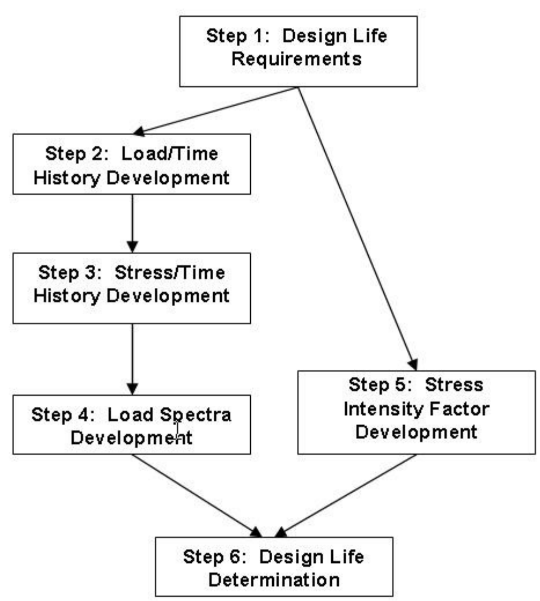

Figure 1. Process Flow

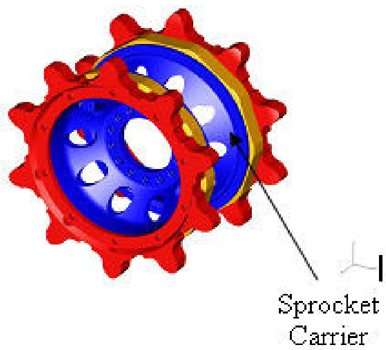

Figure 2

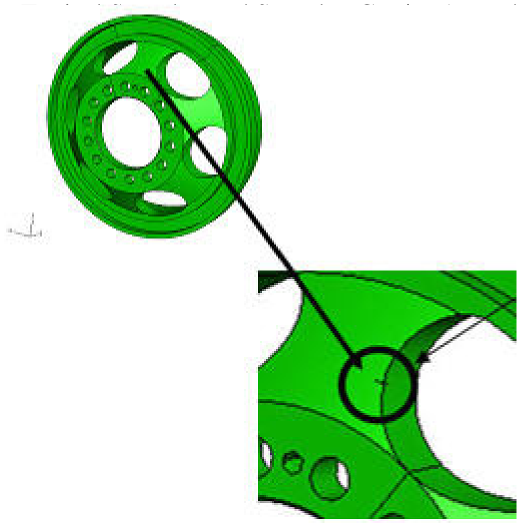

Figure 3
Circular Corner Crack

Step 1: Design Life Requirements

The process for the determination of a component's life begins with a description and understanding of the component's design requirements. Military vehicle components are subjected to loads generated by the vehicle's mission profile, which might include a number of miles over different terrains and obstacles as shown in Table 1. It may also include a number of shots fired from an on-board weapon. Consideration needs to be given to the loadings generated by the component itself, and residual conditions should not be neglected. Each of the mentioned loads will have a different effect at the tip of a crack. Their stress fields may cause defects to change direction. In some cases, such as with impact, large plasticity fields may develop at the crack tip, changing the growth rate of the crack.

Expected Life	Miles Travelled	Simulation Profile
40% Rough Terrain	2400	Perryman III - APG
40% Secondary Roads	2400	Churchville - APG
20% Hard Surface Roads	1200	Ignored

Table 1
Typical Tracked Vehicle Mission Profile

Step 2: Load/Time History Development

The next step in the process is to transform the description of the component life into variable amplitude load/time histories by use of multi-physics codes such as DADS or ADAMS. Rarely will there be simple loading with military vehicles. Classical calculations can be done in the simplest cases, but it is best to look for more robust means. Vehicle courses that meet "worst case" mission profiles (see Table-1), such as those found at Aderdeen Proving Ground (APG), are often used to provide terrain profile inputs for DADS and ADAMS (multi-physics codes). Geometries such as half-rounds and steps can represent some vehicle impacts. Sampling rates for the load/time histories must be carefully determined to ensure that any critical events are not missed or reduced in scale. It is suggested that the Nyquist Frequency (1) would be a good starting point.

$$\text{Nyquist Frequency} = F_n = ½ * \text{Sample Frequency} \quad (1)$$

Donaldson (2) provides an error estimate in peak resolution of a sinusoidal.

$$PK_{err} = 2 \sin\text{^}2\ (\Pi * f_d/2f_s) \quad (2)$$

Here PKerr is a percent error, fd is the data frequency, and fs the sampling frequency. Variable amplitude random sequence load/time histories are then passed to the FEA portion of the process.

