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Effect of Drilling Process on Fatigue Life of Open Holes*

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Abstract: In this paper, a series of fatigue tests were performed to study the effect of drilling process on fatigue behavior of open holes in dog-bone specimens drilled by the traditional drilling process and advanced Winslow drilling process. The evaluations of initial fatigue qualities of the two types of holes were carried out based on the equivalent initial flaw size method and coincidence criterion. Fatigue fracture surfaces were observed by stereomicroscope. The results show that the location where the fatigue crack initiates is unchanged when these two different drilling processes are used. A longer fatigue life shows a more severe dispersibility. When the Winslow drilling process is adopted, the equivalent initial flaw size is smaller than 0.125 mm. The Winslow drilling process meets the requirement of coincidence criterion.

Key words: fatigue life; drilling process; fracture surface; initial fatigue quality

Introduction

In the modern aircraft industry, the main objective of aircraft design is weight saving and reliability of aircraft. The fatigue life of crucial components are mainly determined by the geometrical detail design such as fasten holes and filleting, where stress concentration occurs. According to the statistic, fatigue fracture of fastener holes account for 50%-90% of fracture of aging plane[1]. The decrease of effect of fasten hole's stress concentration could improve the anti-fatigue performance and ensure the reliability and security. Traditional multi-step drilling hole process[2,3] has been widely used in anti-fatigue structure in airplane manufacture. With the increasing demand of aircraft design, the traditional multi-step drilling hole process is unable to ensure fatigue life of fastener holes to meet the requirements of airplane design, and due to this, the Winslow Drilling Hole Process was introduced into China.

The effect of drilling processes on fatigue performance of fastener hole for 7050 aluminum alloy has rarely been reported[4-8]. Ralph et al. studied holes quality with different drilling processes[9,10]. Dong et al.[11] and Cao et al.[12] studied the equivalent initial flaw size for different drilling processes, their results showed that the equivalent initial flaw size should be smaller than 0.125 mm.

The purpose of this paper is to analyze the effect of traditional multi-step drilling process and Winslow drilling process on fatigue behavior of open holes. Specimens containing open holes were fatigued under remote constant amplitude tensile load. Investigations of fracture surface were performed to locate the crack initiation region and to obtain initial fatigue qualities of holes based on equivalent initial flaw size method. Finally, finite element method (FEM) was used to analyze the distribution of stress around the holes when

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load was applied. The FEM results revealed the possible mechanism for crack initiation.

1 Material Property

The material used for this study is aluminum alloy 7050, with chemical composition, 91.63% of Al, 1.12% of Cu, 1.9% of Mg, 0.02% of Mn, 0.08% of Si, 0.19% of Fe, and 0.05% of Ti. Typical mechanical properties of the material along the rolling direction are obtained from tensile tests. The stress-strain behavior of the material is shown in Fig. 1, which shows that Young modulus is 79 GPa, yield strength is 503 MPa. The Poisson ratio is measured to be $\nu = 0.33$.

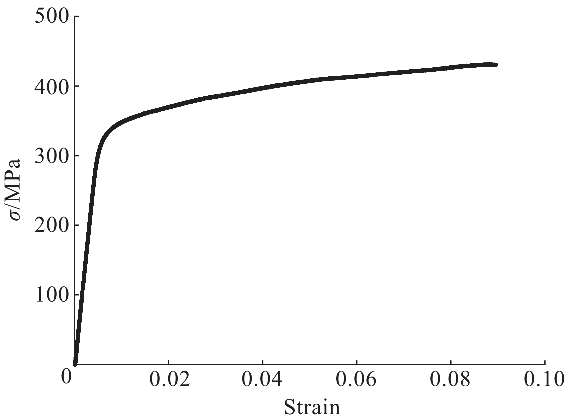


Fig. 1 Stress-strain diagram for alloy 7050

2 Experiment

2.1 Dimension of specimens

The 7050 aluminum alloy is supplied as a sheet with a thickness of 6 mm and cut into dog bone shape with centre holes. The form and the final dimensions are shown in Fig. 2. It is noted that the axis of loading is parallel to the rolling axis of sheet.

