Study of Interaction and Coalescence of Multiple Small Surface Cracks in a High Strength Aluminium Alloy

Q. Liu, C.-H. Wang, S.A. Barter and P.K. Sharp

Air Vehicles Division
Platform Sciences Laboratory, DSTO
506 Lorimer Street, Fishermens Bend
Melbourne, VIC 31207, Australia

ABSTRACT

It has been recognised that the interaction, coalescence and crack shape development of multiple small surface cracks (or defects) have a significant effect on the early fatigue life of a component. Understanding the significance of this interaction during service loading history in existing structures has major implications in accurately assessing or predicting fatigue life of structures. However, during crack growth these multiple surface cracks can interact and coalesce in different ways, depending on; the material, in which they are located, the applied stress, the crack length and their relative positions. The aim of this study was to understand the process of crack initiation, propagation, interaction and coalescence. The cracks were started from 50 to 150 micron long (~15 micron deep) focus ion beam (FIB) cut slots. Different combinations of slots were investigated, including varying slot size, number and configuration (relative locations, coplanar and non-coplanar). The material used was a high strength aluminium alloy (AL7050-T7451), which is widely used in aircraft. The laboratory coupon specimens were tested under constant and variable loads. The results show that the interaction and coalescence of the small cracks produced strongly depended on their relative location and crack size for this material. For a non-coplanar configuration, the crack coalescence occurs only when the geometrical condition (i.e. relative location) satisfied certain conditions. A numerical model- "equivalent" single crack model was developed to predict the damage grown from the FIB slots, based on a short crack model. The results of the numerical prediction agree well with the experimental results.

1. INTRODUCTION

The availability of multiple closely spaced sites for crack initiation makes multiple surface cracking a common problem in the failure of many kinds of materials and structural components subjected to fatigue and corrosion, particularly in commercial and military aircraft. In the early stage of a fatigue failure, these natural cracks are often small or short. The multiple cracks can interact and coalesce in different ways, depending on their spatial resolution, the applied stress, and the component geometry. The phenomenon of multiple cracks is significant when it reduces the overall structural integrity more than would be predicted by the analysis of an individual crack. As the stress is increased and the cracks grow closer together, the interaction and coalescence between these small cracks become an important and common phenomenon. It is now recognised that the interaction, coalescence and crack shape development of multiple small cracks growing from surface defects can have a significant effect on the fatigue life of a component. Therefore, understanding the significance of this interaction and coalescence for multiple small surface cracks during service loading in existing structures has major implications on the accuracy of predicting their fatigue lives. Understanding of the effect of the coalescence of multiple small cracks may enable the avoidance of expensive, complicated repair procedures for ageing or damaged structures, leading to saving in maintenance costs.

Under the current damage tolerance philosophy, the inspection program for an aircraft structure is established on the basis that a single leading crack, propagating between detectable and critical size at limit load, will be detected before failure [1]. However, many experimental results have proven that the interaction of several closely spaced cracks can often take place [2]. *Crack coalescence* can play a significant role because crack growth can accelerate the linkage of several cracks producing a **'jump'** in the crack growth rate beyond that predicted for a single crack. As a result, crack propagation lives may be shorter than would be expected for an isolated crack.

The research work on 7xxx series Aluminium alloys in the Australian Defence Science and Technology Organisation (DSTO) [3] suggests that the initiation of small cracks from flaws or defects and their propagation to a long crack size often consumes a large portion (50~70%) of the total fatigue life of a component in an airframe structure. This phenomenon may not be predicted from the applied stress levels and type of loading history [4]. Newmans' et al work also indicated that crack propagation from a microstructural flaw represented 50 ~ 90% of the total fatigue life of a specimen [5]. As a result, the multiple small surface cracks that initiate independently at the beginning of a components life may, as a result of coalescence, have a substantial effect on airframe component life. This article mainly focuses on experimental observation of the interaction and coalescence of multiple small surface cracks in one of 7xxx series aluminium alloys.

