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Reliability Evaluation of Fatigue Crack Growth Rate of Heat-Treated TIG-Welded Al 6013-t4 by Two-Parameter Weibull

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Keywords: Aging, Fatigue crack growth, TIG-welded Al 6013-t4, Two-parameter Weibull.

Abstract. The limited data of fatigue crack growth (FCG) may cause an inaccuracy assessment of the fatigue crack growth rate (FCGR). For particular parts in aircraft such as fuselage skin, a high-reliability degree due to FCG must be determined accurately for the design and safety requirements. Generally, the 6xxx series of aluminum alloy is used as the material for the fuselage skin in the aircraft. In this study, reliability evaluation of FCGR of heat-treated TIG-welded Al 6013-t4 was investigated by two-parameter Weibull. The FCG tests were conducted by following the ASTM E647 under three different artificial aging time conditions of 6, 18, and 24 hours. The C and m constant values were obtained by drawing the regression line from FCG data following Paris's equation and analyzed employing three methods; the least square fitting method (LSFM), a mean value method (MVM), and a probabilistic distribution method (PDM). The result showed that the PDM and MVM showed a better-fitted line to assess the C and m values than LSFM. From the reliability viewpoints, the two-parameter Weibull was proposed to be applied as the PDM. Furthermore, the MCM was successful in evaluating the probabilistic assessment of the FCGR with the 85% confidence interval.

Introduction

The 6xxx series of aluminum alloy is still be used for structural components such as fuselage skins on aircraft and body panels on the car [1-2]. This alloy is well known for its excellent properties such as high mechanical and fatigue strength, good formability and weldability, and excellent corrosion resistance. The welding method is typically chosen for joining aluminum since it is a simple and low cost, and it is also able to joint significant size components. The butt joint type is the most common one used for the joining. There are two common types of arc welding methods used for joining the aluminum alloy, which is the tungsten inner gas (TIG) and gas metal arc welding (GMAW). The GMAW can give good penetration and deposition in the high-speed welding process, and the welding process can be done continuously regardless of electrode length. Since the GMAW results in high heat input, the problems such as melt through and distortion may occur for aluminum with a particular thickness. On the other hand, TIG welding can be performed better than GMAW in a wide range of aluminum thicknesses and shapes.

The presence of a crack in a component may degrade its performance, and further can cause a failure operation or fracture into two or more pieces. Although the stress condition is below the material's yield strength, the existence of crack may still cause an unpredictable failure. A further process, such as welding, may increase the failure probability [3]. A crack or defective components due to the fabrication process or operating condition may not be avoided. In a fabrication process, it is well known that a product/component may have the highest failure rate due to the manufacturing processes. This characteristic is well known as the bathtub curve characteristic [4]. Following the bathtub curve, the component may fail due to the static and cyclic loading under the operation

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For the design and safety consideration, it is crucial to make sure the fatigue failure may not occur. The FCG should be predicted accurately under the operation condition. Therefore, the comprehensive investigation of FCG must be explicitly done. It is important to make sure that the FCG data obtained by the experiment must be reliable. A considerable number of testing must be conducted, and the tests usually are time consuming and expensive. Even though the FCG tests have generated a large number of data, the data deviation may still be found. Many efforts have also been conducted to produce reliable data of crack propagation by using a deterministic approach based on certain assumptions and fixed material properties [5]. However, the results showed that the conservative assessment arose due to the usage of upper and lower bounds data of material property. Some researchers have the interest to produce reliable data from the probabilistic viewpoints [5-7]. The reliable data were assessed by determining its confidence interval.

In this study, the reliability evaluation of FCGR of heat-treated TIG-welded Al 6013-t4 was investigated. The FCG data was obtained from the FCG tests under three different artificial aging time conditions of 6, 18, and 24 hours. The fatigue crack growth rate (FCGR) characteristics were characterized by applying Paris's equation into the FCG data. The two-parameter Weibull distribution method was proposed to evaluate the reliability values of material constants, *C*, and *m*, where these values relate to the degree of sensitivity of the growth rate to stress [3]. By applying the two-parameter Weibull, a large number of random variables of *C* and *m* were generated by the Monte-Carlo method (MCM).

