Contemporary Engineering Sciences, Vol. 2, 2009, no. 11, 507 - 516

Why does the Initial Fatigue Crack not Nucleate in the Region between Two Neighborly Located Holes in an Aluminum-Alloy Strip?

F. W. Wang and Y. H. Chen*

School of Aerospace, MOE, Xi'an Jiaotong University, 710049, P. R. China
* yhchen2@mail.xjtu.edu.cn

Abstract. This note reports an interesting phenomenon found in our experimental studies for the coalescence between two neighborly located holes in an Aluminum-Alloy strip under cyclic tensile loadings. Unlike expected, the initial fatigue crack is found not to nucleate in the center region between the two holes, where the stress concentration is much larger than other positions, rather, the initial crack does always nucleate at the outside rim of holes far apart from the center region. The coalescence between the two holes always occurs far after the initial fatigue crack nucleation.

Keywords: cyclic loading; crack propagation; holes coalescence; aluminum alloy strip

1. Introduction

The fatigue life of an aircraft component made of Aluminum alloys can be divided into two phases, the *fatigue crack initiation life* and the *fatigue crack propagation life*, which have been widely investigated by many researchers using both experimental measurements and numerical simulations. The first phase has been measured by using notched specimens to simulate the geometry discontinuity in aircraft components, where the stress concentration occurs, whereas the second phase has been analyzed by using the fracture mechanics approach that has been well addressed since Paris reported his famous work (see, e.g., [1-20] among many others). Whereas small holes are widely used in aircraft components due to rivets and cracks may be nucleated at the rims of holes during aircraft service, which might induce a subsequent damage, e.g., a fatigue crack grows through the rims of the two holes (i.e., coalescence of the two holes), and final failure or catastrophic event [7]. This crack growth is quite different from the general meaning of the *fatigue crack propagation life*. This note focuses special attention on this coalescence and reports an interesting phenomenon found in our experimental studies for the crack induced coalescence between two neighborly located holes in an Aluminum-Alloy strip under cyclic tensile loadings. It is found that, unlike brittle materials such as PMMA, the initial fatigue crack does not nucleate in the center region between the two holes, where the stress concentration is much larger than other positions outside the center region, and then a crack induced coalescence between the two holes always occurs far after the initial fatigue crack nucleation and growth at the outside rim of holes far apart from the center region occur. This phenomenon could not be explained by the classical stress concentration theory and the fatigue crack growth theory, from which the initial crack nucleation is expected firstly to nucleate at the points where the stress concentration is maximum as researchers have seen in notched specimens.

2. Experiments and observations

The specimen configuration used by us is shown in Figure 1, where $h=125mm$, $w=27mm$, and $t=3mm$ denote the highness, width, and thickness of the Ly12CZ Aluminum-Alloy strip, respectively; $d=1mm$, and $l=0.5mm$ denote the diameter of the holes and the distance of the two neighborly holes rims. The Young’s modulus and the Poisson’s ratio are 49GPa and 0.33, respectively, whereas the yielding stress of the Aluminum Alloy is 308.6MPa. The specimen is subjected to cyclic tensile loading by using MTS-858 test machine (see Figure 2). The total amplitude of loading is 16kN corresponding to the amplitude of the cyclic tensile loading is 197.5MPa (about 64% of the yielding stress). Thus, the stresses along the holes rims, especially near the points *B* and *C* (see Figure 1), will exceed the yielding strength of the material due to the large stress concentration induced from the two holes. It is expected that the initial crack nucleation would firstly occur at the central region between the nearby rims of the two holes, either at point *B* or at point *C* (see Figure 1), since the distance $l=0.5mm$ is much smaller either than the half width $w/2$ of the strip or than the diameter of the holes. Thus, the stress concentration at point *B* or point *C* located in the center region between the two holes rims are much larger than those at points *A* and *D* outside the center region.