Step 3: Stress/Time History Development

For the finite element analysis (FEA) portion of the process the goal is to produce stress/time histories that will be used for cycle counting and reduction into equivalent loading. Different FEA approaches might be needed. For this example, a global analysis of the carrier was first done, followed by repeated sub-modal analyses to get to the desired crack length and K_{IC} value. The sampling rate that is used to extract data from the time domain analysis is important and use of the Nyquist Frequency (1) is suggested. Very often modal transient FEA is used for the determination of stress/time histories. Care should be taken to ensure that adequate modes are first extracted that will give good dynamic response. Fouier transforms can be done to examine the force/time histories to help ensure a good mode representation, and doubling that number is often practiced.

Breaking the example sprocket carrier into three parts – the “flower pot”, the spokes, and the rim – sample stress/time histories for each part are shown in Figure 4 a, b, and c for the Perryman III terrain crossing.

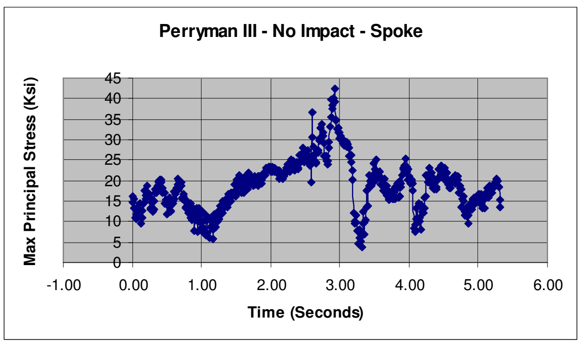

Figure 4a – Spoke
Stress/Time History – Perryman III Crossing

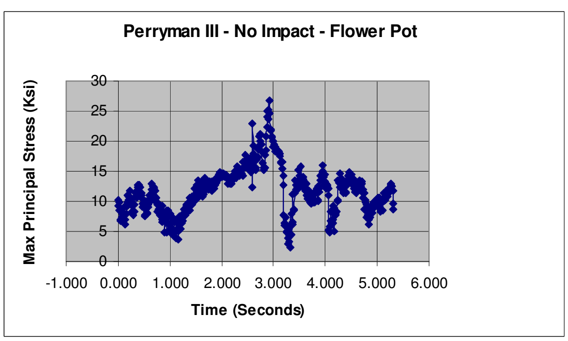

Figure 4b – Flower Pot
Stress/Time History – Perryman III Crossing

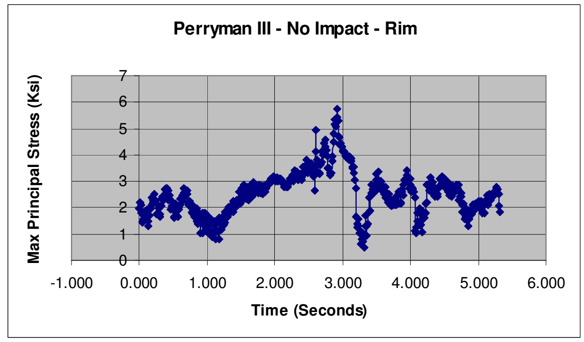

Figure 4c – Rim
Stress/Time History – Perryman III Crossing

Each of these when repeated a number of times will represent the stress/time history life for 2,400 miles of a sprocket’s life when crossing rough terrain. This is repeated for the secondary and hard surface roads.

