International Journal of Fatigue 32 (2010) 398–402

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Fatigue life scatter in 7xxx series aluminum alloys

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ARTICLE INFO

Article history:
Received 11 December 2008
Received in revised form 9 July 2009
Accepted 14 July 2009
Available online 25 July 2009

Keywords:
Aircraft
Aluminum alloy
Fatigue
Fatigue life scatter
Fighter spectrum

ABSTRACT

Specimens of Al 7175-T7452 and Al 7075-T6511 were fatigue tested under several spectra to obtain estimates of the standard deviation of the log of the fatigue life and to determine if there was bimodality as was found for Al 7050-T7451. The 7175 alloy showed no sign of being bimodal when tested under a spectrum which included large compressive loads. The measured standard deviation in the log of the fatigue life was 0.105, which is greater than the value obtained for the 7050 alloy, but not significantly so. The 7075-T6511 alloy tested under both a spectrum with almost no compressive loads and a filtered spectrum derived from this, showed no indication of being bimodal. The measured standard deviation of the log of the fatigue life was found to be 0.138, which is significantly higher than that obtained from the 7050 alloy, and noticeably higher than the value of 0.10 used in determining safe life limits for aircraft aluminum components. These results clearly indicate that the practice of using a single scatter factor for all aluminum alloys is potentially unconservative.

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1. Introduction

Certain parts of fighter aircraft structure are subject to high frequency, low amplitude load cycles called dynamic or buffet loading. Concern has been expressed that these low amplitude cycles may increase the variability in the fatigue life at long lives. As a result, the Structural Integrity Standard for Continuing Airworthiness policy for the Canadian Forces (CF) 188 Hornet fighter aircraft (F/A 18 A/B derivative), on an interim basis, has replaced the original scatter factors in the range 2.3–2.9 with a scatter factor of 5.0 for parts subject to this kind of loading [1]. The value of 5 is arbitrary, and there are no specific data to justify this estimate. An increase in the scatter factor from 2.3 (0.1% chance of failure, $n = 3$, $\sigma = 0.1$) to 5.0 corresponds to a doubling of the standard deviation of the fatigue life. The aim of the larger study of which this work was part, was to measure the effect of dynamic loading on the standard deviation in the fatigue life of typical specimens used in life prediction methodologies for safe life aircraft components. It was anticipated that these data could be used to justify a scatter factor lower than 5 for parts subjected to dynamic loading. If, for example, it could be demonstrated that dynamic loading had no effect on the standard deviation, then the scatter factor could be reduced to the original value. This would result in nearly doubling the allowable service life of the component.

Initial studies [2,3] on Al 7050-T7451 were performed using two different spectra. The first was based on the aft engine hanger location, referred to as the M series spectra [4], and the second on the loads experienced at the aileron inboard hinge, the S series [3] of spectra. At least two different versions of each spectrum, using different levels of filtering were investigated. In the case of both spectral series, the results showed that the distribution of the log of the crack initiation life was normally distributed for the higher levels of truncation. However, when the untruncated spectra, i.e. spectra that retained the dynamic cycle content, were used, the distribution of the log of the crack initiation life became bimodal as shown in Fig. 1 for the M series spectra. Each mode of the bimodal distribution appeared to be normally distributed. For the M series spectra, the standard deviation was 0.032 for the lower life mode and 0.057 for the upper. In the case of the S series spectra, these values were 0.022 and 0.033, respectively. These values were not statistically different and they are considerably less than the standard value of 0.1 used in the Canadian Forces (CF) lifing policy [1,5] and from the values of 0.112 (M19), 0.100 (M11) and 0.096 (S3T) found for the truncated spectra. The difference between the means of the two modes was greater for the M series spectrum, 0.28, than for the S series spectrum, 0.16.

When only a small number of coupons are tested, the bimodal nature of the untruncated spectrum distribution is not readily apparent. Although the life distribution was clearly not log-normal, the standard deviation obtained when the modes for the untruncated spectrum were combined was 0.148, illustrated by a dashed line in Fig. 1. At first glance, this supports the notion that dynamic loading can increase in the scatter of the fatigue life data. However, this is not the case; since the distribution is not normal, the two modes are more accurately treated separately, and the lower life mode has a lower standard deviation than for the truncated spectra.

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doi:10.1016/j.ijfatigue.2009.07.016

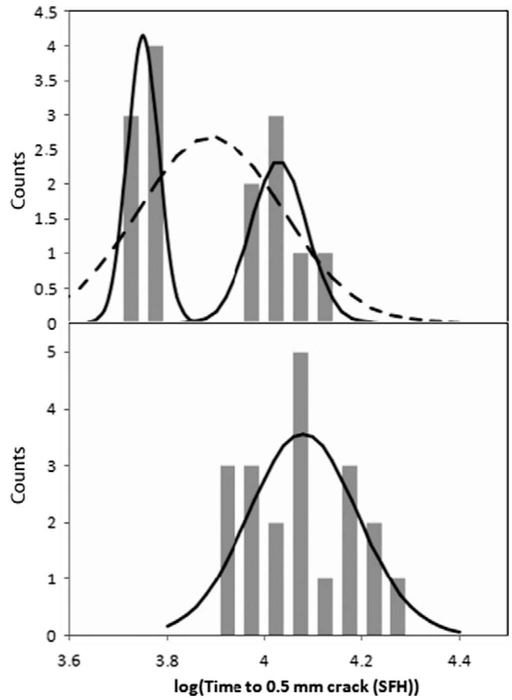

Fig. 1. Comparison of the fatigue life distributions for a spectrum with small cycles (M0) (top) and a filtered spectrum (M19) (bottom) [2]. The solid curves represent normal distribution fits to the data. The dashed curve is a normal distribution fit to all of the M0 data, ignoring the bimodal behaviour.