Indeed, our experiments for brittle materials such as PLMA with the same specimen configuration show this expected result as shown in Figure 3, where the initial fatigue crack does occur at point *B* or point *C* and the crack grows slowly and induces the coalescence between the two holes. The final failure of the PLMA strip is found far after the coalescence of the two holes occurs.

However, for the Aluminum Alloy strip with two holes, experimental observations are quite different as shown in Figures 4(a,b,c,d), whereas the initial fatigue crack does not nucleate at point *B* or *C* as we expected beforehand, rather, the fatigue crack does firstly nucleate at point *A* (or *D*) located at the rim outside the center region between the two holes (see Figure 4(a)). Detailed observations reveal that there are at least five phases from the initial crack nucleation to the final failure of the strip: (i) Under several thousands cycles of the tensile loading with 1Hz, the initial crack firstly occurs at point *A* of the left hole, and then during further loading cycles it grows slowly to a length about half of the diameter of the holes or the width between the two neighborly holes rims; (ii) During further loading cycles it stops to grow, something like waiting for another crack nucleation occurs; (iii) Indeed, after subsequent loading cycles, the second fatigue crack actually nucleates at point *B* located along the left hole rim in the center region as shown in Figure 4(b) and then the second crack begins to grow, whereas the first crack still rests during the second crack grows slowly, something like waiting for the second crack growth reaching the point *C*, i.e., the coalescence between the two holes occurs (in other words, the coalescence is induced from the second crack rather than the first crack: (iv) after further several thousands cycles, the coalescence occurs and then the third crack at point *D* at the right hole rim nucleates and grows as shown in Figure 4(b,c); (v) Finally, both cracks: the first one and the third one, begin to grow during the subsequent loading cycles until the final failure occurs as shown in Figures 4(c,d). The phase (v) can be treated by using the concept of the *fatigue crack propagation life*, whereas as the first four phases occupy a great portion of the total fatigue life and cannot be neglected.

This detailed damage evolution process due to several fatigue cracks nucleation and growth, to the present authors' knowledge, is very difficult to be explained by the classical stress concentration theory and the fatigue crack growth theory, e.g., the Paris theory [15]. It is questioned as why the initial crack nucleation does not firstly occur at the central region, i.e., point *B* or point *C*, under the cyclic tensile loading? Or instead, why the holes coalescence occurs far after the initial fatigue crack nucleates at the outside rim, i.e., point *A* or *D*, far apart from the center region? It is also questioned as why the first crack rests, like waiting for other cracks nucleation?

One of the possible reasons might be the surface roughness [11], i.e., micro-defects along the rims of the two holes as shown in Figure 4(a,b,c,d).

However, we did many specimens for the same experiments and did obtain the similar results. That is, the initial fatigue crack nucleation does always occur firstly at the outside rim, i.e., the point *A* or *D*, rather than the point *B* or *C*, where much larger stress concentration could be found. In other words, the coalescence induced by the crack segment $\underline{BC}$ between the two holes does not occur before the initial fatigue crack forms at another position, i.e., the point *A* or *D*, far apart from the center region. Another possible reason might be the influence of the material plasticity since the center region become fully plastic deformation due to the stress concentration under such large tensile loadings. Thus, a dislocation saturation zone might be formed in the center region as pointed out by Schoeler and Christ [13] who found in their fatigue crack study for a single-phase Ni-base super alloy, *a pronounced cyclic saturation state indicating a dislocation arrangement, which quickly establishes and does not undergo major changes during further cyclic loading*. That is, a large amount of dislocations are saturated and restricted in this zone, which could not move freely under the present cyclic tensile loadings, whereas the plastic region near the point *A* (or *D*) is very small, in which dislocations could move freely without such a restriction. Detailed numerical simulations and discussions are absolutely needed, which are beyond the scope of this short note and will be given in sequel.

Acknowledgement. This work was supported by the NSFC through Grant No. 10932007.

References

[1] A. Buch, Prediction of fatigue life under aircraft loading with and without use of material memory rules, International Journal of Fatigue, 11(1989), 97–106.