Methods

Following the previous investigation, the FCG data of TIG-welded Al 6013-t4 was solution heat treated under three different aging times of 6, 18, and 24 hours at 175 ºC [2]. The FCG data was characterized by the fracture mechanics parameter of stress intensity factor, Δk. The relationship of FCG and Δk is widely well known as Paris's equation, and it can be expressed as follows,

$$\frac{da}{dN} = C(\Delta k)^m \quad (1)$$

where da/dN is the fatigue crack growth rate (mm/cycles), and Δk is the stress intensity factor (SIF) (MPa $m^{1/2}$). The *C* and *m* are values that are obtained by drawing the regression line on the FCG data. Furthermore, the *C* and *m* values were analyzed employing three methods; the least square fitting method (LSFM), a mean value method (MVM), and a probabilistic distribution method (PDM). From the reliability viewpoints, the two-parameter Weibull was proposed to be applied as the PDM. The two-parameter Weibull consists of β and η (shape and scale factors, respectively) [4]. The cumulative failure distribution function $F(t)$ of two-parameter Weibull can be expressed as follows,

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \quad (2)$$

where t is the time (hour), β is Weibull slope (the slope of the failure on the Weibull chart), also referred as the shape parameter, and η is characteristic life or the time by which 63.2 % of the product population will fail, also referred to as the scale parameter [4]. Furthermore, the probabilistic assessment of FCG data was evaluated by generating a large number of FCG data with the MCM. MCM is one of the popular tools involving random variables based on the sample solution. In this study, the MCM was used to generate random numbers of C and m. The random numbers with the two-parameter Weibull distribution function can be expressed as follows,

$$x = (-\ln U)^{1/\beta}\eta \tag{3}$$

where U is a uniform random variable between 0 and 1.

Results and Discussion

Figure 1 shows the log-log plot of da/dN vs. Δk. It can be seen that FCGR is falling between the SIF values of 10 MPa $m^{1/2}$ and 11 MPa $m^{1/2}$, where the weld area is located. It has been reported that the reduction in resistance to the FCGR in the weld area was caused by heat treatment conditions [2]. The residual welding stress on the welding area is relieved by the heat treatment. Furthermore, the three different regression line methods are applied and compared. The values of C and m are listed in table 1. It has been mentioned earlier that the values of material constants correspond to the degree of sensitivity of the growth rate to stress. The C is obtained when the fitting line intersects the x-axis, and the m exponent corresponds to the slope. The material's resistance to the FCGR will increase when the m exponent is lower, and vice versa.

Comparison from three different regression line methods shown that the MVM almost has an identical value with PDM, while the LSFM is significantly different. The LSFM tends to give the lower C, and higher m values than the experimental data since the FCG data distribution influences the LSFM. The FCGR obtained by LSFM is formulated as da/dN=6.12E-15[Δk]$^{8.12}$. The LSFM may not appropriate and will not be used for further evaluation. The C and m values obtained by MVM is generated by taking the mean value of the three values for C and m, which are acquired by taking linear regression on each data of the FCG. The C and m values of MVM are not differing significantly with the experimental data. The FCGR obtained by MVM shows good agreement with all of the FCG data, and it is formulated as da/dN=2.66E-14[Δk]$^{7.59}$.

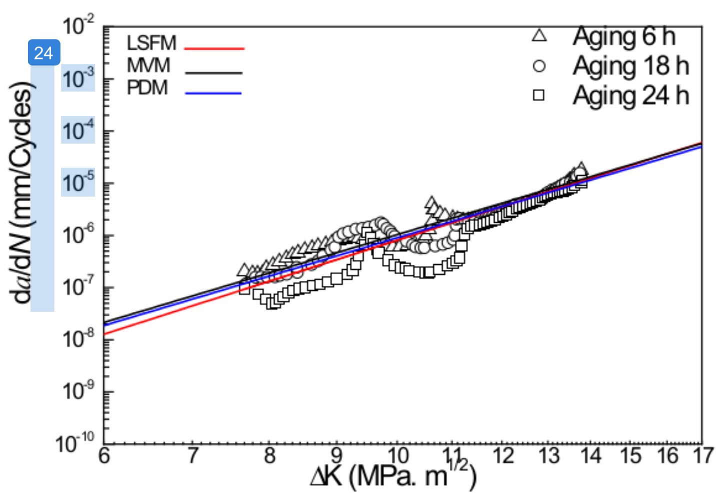
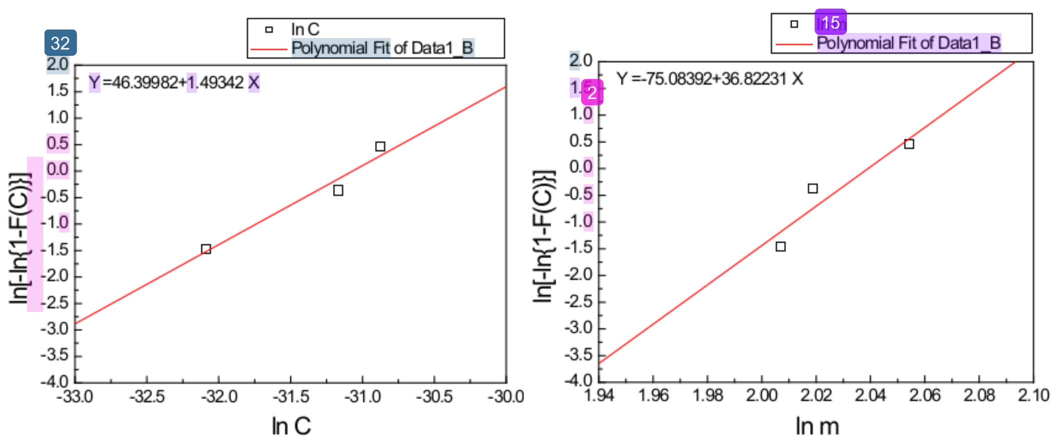