Step 4: Load Spectra Development

With variable amplitude random sequence stress/time histories available, it is time to create the load spectra. Here the word spectra is used to mean a statistical representation of the stress/time histories. Counting will have to be done to determine the stress ranges and exceedances that occur for each range. The exceedances when multiplied by the number of times crossed will become the number of cycles that a defect must allow before failure. There are a number of counting methods from peak counting to rainflow counting. At this time, rainflow seems to be the preferred method for fatigue, and often the differences between counting techniques are small. The result of the counting will be a number of stress ranges that will need to be developed into a number of block loads (stress ranges of constant amplitude) that represent each variable amplitude random sequence stress/time history. Mean stresses will also come from the cycle counting. A reasonable number of equivalent blocks of loading will need to be determined and there are times in which a single amplitude equivalent block loading is used. The maximum number of blocks will depend on the software used for integration of Paris’ Law. For instance, FRANC2D(FRacture Analysis Code 2D)[6] requires a single equivalent loading. Getting to the number of blocks needed is accomplished by using Miner’s rule. A good reference for doing this task is British Standard PDP 6493 (equation 3).

$$\Delta\sigma_{equiv} = ((\Sigma\ \Delta\sigma\text{^}3\ n_i)/10\text{^}5)^{1/3} \qquad (3)$$

Here $\Delta\sigma$ represents the stress ranges found from rainflow counting, and n_j the number of counts for each stress range.

Using this standard, the equivalent block loading for the three events chosen for the spoke on the sprocket carrier were developed (see Figure 5). Care should be taken when developing block loads because some important stress ranges can be left out. For instance, it is easy to remove the effects of low amplitude/high cycle stress ranges in a single block loading. After review, the loading for the hard surface roads was ignored in the example due to minimal crack growth. Blunting effects (high levels of plasticity) at the crack tip will be to be examined to determine if an order of loading is necessary. The severe events that a military vehicle must endure often can cause blunting at a defect. Mean stress effects should also be included for accurate predictions.

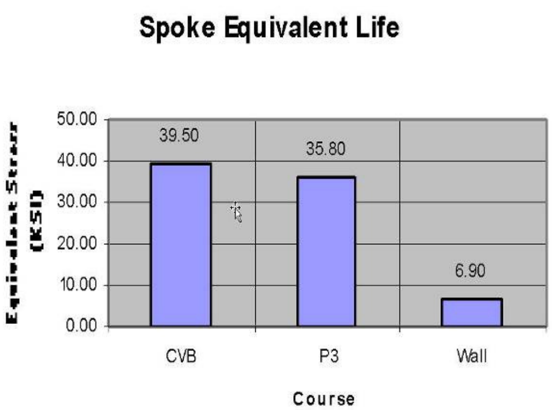

Figure 5
Equivalent Block Loading for the Spoke of a Sprocket Carrier

Step 5: Stress Intensity Factor Development

At this point, the determination of the stress intensity factor must be done if Paris's Law is to be integrated. The stress intensity factor should not be confused with the stress concentration factor. Before beginning this effort, there will be a few material properties needed. For Paris' Law (4) a minimum of two properties for each material will be needed; they are c and m.

$$da/dN = c\,(\Delta K)^m \tag{4}$$

Here "a" is the crack length, "N" the number of cycles, c and m material coefficients, and ΔK the stress intensity range. The term $\Delta\sigma$ is the stress range. The coefficients β_1 and β_2 are corrections to the loading and geometry. Looking at ΔK (5) with Paris' Law:

$$\Delta K = \beta_1 \beta_2\, \Delta\sigma \sqrt{(\Pi a)} \tag{5}$$

Two stress intensity factor material properties will be needed, and they are the ΔK_{TH} threshold stress intensity factor, and $\Delta K_{IC,}$ the critical stress intensity factor. The ΔK_{TH} is very important if stress range truncation is to be considered and ΔK_{IC} is the end point of defect growth. Here the symbol Δ stands for range. To account for mean stress effects, additional testing will be needed. The mean stress effect can be accounted for by empirical equations such as given by Forman (6).

$$da/dN = (c\,(\Delta K)^n)/((1\text{-}R)K_C - \Delta K) \tag{6}$$

Here, c and n are material coefficients found from testing, R is the stress ration ($R=\sigma_{max}/\sigma_{min}$), K_C is the fracture toughness, and ΔK the stress intensity range. To summarize, the importance of good material data cannot be understated.