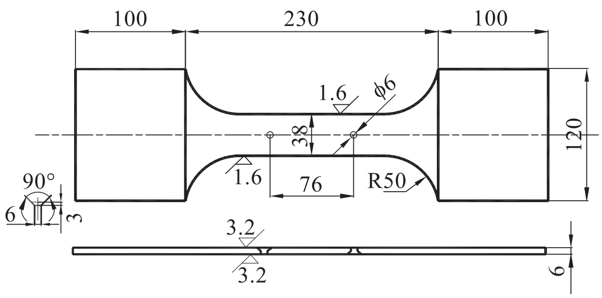


Fig. 2 Geometry and size of specimen (mm)

2.2 Drilling processes

There are 42 specimens concerned in the present study. Half of them are drilled using traditional multistep drilling process, the other half are drilled using advanced Winslow drilling process. After testing, comparing with the traditional drilling technology, the Winslow drilling process is much more precise on the control of hole size and a lower surface roughness value can be obtained. However, there is no change in geometry.

2.3 Fatigue test

All the specimens are tested on a servo-hydraulic fatigue testing machine (Instron8802). During fatigue tests, load spectrum is combined by two types of sine constant load amplitudes blocks, which is used to obtain the relationship between the crack length and fatigue life. For these two blocks, the max stresses are the same. The stress ratio R ($\sigma_{\min}/\sigma_{\max}$) is 0.06 and frequency is 8 Hz in first block. The stress ratio is 0.53 and frequency is 16 Hz in second block. During the test, the first block loads was applied for 3 min and then the second block loads was applied for 9 min. The sequence is repeated until the specimen is fractured.

3 Finite Element Model

In this study, a 3-D FE model is established. The ABAQUS/standard finite element package was used to carry out the analysis[13].

In the ABAQUS element library, ABAQUS linear hexahedron reduced integration elements C3D8R (three-dimensional eight nodded continuum elements) is used to mesh the model (as shown in Fig. 3). In a finite element analysis, selection of mesh size and layout is very critical. It is desirable to use as many elements as possible in the analysis. However, such an analysis will require excessive computational efforts. In order to obtain an optimal result, the mesh around the hole was further refined (as shown in Fig. 4). In this FEM analysis, the number of elements is 36 582.

The boundary conditions are given as follows: one end of model is fixed, the other end of model is uniformly tensile loaded as 80 MPa.

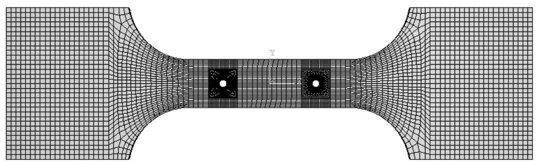


Fig. 3 Finite element model

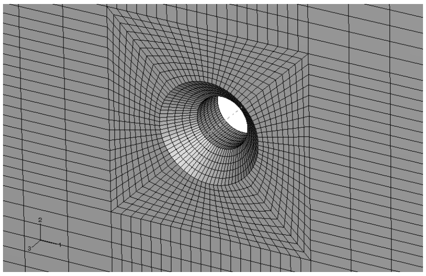


Fig. 4 Refiner mesh near hole

4 Results and Discussion

4.1 Fatigue results

After tests, the mean fatigue lives, coefficient of variation, and the improved multiples of fatigue life are listed in Table 1.

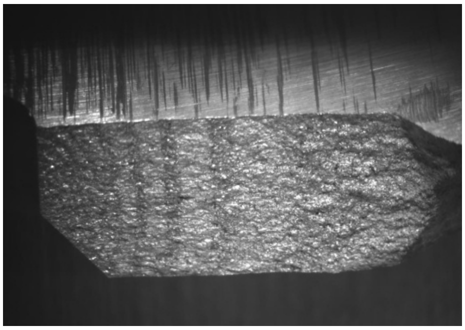
Table 1 Fatigue life of specimens

Drilling process	Stress level (MPa)	Mean fatigue life (cycles)	Coefficient of variation	Multiple
T	80	65 912	0.154 722	1.36
W	80	89 611	0.148 465	
T	90	46 317	0.509 550	1.31
W	90	60 605	0.170 970	
T	100	29 462	0.159 799	1.42
W	100	41 877	0.154 653	

