Fatigue Reliability Analysis of 6156-T6 Riveted Joints based on Detail Fatigue Rating

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Abstract. The fatigue behavior of two kinds of riveted joints 6156-T6 aluminum alloy structures was experimentally investigated. The detail fatigue rating (DFR) values of 6156-T6 is calculated based on statistical analysis of fatigue tests. The fatigue crack initiation and propagation behavior are examined using scanning electron microscopy. The results show that DFR value of 6156-T6 aluminum alloy with riveted lap joints is 97.81MPa, and the DFR value of rivet-filled countersink hole structure is 168.39MPa. The crack initiation sites occurred at the vicinity of the fastener hole in all specimens. The fatigue striations were uniformly spaced in the region of stable crack growth.

1. Introduction

6156 aluminum alloy was developed for higher damage tolerance capability than its predecessors (6xxx series aluminum alloy, e.g. 6056) by France Pechiney Company. In addition, the low density, excellent weldability and corrosion resistance made 6156 aluminum alloy more attractive for widespread used in aircraft structures [1, 2]. She studied the fatigue crack propagation rate of 6156 aluminum alloy in various aging states and different stress ratios [3]. Zhang investigated the effects of two-step aging treatment on the mechanical properties, electrical conductivity, intergranular corrosion and microstructure of 6156 aluminum alloy by means of tensile, conductivity measurement, intergranular corrosion experiments and transmission electron microscopy [4]. Lin researched the effects of aging treatments on the mechanical properties and corrosion behavior of 6156 Al-alloy [5].

However, the fatigue behavior of riveted joints in 6156 aluminum alloy remains rather limited. In the present work, fatigue tests on two kinds of riveted joints specimens from 6156-T6 A1-alloy were carried out. The DFR value of riveted joints was obtained by statistical analysis of experimental data. The fractography of fatigue fracture surface was examined also using scanning electron microscopy (SEM).

2. Experiment

Two categories of specimen were manufactured for fatigue tests: (i) riveted lap joints (RLJ); (ii) rivet-filled countersink hole (RCH). The dimensions of riveted lap joints specimens were shown in figure 1. The specimens were 300 mm-long, 40 mm-wide sheets, with 80 mm-long lap joints made of three two-rivet rows. The dimensions of rivet-filled countersink hole specimens were shown in figure 2. The rivets were NAS1097AD6, spaced 20 mm along the width of the specimen.
Figure 1. Dimension of riveted lap joints specimen.

Figure 2. Dimension of rivet-filled countersink hole specimen.

The specimens was assembled from two aluminum alloy 6156-T6 plates with nominal thicknesses of 1.8 mm. Table 1 listed the chemical composition of 6156-T6 aluminum alloy.

Table 1. Chemical composition of 6156-T6 (mass fraction, %).

|   | Si  | Fe  | Cu  | Mn  | Mg  | Zn  | Cr  | Al  | other |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-------|
|   | 0.83| 0.13| 0.84| 0.51| 0.71| 0.39| 0.10| other|       |

Fatigue tests were performed on INSTRON-8801 servo-hydraulic material testing machine (figure 3) in ambient air. The specimens were loaded in uniaxial tension with an R ratio of 0.06. The fatigue tests have been performed under a frequency of 20 Hz until crack occurred. Fatigue tests were conducted according to HB5287-96 specification.

Figure 3. Riveted joints test.
3. Results and Analysis

3.1. Test Results
Table 2 shows the experimental fatigue results of two categories of 6156-T6 aluminum alloy riveted structures.

Table 2. Test results of fatigue test.

| type | $\sigma_{\text{max}}$ (MPa) | fatigue life (cycle) |
|------|------------------|-------------------|
| RLJ  | 95               | 246585            |
|      |                  | 342293            |
|      |                  | 276885            |
|      |                  | 437748            |
|      |                  | 405612            |
|      |                  | 272703            |
| RCH  | 180              | 292738            |
|      |                  | 198533            |
|      |                  | 160906            |
|      |                  | 228576            |
|      |                  | 176038            |
|      |                  | 238931            |

3.2. Fatigue reliability assessment
The detail fatigue rating (DFR) means the maximum nominal of $10^5$ cycles under constant amplitude loading with stress ratio 0.06, 95% confidence level and 95% confidence [6]. A structural joints having a higher DFR value leads to a better fatigue performance and a longer fatigue life. Existing uncertainties related to fatigue damage assessment are also accounted in DFR method. The relationship between the DFR and other fatigue parameters is shown as follows [7].

