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Estimation of Fatigue Life in Al alloy Specimens Using FEA

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KEYWORDS

J Integral,
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Fatigue Crack Growth,
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ABSTRACT

Acceptable fatigue life assessment of components is desirable for various industries. The fatigue life of a specimen includes the total number of cycles required for crack initiation and the number of cycles required for crack growth. In many industries, such as aerospace or petrochemical and refining industries, due to the high cost of parts, it is necessary for the part to continue to work even after crack initiation. Therefore, to estimate the fatigue life, the fatigue crack propagation should be studied. Experimental fatigue tests are very time consuming and costly. So, it is very important to use finite element software to simulate and study the fatigue crack growth. In this research, with the help of finite element simulation in Abacus software and using the J integral criterion, the growth of fatigue cracks and the estimated life of a sample of 5000 series aluminum alloy was investigated. Comparing the results of experimental and finite element (FE) indicated a good agreement.

1. Introduction

Fatigue damage is a phenomenon that has been known since the 19th century and should be considered as the most important cause of failure in mechanical design [1]. Crack growth laws are needed to estimate the life of a structure after cracking. There are many theoretical and experimental rules to express the growth of fatigue cracking [2]. The J integral parameter is the most important parameter used to express the laws of fatigue crack growth in this area.

Many researchers have studied the growth of fatigue cracks and estimated the life of parts and structures using finite element analyzes. Alam et al. [3] modeled the growth of fatigue cracking and life expectancy using common surface elements. Their results showed that the use of common surface elements to model fatigue crack growth is in good agreement with the experimental results. Ding et al. [4] modeled the growth of fatigue cracks from a groove in steel specimens. Using the finite element, they investigated the effect of stress ratio on the growth rate of fatigue cracks. Their results showed that under the positive stress ratio and negative stress, the growth of fatigue cracks is different. Zhang et al. [5] investigated the crack opening and closing behavior in a semicircular crack using elastic-plastic finite element modeling. They studied a fixed elastic crack and a fixed elastic-plastic crack. Crack growth behavior was modeled using the release of crack tip nodes in each loading cycle. The effects of different node release programs, mesh size, and initial crack length were studied. Alshoaibi et al. [6] investigated the growth of fatigue cracks in hybrid mode using two-dimensional finite element simulation. Comparison of finite element results with experimental results showed that finite element analysis is very effective for predicting crack growth path as well as fatigue life. Camas et al. [7] investigated the schematic effects of fatigue crack growth on the crack closure mechanism using three-dimensional finite element modeling. The results showed that it is better to use stress data instead of loading cycles to open and close the crack tip. Masoudinejad et al. [8] investigated the growth behavior of fatigue cracks and optimized the fatigue life of riveted aluminum alloy joints. They used an elastoplastic three-dimensional model for the simulation. The finite element results were in good agreement with the experimental results. Noghabi et al. [9] investigated the finite element redistribution of residual stress due to fatigue crack growth. The results showed that fatigue loading leads to redistribution of residual stress in aluminum samples.

Due to high cost and time consuming nature of fatigue tests, many researchers use FE software to design and estimate the fatigue life of industrial components. In this research, a FE model was developed in Abaqus to estimate the fatigue life of aluminum parts. In the created model, the integral parameter J was used, which is very efficient for elastoplastic states or states where there is residual stress in the part. The FE model was validated with experimental results. After validation of the FE model using experimental results, FE simulation was used to predict the fatigue life of aluminum specimens.

2. Methodology

If the load forms a large plastic area in the crack tip, the elastoplastic fracture mechanics can provide a better understanding of how the crack grows. One of the most important and widely used parameters in this field is the J integral. The concept of integral J was first proposed by Rice [10]. This integral is path-independent and is defined as Equation 1:

$$J = \int_{\Gamma} \left(W n_1 - T_m \frac{\partial u_m}{\partial x_1} \right) ds \qquad (1)$$

In this research, the adapted form of the Paris equation developed by Dowling [11] and based on the J integral is used to express the law of crack growth:

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$$\frac{da}{dN} = C(\Delta J)^m \qquad (2)$$

The fatigue life of the sample from the initial crack length $a_i$to the final crack length $a_f$is obtained by integrating Equation 2. Given that in finite element simulation, crack is grown discontinuously (element to element), the above integral becomes a set of sentences and can be written as Equation 3 [12]:

$$N = \sum_{i=a_i}^{a_f} \frac{deltaA}{C(\Delta J)^m} \qquad (3)$$

Various crack growth rules have been developed based on theory and experience, the most important of which are listed in Table 1.

Table 1. Comparison of experimental and FE fatigue life estimation

Nature	Growth Law	Reference
Experimental	$\frac{da}{dN} = C(\Delta K)^m$	Paris [13]
	$\frac{da}{dN} = \frac{C(\Delta K)^m}{(1-R)K_c - \Delta K}$	Forman [14]
Deformation in crack tip	$\frac{da}{dN} = C_1 \omega_{max}^m \Delta\omega^p$ $\frac{da}{dN} = C_1 K_{max}^m \Delta K^p$	Erdogan [15]
	$\frac{da}{dN} = \frac{C(1-R)^{4-m} K_{max}^4}{K_c^2 - K_{max}^2}$	Raju [16]
	$\frac{da}{dN} = (\frac{\pi}{32})^{1/2\propto} \left[\frac{2\left(1-\frac{\Delta K_0}{\Delta K}\right)}{\varepsilon_f' E(K_c - K_{max})}\right] \Delta K^{2/\propto}$	Duggan [17]
	$\frac{da}{dN} = \frac{\Delta K^2}{4\pi(1+\mathrm{n})\sigma_{\mathrm{y}}^2} \left[\frac{2\sigma_y}{\varepsilon_f E}\right]^{1+n}$	Schwalbe [18]
Crack tip Geometry	$\frac{da}{dN} = \frac{\Delta\sigma^2 . a}{E^2} (\ln \frac{4\mathrm{E}}{\Delta\sigma} - 1)$	Frost and Dixon [19]
	$\frac{da}{dN} = \frac{8}{\pi} (\frac{\Delta K}{\mathrm{E}})^2$	Pook and Frost [20]
Crack Closure	$\frac{da}{dN} = C(U\Delta K)^m$	Elber [21]
	$\frac{da}{dN} = \frac{(0.886U)^{1+n} \mathrm{p}^{\mathrm{m}}}{500(1-R)^{1+n}} a$	Lal [22]