[2] B. Lü, J. Zhang, C. Ling et al, Experimental study on the fatigue performance of 15MnVN steel, Journal Mechanics Strength, 14(1992), 70–75.

[3] B. Lü, X. Zheng and D. Li, Fatigue crack initiation and propagation in butt welds of an ultrahigh strength steel, Welding Research Supplement, 2(1993), 79–86.

[4] B. Lü, X. Zheng, Predicting fatigue crack initiation life of an aluminum alloy at low temperature, Fatigue Fract. Engng Mater. Struct, 15(1992), 1213–1221.

[5] C. J. Tay, T. E. Tay, H. M. Shang, et al, Crack initiation studies using a speckle technique, International Journal of Fatigue, 16(1994), 423–428.

[6] D. Dupart, A. Davy, R.Boetsch, et al, Fatigue damage calculation in stress concentration fields under uniaxial stress, International Journal of Fatigue, 18(1996), 245–253.
[7] D. Dupart, D. Campassens, M. Balzano, et al, Fatigue life prediction of interference fit fastener and cold worked holes, International Journal of Fatigue, 18(1996), 515–521.
[8] D. Kujawski, F. Ellyin, A unified approach to mean stress effect on fatigue threshold conditions, International Journal of Fatigue, 17(1995), 101–106.
[9] D. Socie , L.A. Waill, and D.F. Dittmer, Biaxial fatigue of Inconel 718 including mean stress effects [M] // K.J. Miller, M.W. Brown, Multiaxial Fatigue, ASTM STP 853 , Philadelphia, PA,USA, ASTM, 1985.
[10] D.Socie, Multiaxial fatigue damage models, ASME Journal Engineering Materials and Technology, 109(1987), 293–298.
[11] G. Thauvin, Influence of surface roughness on fatigue and corrosion fatigue behavior of 0.12C–12Cr–2.5Ni–1.8Mo–0.3V steel, [C] // Proceedings of the 7th International Fatigue Congress, FATIGUE'99.Beijing, China: Higher Education Press, 1999.
[12] K. Golos, F. A. Ellyin, total strain-energy density theory for cumulative fatigue damage, ASME J. Press Vess. Tech., 110(1988), 36–41.
[13] K. Schoeler, H.-J. Christ, Influence of prestraining on cyclic deformation behavior and microstructure of a single-phase Ni-base superalloy, International Journal of Fatigue, 23(2001), 767–775.
[14] P. J. Hurley, M. T. Whittaker, S. J. Williams, et al, Prediction of fatigue initiation lives in notched Ti 6246 specimens, International Journal of Fatigue, 30(2008), 623–634.
[15] W. Schütz, The prediction of fatigue life in the crack initiation and propagation stages — a state of the art survey, Engineering Fracture Mechanics, 11(1979), 405–421.
[16] X. Zheng, A further study on fatigue crack initiation life —mechanical model for fatigue crack initiation, International Journal of Fatigue, 8(1986), 17–21.
[17] X. Zheng, C. Lin, On the expression of fatigue crack initiation life considering the factor of overloading effect, Engineering Fracture Mechanics, 31(1988), 959–966.
[18] X.-L. Zheng, Modelling fatigue crack initiation life, International Journal of Fatigue, 15(1993), 461–466.
[19] Y. Madi, N. Recho and P. Matheron, Low-cycle fatigue of welded joints: coupled initiation propagation model, Nuclear Engineering Design, 228(2004), 179–194.
[20] Y. Madi, P. Matheron, N. Recho, et al, Low cycle fatigue of welded joints: new experimental approach, Nuclear Engineering Design, 228(2004), 161–177.

Figures Captions

Figure 1. The strip configuration with two neighborly located holes.

Figure 2. Experimental specimen when using MTS-858 test machine.

Figure 3. Experimental observation for the PLMA strip with two holes.