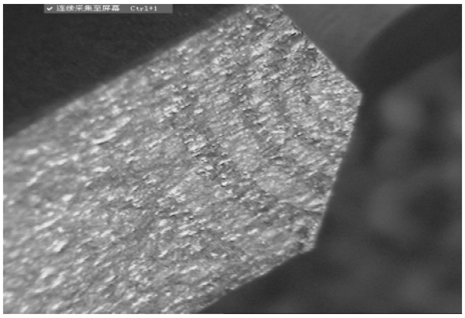
Table 1 shows that: contrasted to traditional drilling process, the fatigue life of open holes is longer when Winslow drilling process is used and the improved multiple of fatigue life is about 1.36 times. Meanwhile, the dispersion of fatigue life is smaller. The main reason is that the Winslow drilling process confines the surface roughness within a small value. According to the fracture mechanics theory, the fatigue performance is associated with surface roughness which means that a lower surface roughness exhibits a better fatigue performance. Moreover, after the improvement of the process, the feed impact on the residual stress is also very strong. Feed has become relatively smaller than the traditional system, and this increases the residual compressive stress and the fatigue life.

4.2 Comparison analysis of initial fatigue quality

After the fatigue test, all fracture surfaces are observed by optical microscope, and the typical fracture surface of fasten hole is shown in Fig. 5, containing the loading axis of the specimen normal to the plane. It can be seen that the crack initiates at the counter holes edge, which is the same for the two types of drilling processes.



(a) Fatigue fracture under traditional process



(b) Fatigue fracture under Winslow process

Fig. 5 Fatigue fracture surface of holes with different drilling process

Due to the effect of two types of sine block loads on crack propagation, bright and dark strips alternatively occurred at fracture surface. Based on the boundary of bright and dark strips, the relationship between crack length and fatigue cycles was retrieved. For aluminum alloy, the crack initiation life corresponds to the crack length of 0.076 mm-0.1 mm[14-16]. Therefore, according to the number of strips on the fracture surface and fatigue cycles, crack initiation life accounts for 80% of total fatigue life of fastener holes.

Using the aforementioned method, the initial fatigue quality of the two types of drilling process is determined and listed in Table 2.

Table 2 Initial fatigue quality

Traditional process (mm)	Winslow process (mm)
0.134 797	0.0866

Table 2 shows that the equivalent initial flaw size is smaller than 0.125 mm when the Winslow process is used, which meets the requirement of coincidence criterion well. The traditional process, which yields an initial fatigue quality of 0.135 mm, is not good enough to meet the requirement of coincidence criterion.

4.3 FEM results

The main purpose of the finite element analysis on open hole is to find the probable locations of crack initiation, mechanism of crack initiation, and comparison of the fatigue results.

The stress counter of open hole is shown in Fig. 6. It can be seen that the max stress occurs at the countersunk holes edge. This is the stress concentration zone, and the stress concentration factor is about 3.9. According to the fatigue results (shown in Fig. 6), the crack initiates at this location. Therefore, the mechanism of the crack initiation of countersunk fastener holes is that the crack is induced by stress concentration.

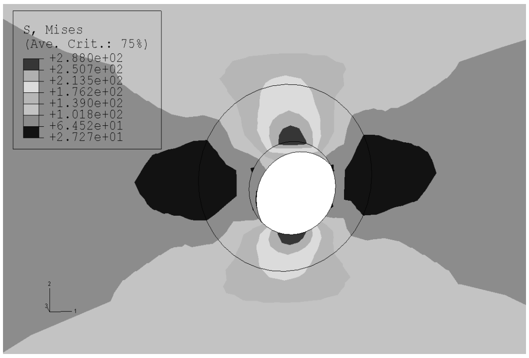


Fig. 6 Stress counter of open hole

5 Conclusions

In this study, a series of tests were conducted in aluminum alloy 7050 to investigate the effect of drilling process on the fatigue behavior of countersunk holes. The following can be concluded:

(1) The crack initiates at the counter holes edge. The fatigue crack's nucleation position is the same for the two types of processes.

(2) When Winslow drilling process is used, the fatigue performance is enhanced with a reduced dispersion. The initial fatigue quality is smaller than 0.125 mm. Winslow drilling process meets the requirement of coincidence criterion.

(3) The mechanism of the crack initiation is that the crack is induced by stress concentration. Crack initiation life accounts for 80% of total fatigue life of fastener holes.

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