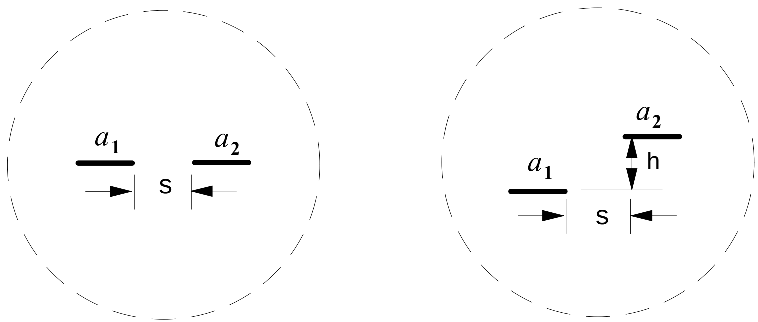
2. MATERIAL AND EXPERIMENTAL PROCEDURE

2.1. Material and Specimen Configurations

Material used in this study is AL7050-T7451. The chemical composition is 2.13%Cu, 2.26%Mg, 6.18%Zn, 0.13%Zr, less than 0.1%Fe+Si and remainder Al. A low Kt dogbone style specimen was used.

2.2 Micro-Crack Configurations and Measurement of Crack Length

In this testing, we use artificial cracks to study the behaviour of single and multiple cracks in a typical aluminium alloy. The artificial cracks were made by the focus ion beam (FIB) milling technique. Fig.1 illustrates the configurations of different artificial cracks. In order to clearly observe crack initiation, coalescence and the particular areas on the surface, the surfaces were metallographically polished.



(a) (b)

Fig.1 Typical artificial crack configurations. (a) coplanar and (b) offset non-coplanar.

The crack extension during fatigue loading was measured on the surface of a specimen by a powerful digital optical microscope triggered by the test machine at either pre-determined programs (SP) or pre-determined number of cycles (CA).

2.3 Load Sequence

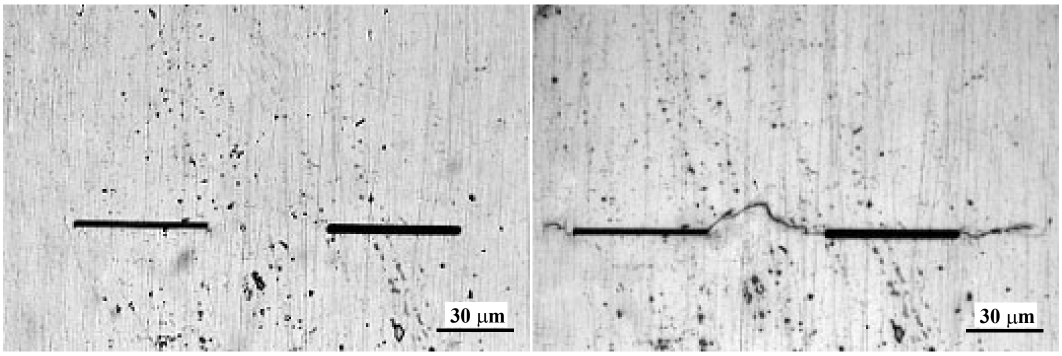
The fatigue tests were carried out in a MTS 100kN, digitally controlled testing machine, under load control mode. Two kinds of applied load sequences were used. One was a wing root-bending spectrum, which is representative of an aircraft load sequence, where the applied peak stress was 390 MPa. The other loading used constant amplitude with the same stress, R ratio -1 and frequency 2 Hz.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Observations of Multiple Surface Crack Interaction and Coalescence