Figures 4(a,b,c,d). The detailed evolution process of the macro-crack nucleation and growth under the cyclic tensile loading. (a) The initial fatigue crack nucleation at the left hole rim (the first crack); (b) The first crack rests waiting for the second crack nucleation and growth in the center region; (c) after the coalescence between the two holes occurs, the third crack nucleates at the right hole rim; (d) Both the first and the third cracks begin to grow.

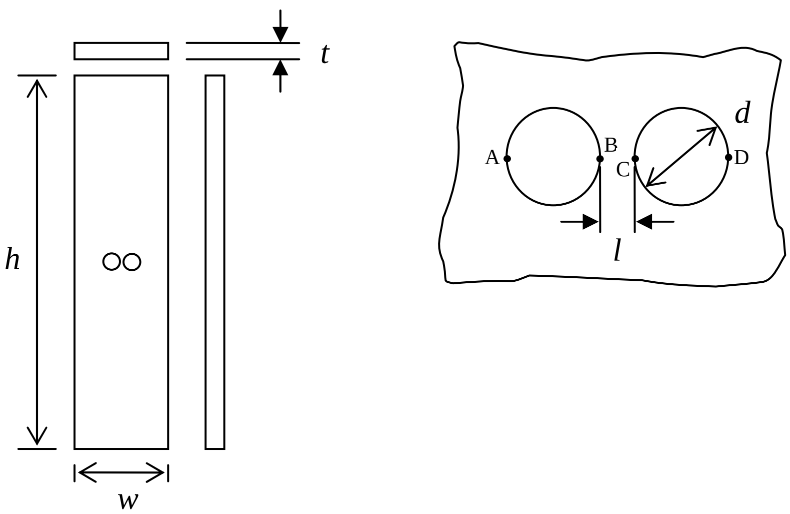


Figure 1.

Figure 2.