It is assumed that the fatigue life follows a two-parameter Weibull distribution, which can be expressed as:

$$F(N) = 1 - \exp\left(-\frac{N}{\beta}\right)^\alpha$$  \hspace{1cm} (1)$$

where $\beta$ is characteristic fatigue life, $\alpha$ is the scale parameter, which determines the shape of the distribution density curve of Weibull distribution.

According to maximum likelihood method, the point estimation of characteristic life can be expressed as:

$$\hat{\beta} = \left(\frac{1}{n} \sum_{i=1}^{n} N_i^\alpha\right)^\frac{1}{\alpha}$$  \hspace{1cm} (2)$$

where $n$ is number of valid data, $N_i$ is experiment life, The fatigue material parameters used here is $\alpha = 4$ for aluminum alloy.

The reliable fatigue life $N_{95/95}$ can be determined by:

$$N_{95/95} = \frac{\hat{\beta}}{S_C \cdot S_R \cdot S_T}$$  \hspace{1cm} (3)$$

where $\hat{\beta}$ is the point estimation of characteristic fatigue life, $S_C$ is the confidence level factor, $S_R$ is the reliability level factor and $S_T$ is the specimen factor. $S_C$ with a 95% confidence level for $n=6$ is 1.15. $S_C$ with a 95% confidence level is calculated as $S_R=2.1$. Specimen factor $S_T$ is determined as 1.3.

Finally, the DFR of a structural detail can be calculated as:

$$DFR = \frac{(1-R)\sigma_{m0}}{0.94\sigma_{m0}/\sigma_{\text{max}} S^{(5-\lg N)} - 0.47S^{(5-\lg N)} - 0.53} - R(0.47S^{(5-\lg N)} + 0.53)$$  \hspace{1cm} (4)$$

The fatigue life reliability assessment method is applied here to a structure subjected to a constant amplitude fatigue loading. The fatigue material parameters used here are $S=2$ and $\sigma_{m0}=310$MPa for aluminum alloys.
The calculated results of fatigue reliability assessment of 6156-T6 aluminum alloy are shown in table 3. The DFR value of 6156-T6 aluminum alloy with riveted lap joints is 97.81MPa, and the DFR value of rivet-filled countersink hole structure is 168.39MPa.

### Table 3. Statistical analysis of test results.

| Type    | $\hat{\beta}$ | $N_{95\%}$ | DFR (MPa) |
|---------|----------------|-------------|-----------|
| RLJ     | 352483         | 112273      | 97.81     |
| RCH     | 229057         | 72960       | 168.39    |

#### 3.3. Fractography

Figure 4 is the SEM image of fatigue fracture surface. Fatigue fracture can be divided into three areas: fatigue source area, fatigue crack growth area and instantaneous fracture area, as seen in figure 4(a). The crack initiation sites occurred at the vicinity of the fastener hole in all specimens. Fracture surfaces near the crack initiation sites show a cleavage-like microstructure caused by transcrystalline sliding fracture, as seen in figure 4(b). This is frequently observed in aluminum alloys when fatigue tests are conducted under ambient air. The fatigue crack growth area (figure 4(c)) shows very fine fatigue striations. The fatigue striations were uniformly spaced in the region of stable crack growth providing evidence of the nature of crack propagation characteristics of the alloy in the T6 microstructural condition. The instantaneous fracture area (figure 4(d)) shows a ductile fracture feature resulting from void growth and coalescence. Dispersion of microscopic voids and a number of shallow dimples are present at the grain facets.

**Figure 4.** SEM image of fatigue fracture surface.

#### 4. Conclusions

Fatigue tests on two kinds of riveted joints 6156-T6 aluminum alloy specimens are carried out. The DFR values of riveted joints are calculated by statistical analysis of experimental data. The DFR value of 6156-T6 aluminum alloy with riveted lap joints is 97.81MPa, and the DFR value of rivet-filled countersink hole structure is 168.39MPa. Fatigue fractography can be divided into three typical areas:
fatigue source area, fatigue crack growth area and instantaneous fracture area. The crack initiation sites occurred at the vicinity of the fastener hole in all specimens. Fatigue source area shows a cleavage-like microstructure. The fatigue striations were uniformly spaced in the region of stable crack growth, which is the crack growth characteristics of the alloy in the T6 microstructural condition. The instantaneous fracture area shows a ductile fracture feature resulting from a number of shallow dimples and microscopic voids.

5. References
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