3.1.1 Coplanar Cracks

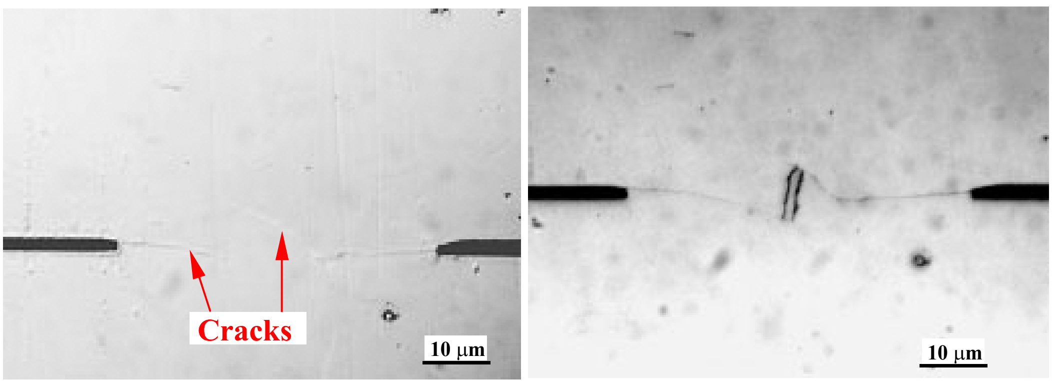
Fig.2 gives the experimental results for the specimen containing two-coplanar cracks under the constant amplitude loading. Fig.2 (a) is the initial state of the cracks. No obvious interaction of the early fatigue crack growth was observed. With the extension of the fatigue cracking, the interaction became more and more strong. At about 1000 cycles, both cracks began to join together, and form a single crack, as shown in Fig.2 (b). It is noticeable that the crack coalescence is not in the original growth direction. Before the coalescence occurs, the cracks actually deviate and then join together via a mixed mode or shear mode because of the change in the local stress field due to the interaction of the cracks.



(a) (b)

Fig.2 Crack propagation and coalescence behaviour of two small coplanar surface cracks under constant amplitude loading: applied peak stress of 390MPa and R ratio -1. The initial slot length is about 50 μm and the horizontal separation between neighbouring (or inner) tips is 50 μm. (a) The initial state of two coplanar artificial cracks (slots). (b) After 1000 cycles.

Similar behaviour was also observed in the specimen containing two-coplanar cracks under spectrum loading, as shown in Fig.3. It is clearly seen in Fig.3 (a) that before crack coalescence, the cracks attempt to avoid each other. The reason for this could be that the stress fields at both crack tips interact and force the crack growth in different directions. After the cracks pass each other, both cracks finally join together via an angle to the loading direction (Fig.3 (b)). This implies that the shear fracture mode may be involved. Actually, relatively large plastic deformation around the coalescing tips occurs during the final stage of the crack coalescence.



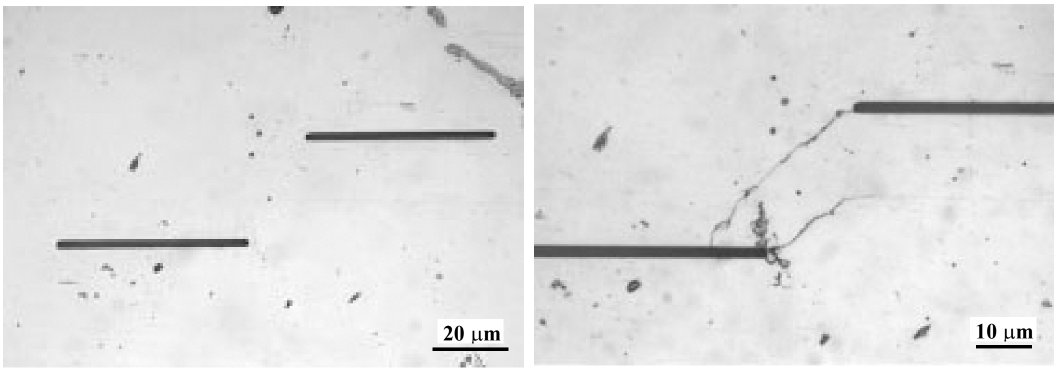
(a) (b)

Fig.3 Crack propagation and coalescence behaviour of two coplanar surface cracks under spectrum loading: applied peak stress of 390MPa. The initial artificial crack (slot) length is about 50 μm and the horizontal separation between neighbouring (or inner) tips is 50 μm. (a) After 17 blocks and (b) After 19 blocks.