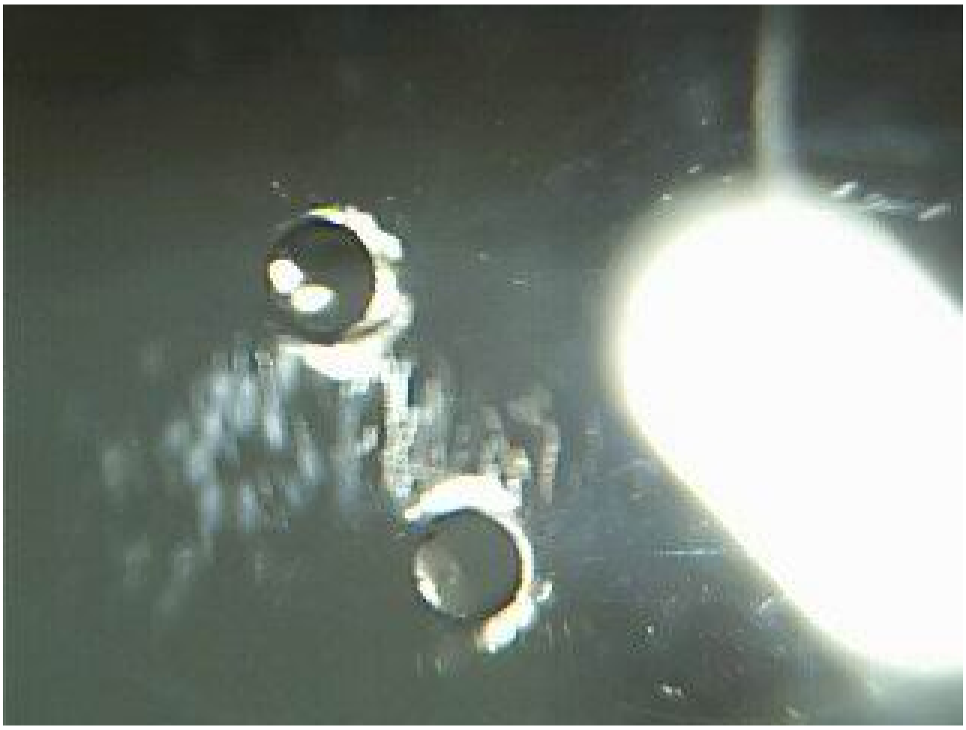
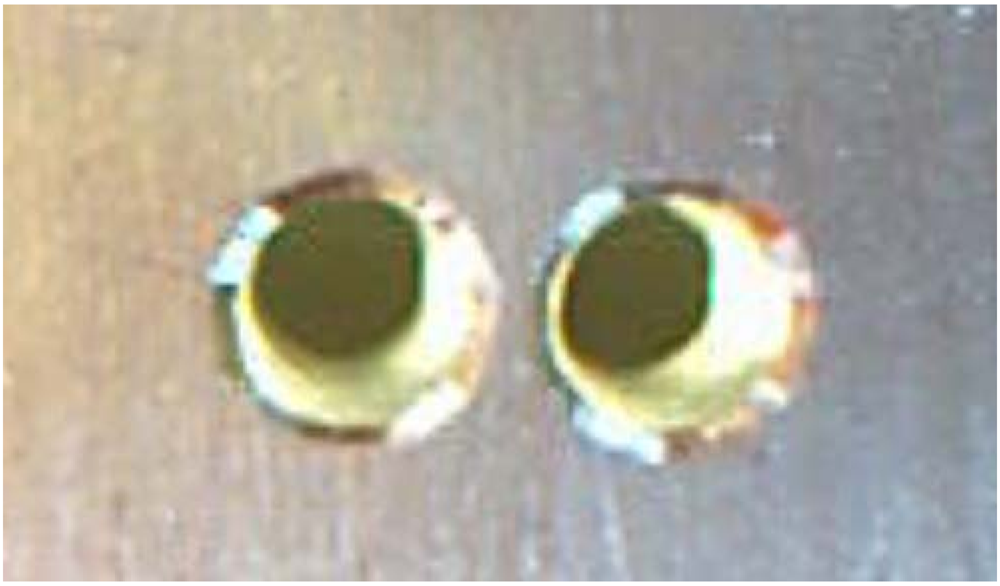
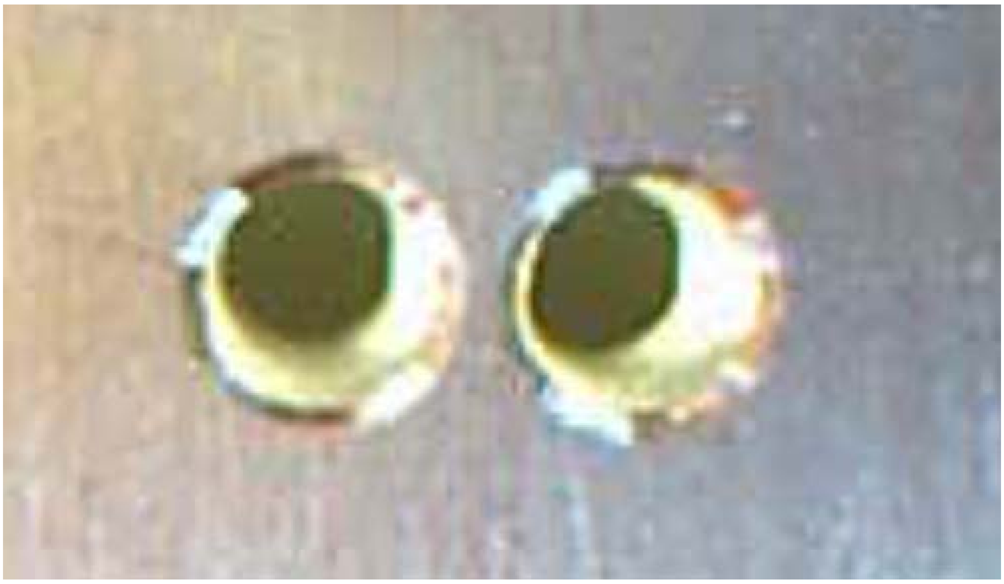