Fig. 1. Comparison of FCGR by LSFM, MVM, and PDM.

Figure 2 shows the PDM method obtained by the two-parameter Weibull distribution. The values of C and m are arranged by median rank. The median rank is the only method that is generally used to solve a cumulative distribution function [4]. The median rank method can also minimize the error. Figures 2 (a) and (b) show the probability plot for C and m values that are ranked by the median method. The figures show that the values of C and m have excellent linearity with the fitted linear line. The PDM values are almost the same as the MVM. Following Paris's equation, the FCGR values with PDM are obtained as da/dN=2.36E-14[Δk]$^{7.58}$. By using the values of C and m in figure 2, the β and η parameters are then determined. The parameters are determined by applying the eq. 2. The β parameter is determined from the slope of the distribution graph, and the η parameter is determined from the intersection line with the *x-axis* when the probability value is zero [4]. The parameter values of β and η are summarized in table 2.

Table 1. Constants value of *C* and *m*.

	C	*m*
Aging 6 h	3.89E-14	7.44
Aging 18 h	2.92 E-14	7.53
Aging 24 h	1.16 E-14	7.80
Mean value method (MVM)	2.66E-14	7.59
Least square fitting method (LSFM)	6.12E-15	8.12
Probability distribution method (PDM)	2.36E-14	7.58



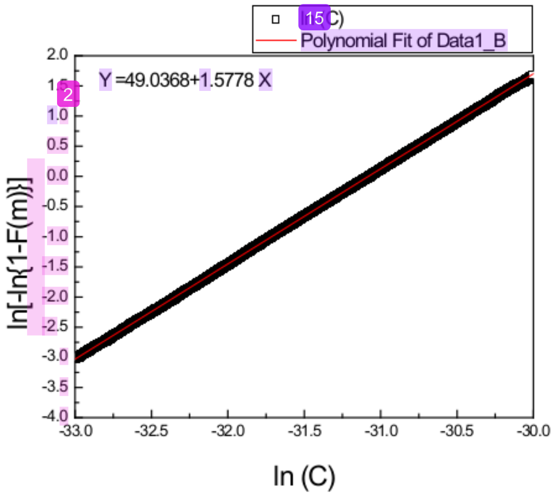
(a) (b)

Fig. 2. Two-parameter Weibull distribution ;(a) constant *C*, (b) constant *m*.

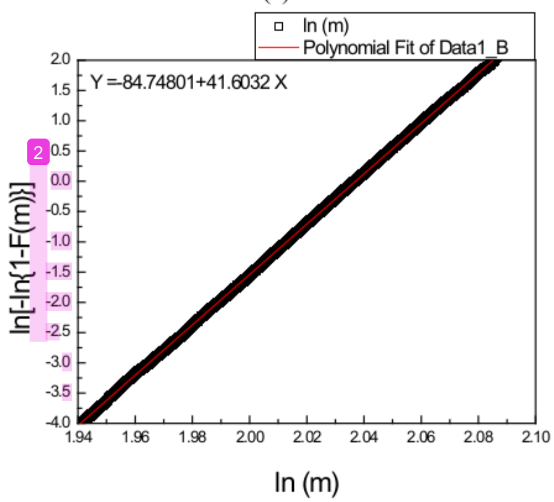
Table 2. Shape and scale values obtained by Weibull distribution.

Weibull parameter	ln *C*	ln *m*
β	1.56	41.93
η	3.17E-14	7.67

Figures 3 (a) and (b) show the 20.000 random numbers of *C* and *m* values that are generated by MCM. The random number is obtained by applying the eq. 3. The result shows that the *C* and *m* values generated by MCM are closely linear with the *C* and *m* values in figure 2. The linear equations of the experimental data and MCM are not significantly different. Following this result, the MCM is initially successful in predicting the values *C* and *m* by two-parameter Weibull.



