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Abstract. Anodizing treatment can improve corrosion resistance of aluminum alloy but decrease the fatigue life significantly. Introducing cold expansion before anodizing can increase the fatigue life of the specimen with open-hole structure by 2582% than the anodized one. Scanning electron microscopy (SEM) was employed for microstructure and fracture surface observation. Residual stress distribution near the sample hole edge was measured to elucidate the strengthening mechanism. The results revealed that although anodizing treatment decreases the surface integrity, the cold expansion is an effective method to improve the open-hole structure specimen remarkably.

1. Introduction

Aluminum alloys have excellent specific strength and specific stiffness, which are widely used in aviation industry [1]. Fatigue behavior is an important aspect which should be taken into account in design and service [2, 3]. The corrosion resistance, especially which of Al alloy, is another critical factor when the component is being considered for the applications in complex environments. Anodizing is the most practical method used for Al alloys that may contribute to the improvement of corrosion resistance and preventing potential corrosion failure [4, 5]. On the other hand, however, it has a significant negative influence on the bulk fatigue properties: decreasing the fatigue life for as large as several orders of magnitude [6].

The cold hole expansion process is a typical mechanical method, which can induce compressive residual stresses near holes. It can improve the fatigue life of structural components of kinds of alloys [7]. Generally, an oversized rigid tool is displaced across a hole, and then the elastic-plastic strain incompatibilities can be obtained through the expansion [8]. Cold expansion process can improve the fatigue life by means of slowing down crack propagation rates, or stopping propagation of fatigue cracks [9].

In this work, Al alloys were treated by a combination of cold expansion and anodizing for synergistic enhancement of fatigue performance. The original specimen and anodized one were also prepared in order to be compared with the cold expansion one. Effects of anodizing and cold expansion on fatigue performance of Al alloy were explicitly studied by detailed analysis regarding to surface morphology characterization, residual stress measurement, fatigue testing, and fracture characterization.

2. Materials and experimental procedures

2.1. Materials

The material used in this study is 7050 Al alloy rolled plate, with the thickness of 95mm, being widely used in aeronautical applications. The chemical composition of this Al alloy is listed in Table 1. The tensile and yield strength are 526MPa and 456MPa, respectively. The specimens were cut from as received plate at the position of 1/4 thickness, which is known as the representative position in a rolled plate [10]. The microstructure of 7050 Al alloy observed by an optical microscope is shown in Fig. 1. Some recrystallized grains are elongated in the rolling direction. The main irregular coarse constituent particles are Al_2CuMg and Al_7CuFe which had been identified by energy disperse spectroscopy (EDS).

Table 1. Chemical composition of 7050 Al alloy

Element	Mn	Si	Cr	Ti	Zn	Cu	Fe	Mg	Zr	Al
Wt.%	0.02	0.0005	0.001	0.04	6.01	2.12	0.08	2.01	0.11	Bal.

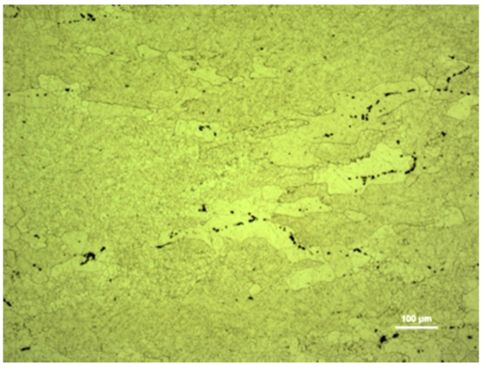

Figure 1. Microstructure of 7050 Al alloy observed by optical microscope

2.2. Specimen preparation

The shape and dimensions of the specimen is shown in Fig. 2. The loading direction is paralleled to the transverse direction of the rolling plate. The specimens surface was polished by milling machine to get an initial surface roughness of Ra=3.2μm. The roughness of hole wall is also 3.2μm.

Anodizing treatment was carried out in H_2SO4 solution (180-250g/L), with the oxidation voltage of 13V at 15-35℃ for 45 min. The thickness of anodic film was about 13-18 μm. The non cold expansion holes were milled to a diameter of 6 mm directly, while the cold expansion holes were firstly milled to a diameter of 5.856 mm and subsequently expanded to 6 mm using the tapered mandrel. The maximum diameter of tapered mandrel was 6.1 mm, which means that the degree of cold expansion in this work was 4.2%, which was the recommended value for aluminum alloy [11].