To determine the coefficients of the adapted Paris equation, crack growth experiments were performed on CT components according to ASTM E647 [23] with the dimensions given in Figure 1.

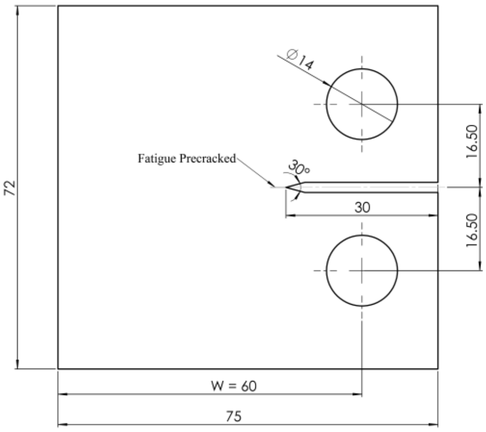

Figure 1. Geometric dimensions of CT sample

Figure 2 shows the mesh of the sample in FE model. 4-node elements were used in the model. As the mesh approached the crack tip, the elements became smaller in several steps so that the elements were small enough in the crack tip areas.

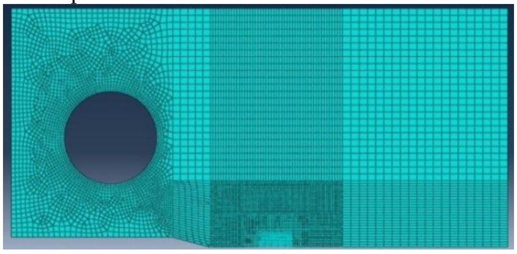

Figure 2. Meshing of CT sample

3. Results and Discussion

Figure 3 shows the experimental graph of the fatigue crack growth rate in terms of the integral interval J. Using the fit of the curve on the data in Figure 3, the material coefficients in Equation 2 are obtained as follows:

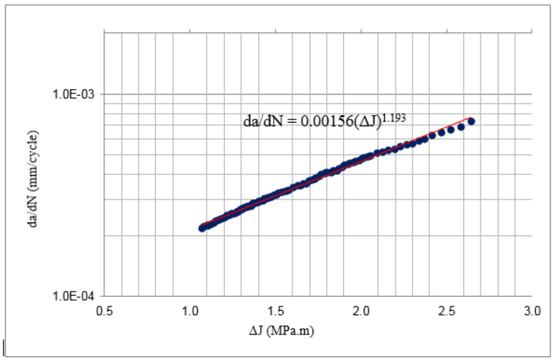

Figure 2. Meshing of CT sample

FE simulations were performed for 3 different loads with maximum load P_{max} = 4kN, P_{max} = 6kN and P_{max} = 8kN with constant stress ratio R = 0.1. To ensure the accuracy of the FE results, the J integral results obtained from the FE were compared with the experimental data. The FE and experimental results for P_{max} = 4kN are compared in Figure 4. As shown in Figure 4, there is a good agreement between the results of the FE and the experimental test.

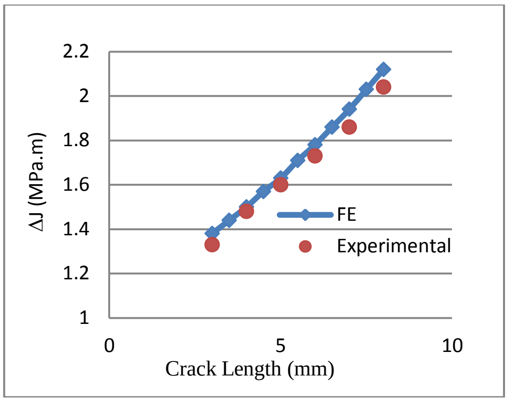

Figure 3. Integral J versus crack length

To validate the results due to finite element and estimate the life with Equation 3, the fatigue life for loading P_{max} = 6kN and P_{max} = 8kN was calculated using finite element analysis using Equation 3 and compared with the experimental results. The results of this comparison are shown in Table 2. The results show that the estimation of finite element life is about 5% different from the experimental results. The finite element method also predicts life less than the actual value, which in fact leads to a conservative estimate of fatigue life.

Table 2. Comparison of experimental and FE fatigue life estimation

Model	Experimental	FEM
P_{max}= 6kN	38211	36230
P_{max}= 8kN	21728	20350

4. **Conclusions**

In this study, the fatigue life of aluminum parts was investigated using finite element software. Experimental test results were used to evaluate the finite element model. The results of this study indicate that using finite element analysis and knowing the fatigue properties of the material, the fatigue life of an aluminum alloy structure can be well predicted for desired loads.

Comparison of finite and experimental element results showed that integral J is a suitable parameter to express the laws of fatigue crack growth in the elastic-plastic domain. The use of the finite element method with the simplifications made leads to a conservative prediction of the fatigue life of a part.

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