(a)



(b)

Fig. 3. MCM results; (a) constant *C*, (b) constant *m*.

Figure 4 shows the predicted FCGR by MCM. By applying for 20.000 random numbers, the MCM has successful in assessing the predicted FCGR from the three experimental data. Figure 5 shows the determination of the confidence interval for the FCGR. Almost 85% of FCGR lies between the lower and upper bounds. About 5% of data lies below the lower bound, and 90% data lies above the upper bound. The lower and upper bounds correspond to the limit of conservative prediction of the fastest and slowest FCGR [3].

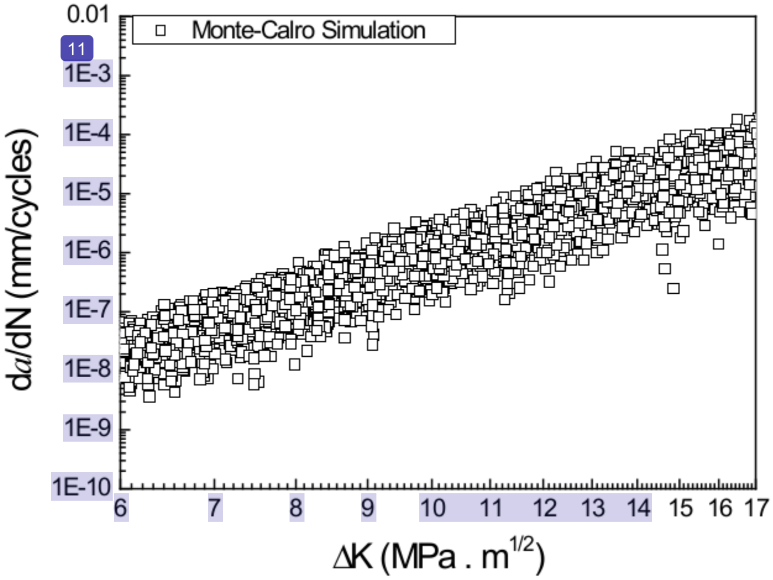


Fig. 4. Probability distribution of FCGR generated by MCM.

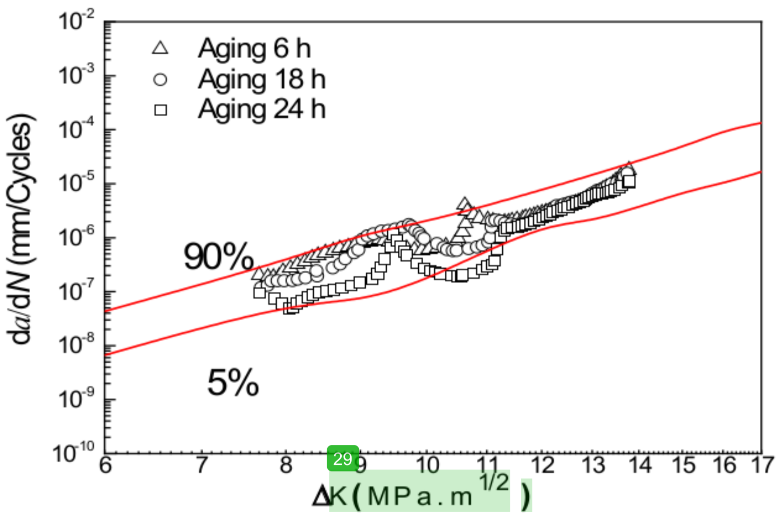


Fig. 5. Determination of confidence interval of FCGR.

The 85 % confidence interval seems quite broad and not precisely due to the small number of FCG test. As the number of FCG test increases, the confidence interval may be narrower and closer to the median rank [4]. The respective bounds of 5 and 90% may come to be more intimate by increasing the number of FCG test.

Summary

This paper had comprehensively investigated the reliability evaluation of FCGR of heat-treated TIG-welded Al 6013-t4 by two-parameter Weibull. The two-parameter Weibull had initially succeeded in assessing the reliability values of C and m. Furthermore, the MCM was able to predict the probability interval of FCGR from the two-parameter Weibull with 20.000 random numbers. All predicted of FCGR data lay on an 85% confidence interval. With the 85% confidence, under particular SIF, the FCGR can be explicitly determined. The conservative prediction showed that the upper limit bound was located at 90% where the fastest FCGR occurred, and the lower limit at 5% where the slowest FCGR occurred.

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