2011 SREE Conference on Engineering Modelling and Simulation (CEMS 2011)

Comparison of the simulation and experimental fatigue crack behaviors in the aluminum alloy HS6061-T6

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Abstract

This work deals with rotating bending fatigue tests on aluminum alloy HS6061-T6. Results have been obtained for two sizes of narrow section diameter for specimens with one hole. Results show that fatigue endurance is reduced in the case of the hole. In order to explain this behavior, numerical analysis by FEM were carried out to determine the stress concentrations for the two types of specimens. It is found that the important factor affects fatigue life is the narrow section diameter of the specimens, and the maximum damage occurs in the outer part of the specimen at the first stages of loading, however, it moves toward the center of the bar under uniaxial loading. The number of cycles to failure predicted numerically is higher than the experimental one. This difference is attributed mainly to an upper stage of fatigue crack growth, particularly, the interaction between fatigue crack growth and growth that can not be accounted for in the numerical model.

Keywords: fatigue crack; FEM; Aluminium alloy HS6061-T6; stress concentration;

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1. Introduction

The aluminium alloy 6061-T6 is a precipitation hardening alloy with high content of magnesium and silicon, presenting good mechanical properties and weldability and one of the most common aluminium alloys for general-purpose use: aircraft fittings, brake pistons, hydraulic pistons, appliance fittings, valves and valve parts, bike frames, camera lens mounts, couplings, marines fittings and hardware, electrical fittings and connectors, decorative or misc. hardware, hinge pins, magneto parts and others. Modern industrial applications of aluminum alloys imply frequently heave loading; this is the reason of some recent works dealing with the problem: development of the "Fatigue Crack Growth Law" [1].In our previous work, the HS6061-T6 was obtained high strength by ECAP method. However, the fracture mechanics typically offers a reliable foundation for the description of the fatigue growth of cracks. It is well known that residual stress plays a crucial role in fatigue crack growth behavior [2-4]. LSP is a competitive technology as a method of imparting compressive residual stresses into the metal surface to improve fatigue and corrosion properties [5, 6]. A numerical model for predicting the depth of plastic deformation and resulting residual compressive stress at the surface has been completed by Abul Fazal [7]. The plastic behavior near the tip of stationary crack in engineering materials has been intensively studied by using classical plasticity theory based on the Von-Mises yield criterion [8] and the associative flow rule [9]. Ray and Patanker [10] derived the crack closure models on the crack opening stress by finite element computations. Then, the theoretical analysis work which confirmed the effect of the compressive residual stresses generated by LSP on the SIF has been put forward [11], showing the influence of compressive stress on the 3D non-through hole-edge crack's SIF after LSP. This work is devoted to the study of fatigue endurance of aluminium alloy 6061-T6 under rotating bending fatigue tests, when one artificial hole are machined at the narrow section of the hourglass shape specimen. Special attention was focused on the stress concentration factors caused by the holes and the relationship to experimental fatigue endurance.

2. Material

The chemical composition of aluminum alloy HS6061-T6 aluminum alloy is (in Wt. %): Al 95.8~98.6/Cr 0.04~0.35/Cu 0.15~0.4/Fe Max0.7/Mg 0.8~1.2/Mn Max.0.15/Si 0.4~0.8/Ti Max. 0.15/Zn Max. 0.25/Other, each Max. 0.05/Other, total Max. 0.15; and the mechanical properties of aluminum alloy HS6061-T6 are Density 2700 kg/m^3, Hardness, Brinell 95, Elastic limit σ_y 270 MPa, Nominal stress σ_n 330 MPa, E 68.9 GPa , Poisson ratio ν 0.33, Elonga. at Break 17%, respectively, for the tested material.

3. Specimen and testing conditions.

Figure 1 presents the image, shape and dimensions of "dog bone" shape testing specimen. An important parameter is the narrow section diameter D_0, where the stress concentration is located under rotating bending fatigue. International standardization is available for the rotating bending fatigue test specimen; then, the specimen dimensions were fixed from machining and numerical simulation criteria and references [12].Tests were carried out at room temperature; a cooling system with cooling air was implemented in order to keep the testing temperature below 60 °C at the critical specimen narrow section. Under this condition, no modification in the crystallographic structure of testing material was expected. Machining process for all specimens was as homogeneous as possible in order to avoid important variation on the surface roughness.
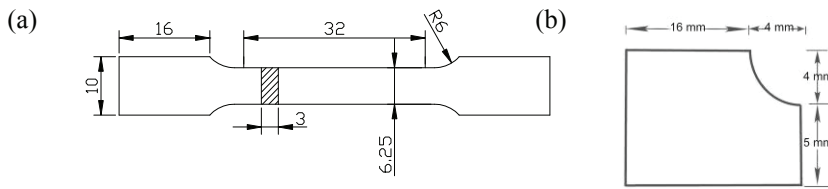
Figure 1 Specimen picture and dimensions (mm) (a) Specimen 1 with single hole 0.80 mm×0.8 mm×0.4 mm; (b) Specimen 2 with single hole 0.80 mm ×0.8 mm×0.4 mm;