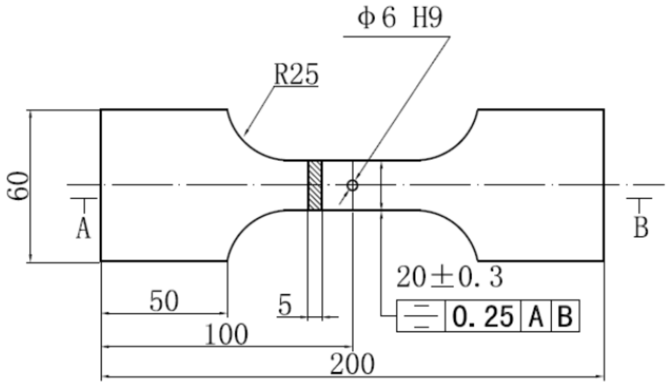

Figure 2. Fatigue specimen geometry (Unit: mm).

2.3. Residual stress measurement
Residual stresses were measured through {311} plane diffraction using LXRD (PROTO, Canada) with Cr-Kα radiation. The diameter of irradiated area was 0.5mm. The measured position is shown in Fig. 3. The first position locates near the hole edge with a distance of 0.5mm, the other four are with 1mm interval in the same side. The measured stress direction is parallel to the loading axis.

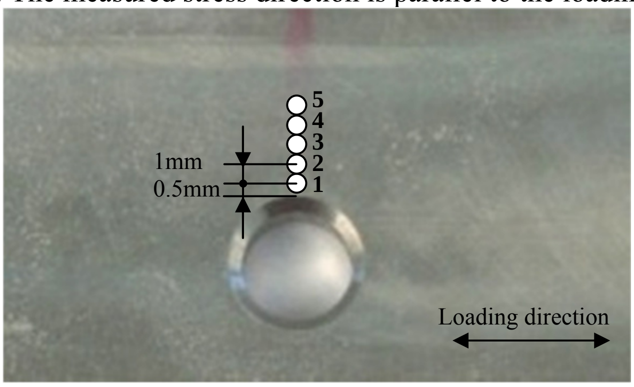

Figure 3. Residual stress measurement positions.

2.4. Fatigue test and fracture observation
Axial tension-tension fatigue tests had been performed at 8Hz with stress ratio R=0.1 at room temperature. All tests were conducted using a 100kN servo-hydraulic MTS machine under load controlled condition. The nominal maximum cyclic stresses were set at 140MPa. The tests were stopped at 1×10^6 cycles if the specimen did not fail. Fracture surfaces were observed by SEM (FEI Nova Nano 450).

3. Results and discussions

3.1. Surface morphology of anodized specimen
Fig.4 shows the surface morphologies of specimens after anodizing. A smooth anodic coating with numbers of pits had formed upon the surface. It has been found that the constituent particles would be dissolved during anodizing process, resulting in pits. These pits could be acting as the initiation area due to stress concentration during fatigue and can affect the fatigue life through reducing the initiation period [3, 12].

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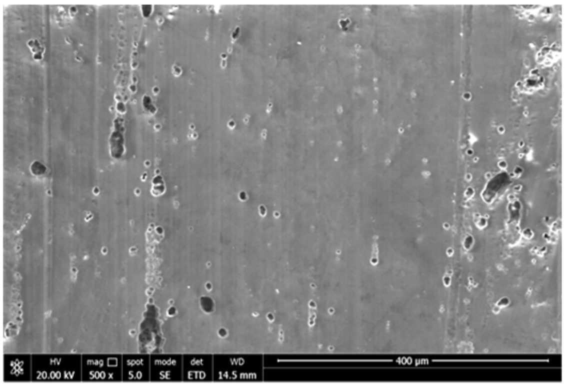

Figure 4. SEM micrograph of the anodized specimen surface

3.2. *Residual stress*

Residual stress results of as-machined, anodized and cold expansion+anodized specimen are shown in Table 2. As-machined specimen shows a small compressive residual stress near the hole. The value from zone near edge to far from edge appears almost the same, which is related to the status of machining process. The compressive residual stress increases after anodizing.

Hole cold expansion is well known as inducing compression stress to the hole edge due to the plastic deformation and work hardening [13]. In this experiment, the residual stress of the specimen after cold expansion + anodizing processes exhibits obviously large compressive stress near the hole edge. Especially within the distance of 2.5mm from edge, the compressive stress decreases with the distance increasing. The variation trend can be clearly seen from the detailed residual stress distribution of different processes at each position, as shown in Fig.5.