3.1.2 Non-Coplanar Cracks

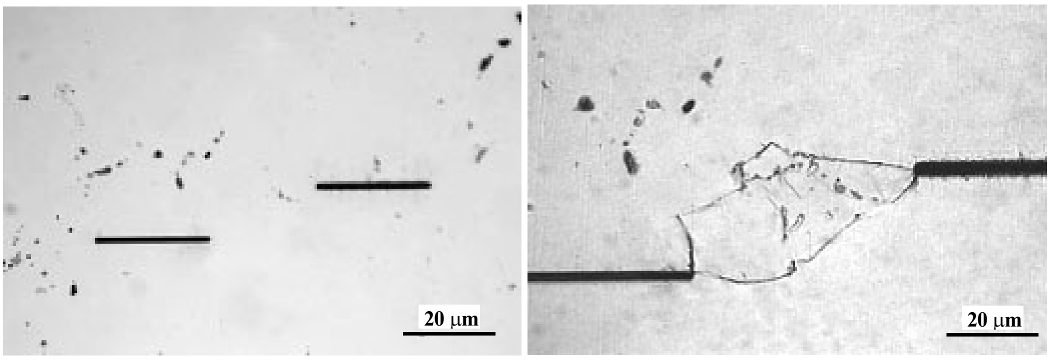
In the coplanar crack configuration, the cracks always join together after a certain number of cycles in the constant amplitude loading or blocks in the spectrum loading. However, in the non-coplanar (or offset) crack configuration, the crack coalescence mainly depends on whether the geometrical configuration satisfies certain conditions.

The experimental results show that the crack coalescence strongly depends on the relative positions between the cracks and their lengths for this material. Fig.4 gives an example of a non-coplanar crack configuration, where two cracks are located in different planes. The vertical separation between them, in this case is 15.2 μm and the horizontal separation is 26.8 μm. The specimen was subjected to constant amplitude loading with a peak stress of 390MPa and R ratio of –1. After 3800 cycles, both cracks joined together. Similarly, under the spectrum loading, after about 27 blocks, the cracks also merged, as shown in Fig.5. The so-called "island" was left after crack coalescence (Fig.5 (b)).



(a) (b)

Fig.4 Crack propagation and coalescence behaviour of two non-coplanar (offset) cracks under constant amplitude. The initial artificial crack length is about 50 μm and the horizontal separation between neighbouring tips is 26.8 μm. The vertical separation is 15.2 μm. (a) The initial state of two non-coplanar artificial cracks. (b) After 3800 cycles.



(a) (b)

Fig.5 Crack propagation behaviour of two non-coplanar (offset) cracks under spectrum loading. The initial artificial crack length is about 50 μm and the horizontal separation between neighbouring tips is about 49.2 μm. The vertical separation is about 24μm. (a) The initial state of two coplanar artificial cracks. (b) After 27 blocks.

3.2 Fatigue Crack Growth Behaviour

The fatigue crack behaviour of multiple small cracks on the specimen surface has been observed. The crack growth at each tip before and after the coalescence was measured by the imaging process. Fig.6 gives a crack length as a function of number of cycles for the constant amplitude loading for different crack configurations. It is understandable that during the crack coalescence process, the crack jumps because the multiple cracks form a single crack. The amount of the crack jump is dependent on the horizontal and vertical separations between the cracks. It is also observed that the behaviour of the crack growth in an isolated crack is slightly different from that in the two-coplanar crack case if the same total crack length is considered. In other words, the crack growth after the crack coalescence is slightly faster, compared to that in a single crack. However, for the non-coplanar crack configuration, the fatigue life is relatively complicated because the crack growth direction continuously changes (Fig.5 (b)), where a larger plastic deformation is produced due to the shear mode more energy is consumed in the cracking process. Under spectrum loading, after crack coalescence, the behaviour of the isolated crack is very similar in the non-coplanar configurations, as shown in Fig.7. This provides a basis for the prediction of the action of multiple coalescing cracks as a single crack for certain conditions.

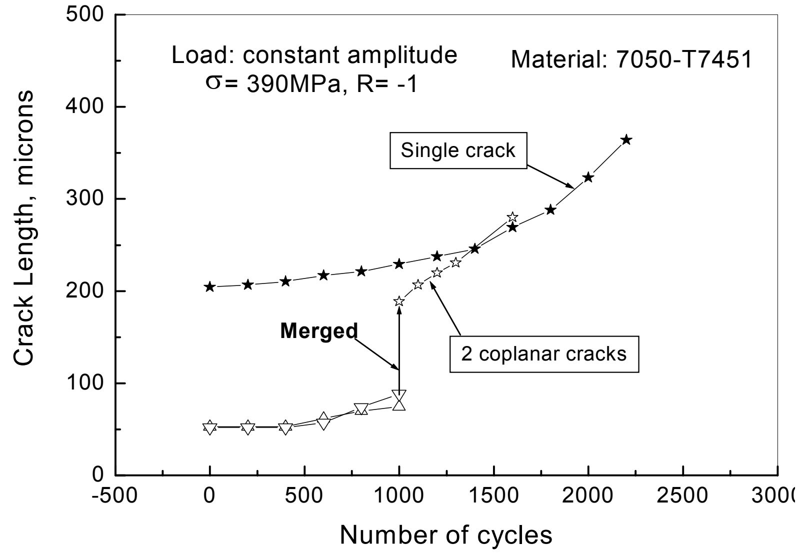


Fig.6 Experimental results of single and two coplanar cracked specimens of 7050 Al alloy under constant amplitude loading