In this approach, elastic fracture mechanics will be used. If fracture is accompanied by considerable plastic deformation, then elastic–plastic fracture mechanics is used. For linear-elastic fracture mechanics, the stress at the defect tip must be proportional to the applied stress (7).

$$\sigma_{defect\ tip} \approx \sigma_{(applied)} / \sqrt{(2\Pi x)} \tag{7}$$

Here x is a directional value from the defect. Because a military vehicle must perform when required, components should be designed to be in the linear stress area.

After examining the modes of failure, loading, and geometry, the process of obtaining the needed ΔK begins. There are a number of classical solutions for ΔK by such authors as Anderson [7]. When applied with proper assumptions, they can be accurately used within the limits of those approximations. Figure 6 shows a classical solution for a circular corner crack. With assumptions, it can be used to represent the spoke of a sprocket carrier with a circular corner crack.

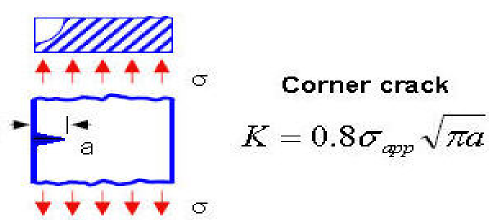

Figure 6
Classical Solution for a Circular Corner Defect

These assumptions can lead to serious error if poorly applied. Software such as AFGRO and NASA/FLAGRO[4] are available that incorporate the classical solutions. These came from the aircraft and space industries. Again, with good assumptions, they can be very useful. There are efforts, at such places as Cornell University that are working on FEA based solutions to the two coefficients β_1 and β_2. FRAN3D(FRacture Analysis Code 3D)[6] was an early version of those efforts that modeled an actual geometry and used single amplitude loading or blocks of single amplitude loading to come to a solution. More recent work by Cornell University with FRANC3D – Next Generation(NG)[6] is making the calculation of ΔK very practical. This latest solution is demonstrated in Figure 7. Here a circular corner crack was inserted into an ABAQUS sub-model of the actual spoke geometry using FRANC3D-NG.

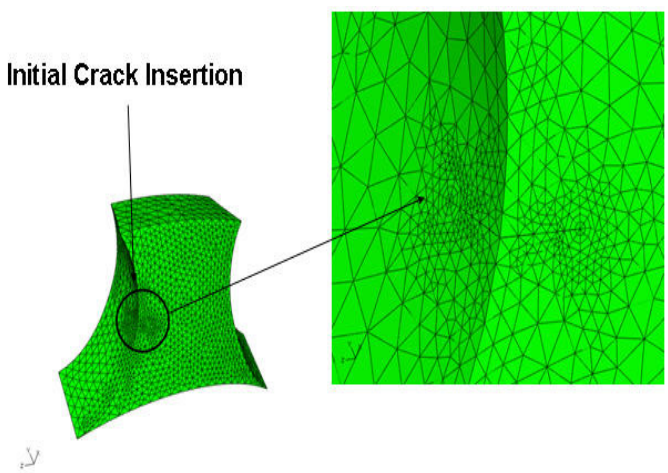

Figure 7
Insertion of a Corner Defect – FRANC3D – NG

Now using the above block loading, ABAQUS and FRANC3D-Next Generation, moving back and forth between softwares, the ΔK for modes 1, 2, and 3 are developed for defect growth (see Figures 8a, b, and c). ABAQUS is used for the finite element analysis (displacements) and FRANC3D-NG I is used for preprocessing (inserting a crack using displacements from ABAQUS) and post processing of the fracture solution (stress intensity factor).