Table 2. Residual stress results of different processes (Unit: MPa)

Distance from hole edge(mm)	0.5	1.5	2.5	3.5	4.5
As-machined	-38	-32	-23	-13	-20
Anodizing	-82.9	-98.2	-105.6	-100.5	-97.3
Cold expansion+anodizing	-253.2	-240.9	-176.6	-98.8	-92.7

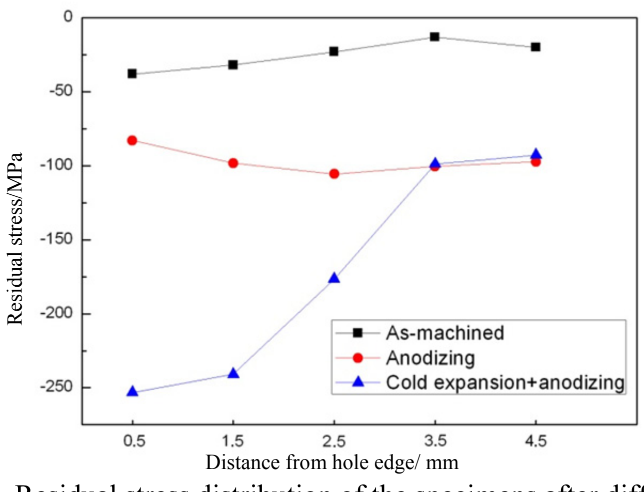

Figure 5. Residual stress distribution of the specimens after different processes

During the cold expansion process, the value and distribution of residual stress is related to the size of plastic zone [14]. In the first stage, the plastic zone develops from the edge of the hole to the matrix with the hole expanding. When the hole expands to a certain degree, the plastic zone keeps constant, and the residual stress becomes stable [15]. Therefore, as shown in Fig.5, the value of residual stress shows almost the same as in anodized specimen from 3.5mm.

3.3. Fatigue test and fracture analysis

Average fatigue lives obtained at stress level σ_{max} = 140 MPa are listed in Table 3, which include the tested fatigue life (four samples for each process), average fatigue life value (Avg.), variance (Var.) and coefficient of variation (CV). The difference of average fatigue lives between the three processes is shown clearly using bar diagram in Fig. 6. The anodized sample shows the shortest fatigue life among three processes. The cold expansion + anodized specimens presented the longest average fatigue life, with increase 37% than the as-machined one, 2582% than the anodized one. This shows that the hole cold expansion process plays a very important role to increase fatigue life of specimens, even combined with anodizing process which affects the surface integrity strongly. The variance of as-machined specimen shows the largest value among three processes. The faigue life of as-machined specimen may be related to the machining marks, which could induce the crack initiation during fatigue test and affect the fatigue life significantly.

Table 3. Fatigue test results of specimens after different process

No.	Process	Fatigue life	Avg: $\bar{x}$	Var: s^2	CV: C
1	As-machined	406137 1000000 1000000 320136	681568	1.36×10^{11}	0.542
2	Anodizing	35088 30476 37135 36872	34893	9.50×10^{6}	0.088
3	Cold expansion+ anodizing	1000000 743715 1000000 1000000	935929	1.64×10^{10}	0.137

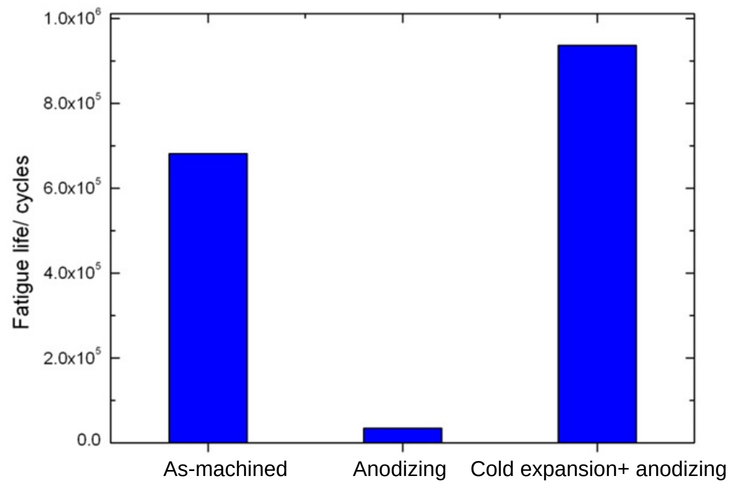

Figure 6. Fatigue life comparison of different processes

Fracture surface morphology of specimens of different processes after fatigue tests at 140MPa are shown in Fig. 7. Generally, fatigue crack initiation is related to the stress concentration area, such as defects, geometry corners, machining marks, etc [16]. For the three processes specimens, all of the cracks initiated from the wall of the open-holes. For as-machined specimen (Fig. 7a), the crack initiated from multi machining marks, which makes the fracture surface looking uneven compared with the anodized one in the source area. In the anodized specimen (Fig. 7b), some pits could be seen on the initiated hole wall. The extension traces can be seen clearly from the origin line transmitted to the rest part. After anodizing, there are numbers of pits on the oxidized surface, which caused stress concentration as defects. Some of these pits form to short lines, which become crack initiation. A few lines on the surface composed a multi-crack initiation area, which reduced the fatigue life significantly. Fig. 7c shows the fracture surface of the specimen after hole cold expansion+ anodizing, although the crack still initiated from the hole wall, machining marks and pits can not be found in the source area. Theoretically, after hole cold expansion, a plastic deformation layer formed on the hole wall, which hardened the surface dramatically. The crack initiation and propagation has been suspended due to the plastic deformation of cold expansion surface. Both of the compressive residual stress and microstructure contributed to the improvement of fatigue life of specimens.