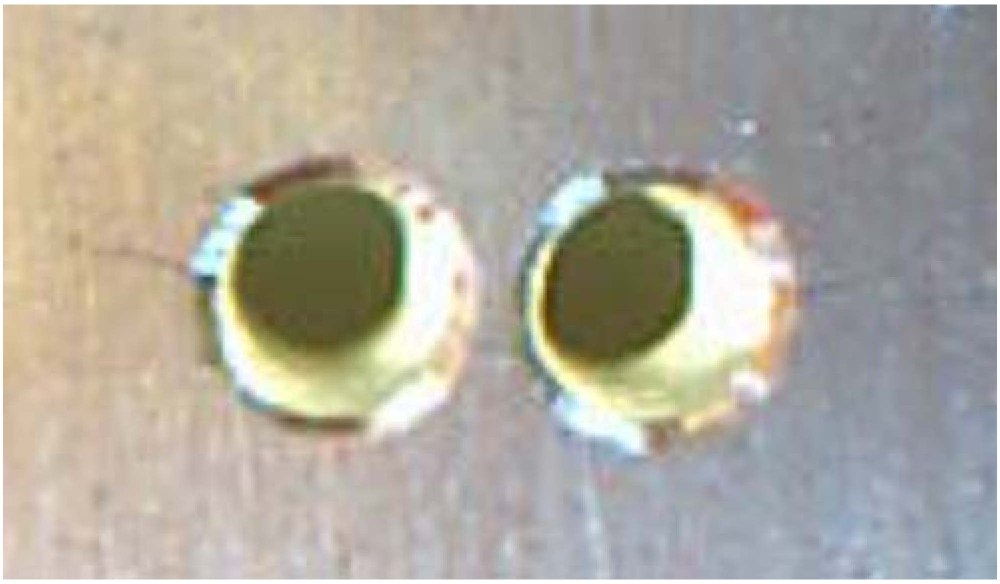
Figure 3.



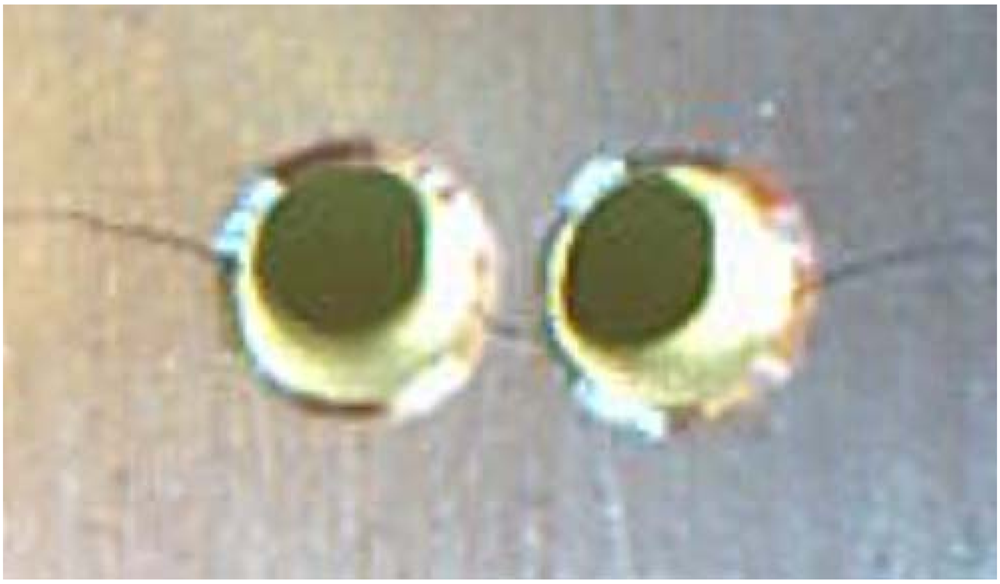
(a)



(b)



(c)



(d)

Figures 4(a,b,c,d).

Received: August, 2009