Uniaxial fatigue loading was achieved for the two types of testing specimens; the stress concentration factor for the single hole (rectangular surface cavity), is evaluated according the expression [13, 14]:

$$K_t = 1.522 \left(1 + \frac{2}{7 - 5v}\right) \qquad (1)$$

Here v is the Poisson coefficient. For an aluminium alloy with v = 0.33, the stress intensity factor K_t = 2.09;important increase on stress is developed at the bottom of hemispherical cavity for one artificial hole [15];the stress is higher for the same applied load P in the case of two close holes located at the narrow section of specimen. The stress concentration factor and fatigue endurance relationship for tested specimens is analyzed in further sections of this work [16].

4. Numerical simulation

In order to determine the loading condition, the stress distribution and the fatigue crack behaviors inside the specimen, numerical simulation by software COSMOS were carried out, as shown in Figure 2.
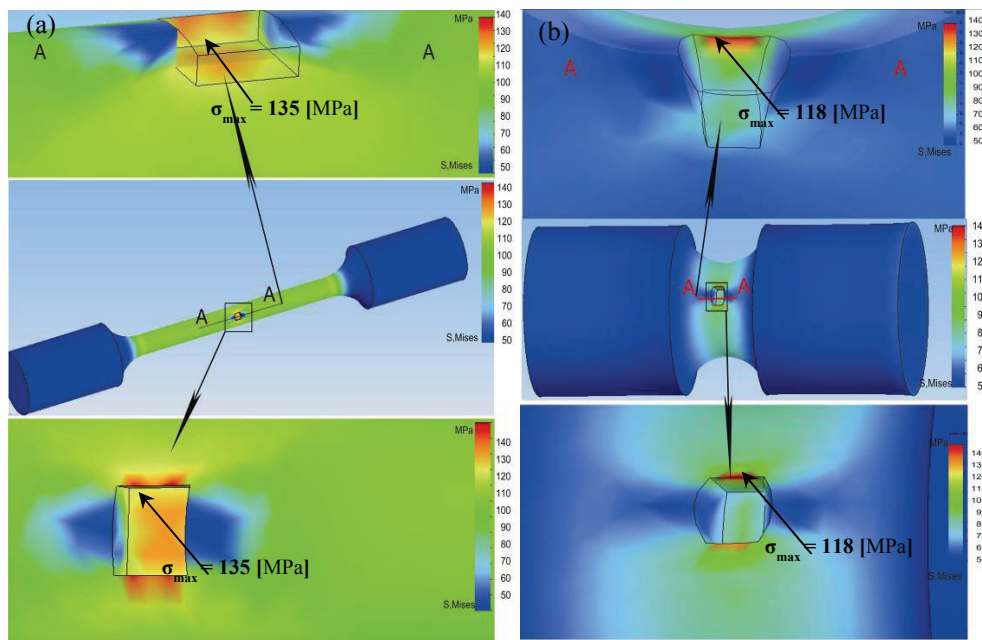

Figure 2 Numerical simulations of fatigue crack behaviors in the aluminum alloy HS6061-T6 fatigue failure cycle 2.0×105)
(a) Specimen 1 with single hole 0.80×0.8×0.4; (b) Specimen 2 with single hole 0.80×0.8×0.4;

It was found that with a bending load of P=42 N for Specimen 1, and P=107 N for Specimen 2. The fatigue failure cycle 5.0×10^4, the induced Von Mises stress at the narrow section of the specimens without was close to σ_n =135 MPa, the 50 % of elastic limit of this material: 270 MPa for Specimen 1; and σ_n =118 MPa, the 43% of elastic limit of this material: 270 MPa for Specimen 1.

It is possible to observe that the propagation of the crack is nearly perpendicular to the applied load. Also, we can observe that the maximum displacement in function of the crack propagation is presented in the specimens 1 and 2, which is attributed to the mechanical properties and microstructural condition of the material. These results seem agree with analytical results presented by G.M. Dominguez Almaraz, *et al.* [17]; the hole under uniaxial loading may induce stress concentration in function of its proximity when the geometrical dimensions of hole remain constant.

5. Results and Discussion.

The experimental parameters and FEM simulation results are shown in Figure 3. The test frequency was 50 Hz, P=4 for Specimen 1, P=107 N for Specimen 2 were used in all tests for applying load. Fatigue life for specimen 1 with one hole was comprised between 2×10^4 and 4.9×10^4 cycles, whereas for the specimen 2 these values were 2.8×10^4 and 6.2×10^4 cycles. It is observed the experiment results seem agree with FEM simulation results presented; and the important factor affects fatigue life is the narrow section diameter D_0 of the specimens. The number of cycles to failure predicted numerically is higher than the experimental one. This difference is attributed mainly to an upper stage of crack growing, particularly, the interaction between fatigue crack growth and growth [18, 23], that can not be accounted for in the numerical model.