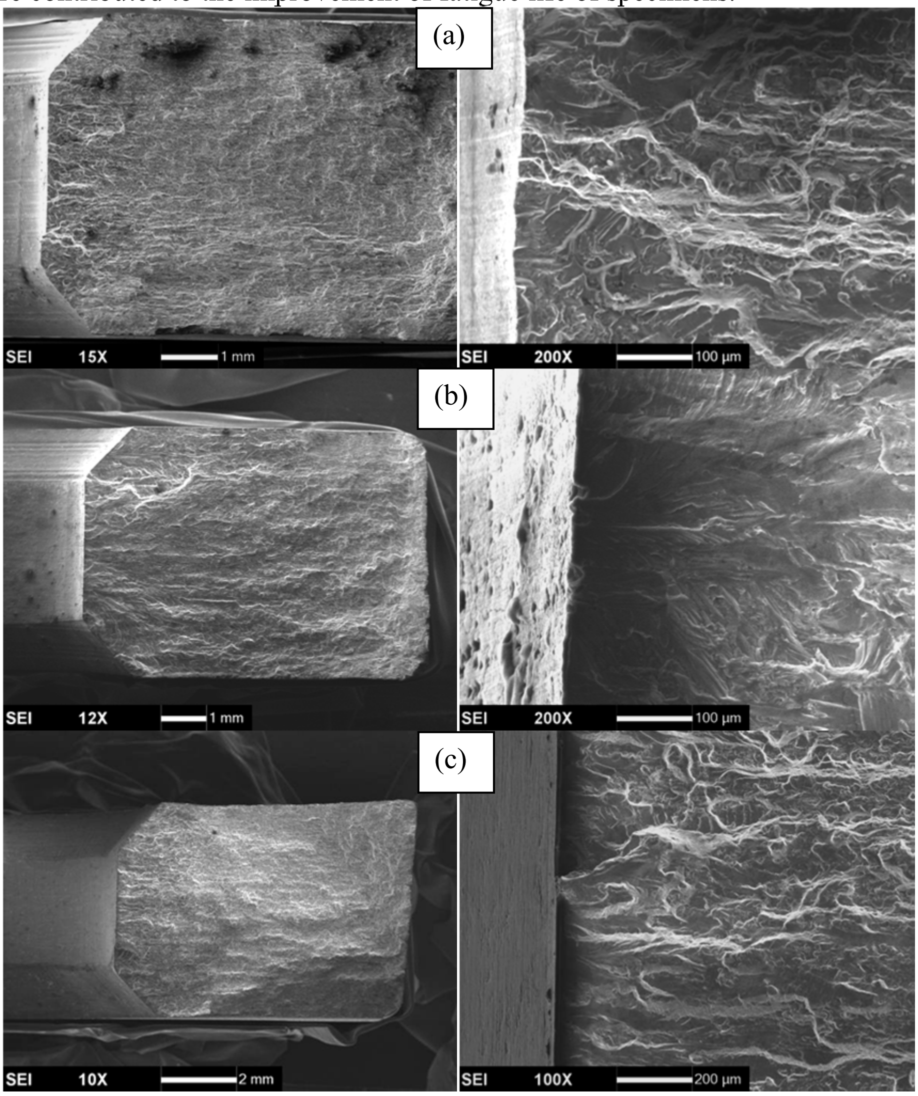

Figure 7. Fracture surface observation of the fatigued specimens: (a) as-machined, (b) after anodizing, (c) after hole cold expansion+ anodizing.

4. Conclusion

The fatigue life of 7050 Al alloy had been tested and analyzed for different hole process. Surface morphology characterization, residual stress tests and fracture surface analysis explained diversity of the fatigue life explicitly. Generally, anodizing treatment can improve the corrosion resistance, but decrease the fatigue life in normal environment significantly. Introducing the hole cold expansion before anodizing process can increase the fatigue life by 2582% at 140Mpa than that only treated by anodizing. Through observing the fracture surface of specimens after fatigue test, it is found that the crack initiated from the hole wall uniformly, instead of from machining marks in the as-machined one and from pits in the anodized one. Cold expansion process is verified to be an effective way to improve the fatigue life of specimens significantly, even combined with anodizing treatment.

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