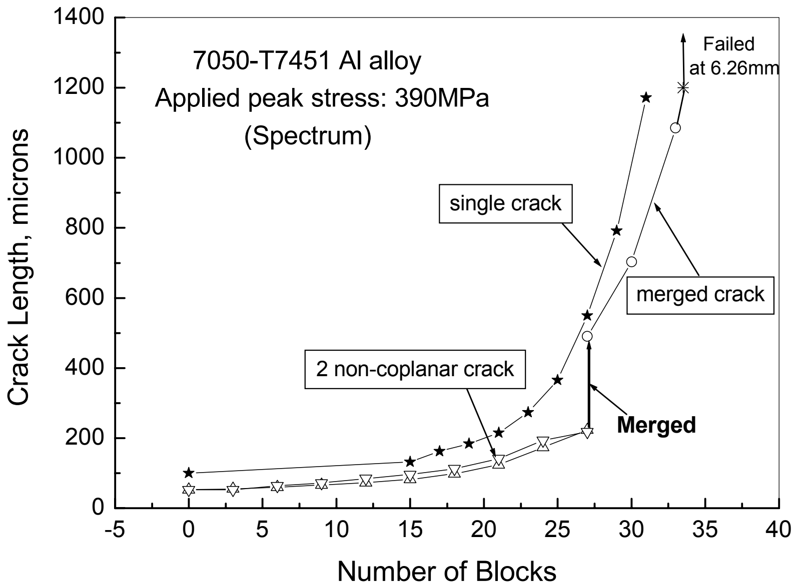


Fig.7 Experimental results of single and two non-coplanar cracked specimens of 7050 Al alloy under spectrum loading

4. CONCLUSIONS

The behaviour of multiple small surface cracks has been studied under both constant amplitude and spectrum loadings. The following conclusions were drawn.

(1) The interaction between the adjacent cracks depends on geometrical parameters, crack length, a material and loading condition. For a short crack, the interaction may be small when loading is

low. However, the interaction will be significantly high when the loading is high enough because the interaction of the plastic zones ahead of the inner crack tips becomes very strong.
(2) For a coplanar crack configuration, crack coalescence is not in the original growth direction. Before the coalescence occurs, the cracks actually deviate and then join together via the mixed mode or shear mode because of the change of the local stress field due to the interaction of the cracks.
(3) For a non-coplanar crack configuration, at a given material and loading condition, crack coalescence is strongly dependent on the geometrical parameters, particularly the vertical separation (h) and the crack length. Additionally, it is observed that a small “island” is left after crack coalescence in most cases examined here.
(4) The growth behaviour of the coalesced crack is very similar to that of a single crack. Therefore, the “so-called” equivalent single crack approach may used to predict the fatigue life of multiple cracks under certain conditions.

5. REFERENCES

1.Y.-Z.Wang, J.D.Atkinson, R.Akid and R.N.Parkins, Fatigue Fract. Eneng Mater. Struct., **19** (1996), p.51.
2.Z.X.Wu and H.Xu, Acta Metallurgica Sinica (English Letters), **9** (1996), p.65.
3.S.A.Barter, B.Bishop and G.Clark, Aircraft materials Report 125, AR-006-618, Department of Defence, Defence Science and Technology Organisation, Aeronautical Research Laboratory, Melbourne, Vic, Australia (1991).
4.S.Suresh and R.O.Richie, Int. Metals Rev., **29** (1984), p.445.
5. J.C., Jr. Newman, E.P.Phillips, M.H.Swain and R.A., Jr.Everett, ASTM STP 1122, Eds., M.R. Mitchell and R.W. Landgraf, American Society for Testing and Materials, Philadelphia, p.5.