From the FEM simulation, it can be observed that the maximum damage occurs in the outer part of the specimen at the first stages of loading, however, it moves toward the center of the bar under uniaxial loading. This can be justified by the fact that at early stages of loading the hydrostatic stress is low and the damage evolution is affected by the plastic flow. Thus the damage grows in outer layers where the maximum equivalent plastic strain occurs. However, by increasing the number of fatigue failure cycles, the hydrostatic stress increases and its effect becomes dominant. Hence, the damage critical point moves toward the center of the bar where the maximum value of hydrostatic stress occurs. This phenomenon is also observed experimentally by Hancock, J.W. *et al* [21] where the failure of the bar initiates from the center of
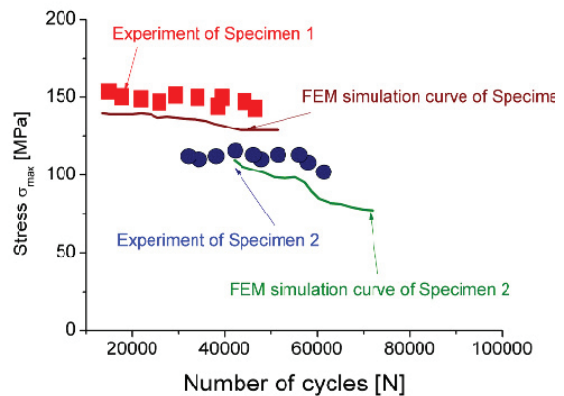

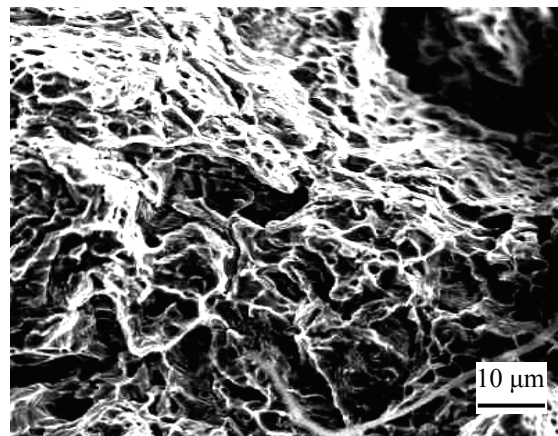Figure 3 The *S-N* graph of the aluminum alloy HS6061-T6

Figure 4 Fracture surfaces of the specimens 2

the bar. A comparison of the damage variable evolution at the centre of the specimen between the present study and 2D results reported by de Souza Neto *et al*. [22].

Fracture surfaces picture was taken in order to analyze the trend of stress concentration and fatigue life of some tested specimens, shown in Figure 4. Under rotating bending fatigue tests the high stress zones are located at the fracture surface perimeter and decrease to the fracture surface center: the size of grooves decreases from fracture surface perimeter to the center [18]. For this last fracture surface, the applied load at the narrow section of specimen surpasses the elastic limit of material. The "Multiracial fatigue limit criterion for defective materials" has been presented in recent works [19, 20] relating fatigue endurance and stress distribution. It was corroborated that the gradient of the hydrostatic part of the stress distribution at the tip of the defect seems to be a good parameter to represent the defect influence on the fatigue resistance in the range of the fatigue limit under multiracial loading.

Nevertheless, the analytical development based on one single defect, which is a very hypothetical case in real material with surface defects. Then the further investigation should be necessary for the understanding of fatigue-corrosion phenomena; particularly, the interaction between fatigue crack growth and growth [23]; holes geometrical dimensions and proximity; grain boundaries, size, shape, and orientation versus fatigue-corrosion [24]; multiracial loading and others factors [25].

6. Conclusion

Fatigue endurance under rotating bending fatigue tests of aluminum alloy HS6061-T6 decreases with the presence of one hole. FEM analyses were carried out to determine the effective stress intensity factor at the crack tip. Reasonably good agreements have been obtained from both the simulation and experiment results. It is found that t that the maximum damage occurs in the outer part of the specimen at the first stages of loading, however, it moves toward the center of the bar under uniaxial loading. It is observed the important factor affects fatigue life is the narrow section diameter D_0 of the specimens. Fatigue life for specimen 1 with one hole was comprised between 2×10^4 and 4.9×10^4 cycles, whereas for the specimen 2 these values were 2.8×10^4 and 6.2×10^4 cycles. The number of cycles to failure predicted numerically is higher than the experimental one. This difference is attributed mainly to an upper stage of crack growth, particularly, the interaction between fatigue crack growth and growth that can not be accounted for in the numerical model.

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