An examination of the initiation points of the fatigue cracks demonstrated that for all of the cracks belonging to the short life mode, there was a particle, typically on the order of 20 μm in size, buried just inside the surface of the material. Such particles amplify the local stress field and would cause these specimens to initiate fatigue cracks early compared to those without particles at the surface. On the other hand, most, but not all, of the cracks that belonged to the long life group did not have such particles at their initiation point. This suggested a physical explanation for the observed bimodality. When small cycles are left in the spectrum, they are able to promote the initiation and growth of cracks with particles, but not those without. When the small cycles are removed, the larger cycles that remain can promote the growth of cracks growing from both types of initiation points.

The present work sought to expand on the previous results by investigating whether or not the bimodal distribution was found in other airframe alloy systems, specifically 7175-T7452 and 7075-T6511. In addition, this study sought to determine whether or not it was appropriate to use a single value for the standard deviation of the log-normal fatigue life distribution for aluminum alloys in general as is done in the current lifing policy. In this work, spectra representative of the loads experienced by the CF-188 aileron inboard hinge were used to examine the effect of truncation on the distribution of the fatigue life.

2. Experimental

Double edge notched specimens of Al 7175-T7452 were made as shown in Fig. 2. The stress concentration factor, K_t, for these specimens was 2.09 with respect to the net cross-section (K_t always refers to net section throughout this paper). The machining of each specimen was performed on a 3-axis computer driven mill. The double edge notches were made with two end mills: one for the roughing cuts and a second for the finishing cut. The second end mill was used only for this study and was new at the start of

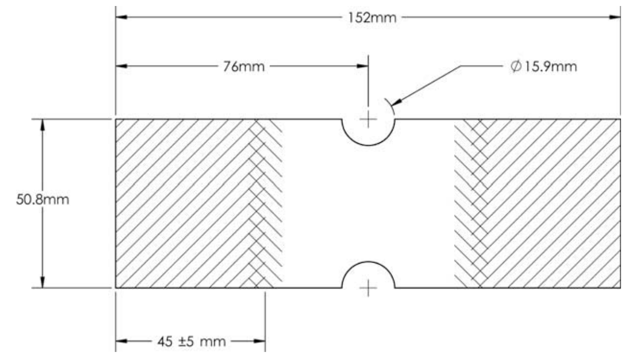

Fig. 2. Short fatigue specimen made from half of the long specimen. Hatched area shows portion of the specimen that was gripped.

the processing. This ensured a consistent quality of surface finish between the specimens. The specimens were all 6.35 mm (0.250 in.) thick. No surface hardness or residual stress measurements of the machined surfaces were made.

The load spectrum used was the S3B spectrum that had been used previously on Al 7050-T7451 specimens with the same specimen geometry and the same load levels, allowing direct comparison of these results with those from the earlier study [3]. The key parameters describing the S3B spectrum are shown in Table 1. The maximum notch root stress of 422 MPa is less than the nominal yield stress of 470 MPa for this alloy. Fig. 3 shows the distribution of the cycles obtained using a rain flow analysis on the baseline spectrum. It can be seen that this spectrum contains large compressive loads. However, most of the small cycles occur under tension.

In order to measure crack initiation life, the specimens were cycled for a fixed period and then stopped under load. An acetate replica was taken in both notches. The fatigue test was then continued for another fixed period and the inspection process was repeated. Once a crack was identified in a replica, earlier replicas were examined to see if the same crack could be found. In this manner, cracks as small as 0.1 mm could be detected. A plot of crack length vs. cycles was then made for each specimen. The life to form a crack 0.5 mm in surface length was interpolated from the crack growth curves and used as the crack initiation life throughout the rest of this work. The sensitivity of using different crack lengths was also examined, but the scatter factors did not change significantly for crack lengths up to 1.0 mm as the initiation point. Cracks always initiated near the centre on the inside surfaces of the notches.

For the 7075-T6511 alloy, specimens similar to those used in the original study [2] on 7050-T7451 were used (Fig. 4). The stress concentration factor, K_t, for these specimens is 1.63. As in the case of the 7175 coupons, the specimens were machined on a 3-axis computer driven mill using two end mills, one for the initial cut and one for the finishing cut.

The specimens were tested using both the baseline M0 spectrum and its truncated form M19, both of which were used in an earlier study [2], which also contains mean stress range diagrams similar to Fig. 3 for these two spectra. The major difference between the M series spectra and the S3B spectrum is that the former contains a significant number of compressive loads (minimum stress = −90% maximum stress), while the M series spectra do not (minimum stress = −12% maximum stress) The maximum stress in the notch root of these specimens was increased from the value (414 MPa) used in the original study on 7050 alloy to a value of 535 MPa in order to get specimen fatigue lives in the range of 10,000 simulated flying hours (SFH).

Testing on the M19 specimens was conducted as described above, with replicas being taken at regular intervals to determine

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