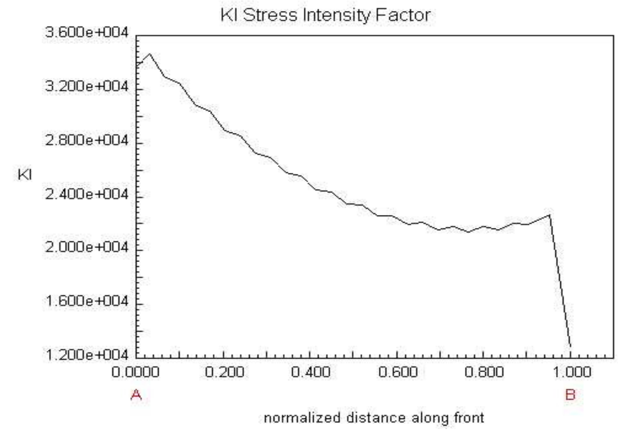

Figure 8a

K_I for a Corner Defect in a Carrier Spoke

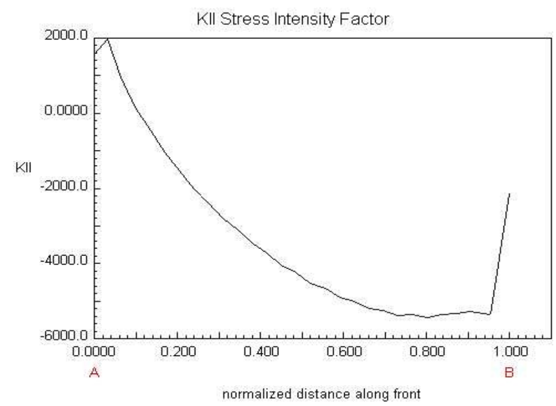

Figure 8b

K_{II} for a Corner Crack in a Carrier Spoke

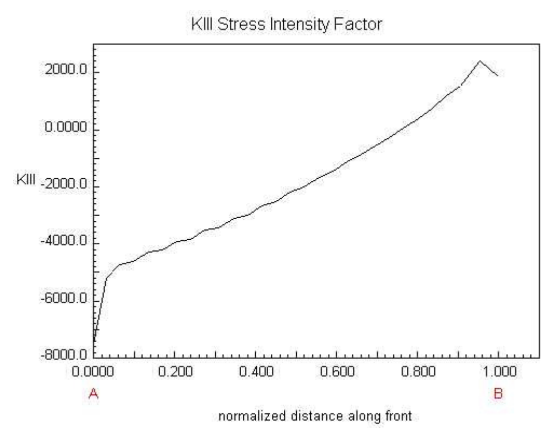

Figure 8c

K_{III} for a Corner Crack in a Carrier Spoke

Note the uneven ΔK across the crack front.

The final crack profile is shown in Figure 9. Note the crack change of direction. The classical solution to the ΔK assumes a straight crack growth trajectory. In reality, this isn't true; actual field failures confirm the accuracy of Figure 8.

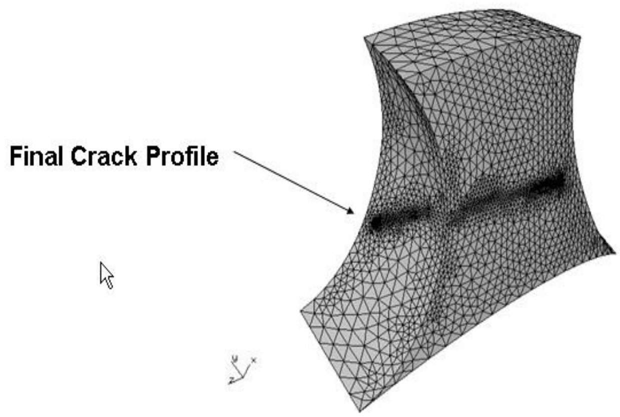

Figure 9
Final Crack Profile

Assembling each stress intensity history gives Figures 10a and b. In this case, a history of K_I is shown. By observation, crack growth along point A of the crack tip provides the worst case.

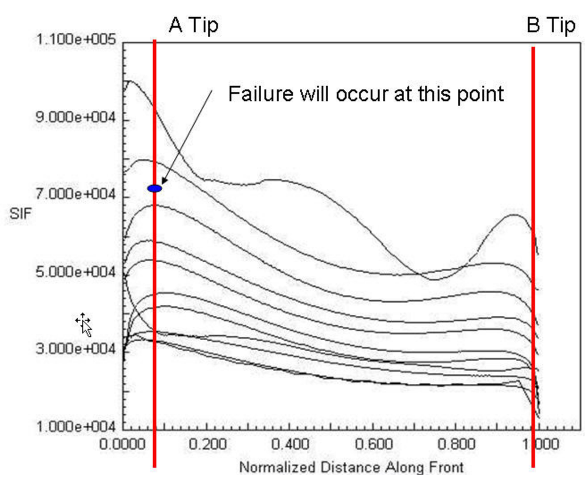

Figure 10a

Stress Intensity K_I History Profile

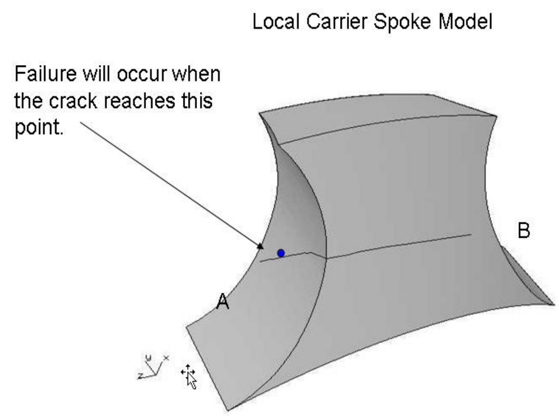

Figure 10b

Stress Intensity K_I History Profile

Step 6: Design Life Determination

Finally, given all of the parameters needed, Paris' Law (8) can be integrated using a simple constant amplitude loading, or with a block of single amplitude loadings to attain the number of available cycles of life for the component being examined.

$$N = \int (da/C(\Delta K)^m \quad (8)$$

Having done so, the life of the component can be predicted. The final integration for the example was done in FRANC3D. Figure 11a shows the resulting crack growth. The results show that for that crack growth 120,000 cycles are achieved (see figure 11b). The needed number of cycles was 100,000 cycles. So, life expectancy was met.

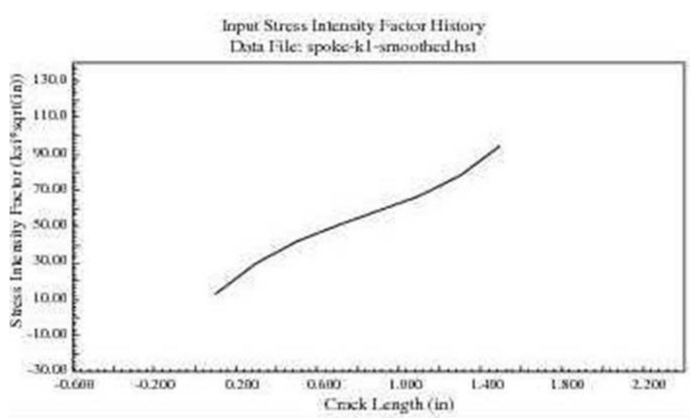

Figure 11a
Final Crack Growth Results for the Corner Crack in a Sprocket Carrier Spoke

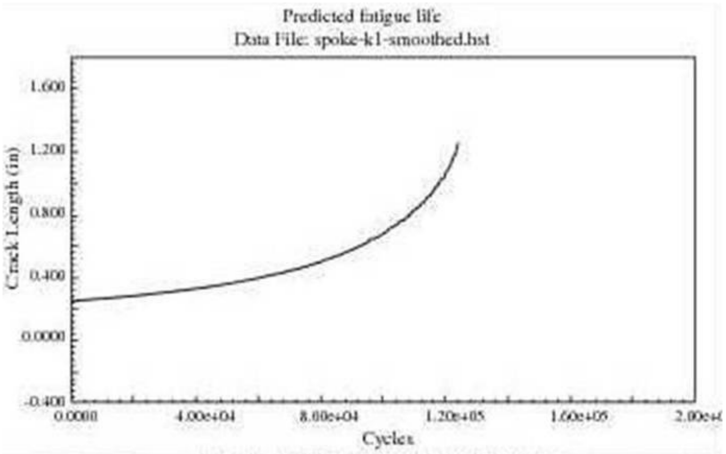

Figure 11b
Final Crack Growth Results for the Corner Crack in a Sprocket Carrier Spoke

CONCLUSION

In summary, this paper presents a process that can be used to prediction the life of a component with the presence of a defect. It requires different steps that first define the life requirements, develop the loading and stress/time histories, develop the needed properties such as ΔK, and conclude with the integration of Paris' Law. By following this procedure, the life of a component on a military vehicle can be determined. In the example, the sprocket carrier required a minimum of 100000 equivalent cycles and was able to exceed that requirement

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