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Investigating the Fatigue Crack Initiation Location in Interference Fitted and/or bolt Clamped Al 2024-T3 double shear lap joints

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***Abstract*—**In this paper the fatigue crack initiation location of double shear lap joints, treated by interference fit and bolt clamping, have been investigated both experimentally and numerically. To do so, using the fracture section of available fatigue tested specimens of interference fitted and torque tightened Aluminum 2024-T3 plates, the crack initiation location was determined. The stress distribution attained from the finite element analysis was used to help explain the results observed in the experimental tests. The results showed that the fatigue crack initiation location changes from top and mid plane at the hole edge to somewhere far from the hole edge (stress concentration region) in different combination of clamping force, interference fit size and applied cyclic load ranges. It is worth mentioning that the fatigue crack initiation location affects the fatigue life of the specimens too.

***Keywords*—**Fatigue crack initiation, Interference fit, Bolt clamping, Double shear lap joint

I. Introduction

INVESTIGATIING the fatigue behaviour of mechanical fastened joints is essential in engineering design in metallic and specifically in aerospace structures. In such structures, implementing riveted or bolted joints needs the components to be drilled to create fastener holes, which cause geometrical discontinuities and entail local stress concentration during loading. In order to countervail the disadvantage of the holes, different fatigue life improvement techniques have been proposed such as pin interference fitting [1, 2] and bolt clamping [3]. When bolt clamping, in addition to compressive pre-stress, a resistant force is created against fatigue crack growth by means of frictional shear stress when the contacted surfaces are pressed in the joint [3, 4]. Interference fitting a hole in a cyclic loaded specimen reduces the local cyclic stress amplitude around the hole which increases the fatigue life, but also increases the mean stress which causes the fatigue life to be reduced [3, 4].Researchers have shown that the efficiency of the mentioned techniques is related to geometrical specifications (such as the size of interference fit, the shape of the joint), the type of subsequent loading, lubrication, quality of contacted surfaces, tightening torque in bolt clamped specimens and many other parameters [5-7]. Crack initiation and growth location in the specimens is another important parameter that affects the fatigue life of the specimen. In this paper the location of fatigue crack initiation and growth in different geometric and loading conditions is investigated both experimental and numerical.

To do so, using fracture section of the available double shear lap experimental fatigue tested specimens of Al 2024-T3 alloy the fatigue crack initiation location has been investigated. Results show that mostly the crack nucleates near the entrance plane in interference fitted specimens and from the mid plane in the bolt clamped specimens. However, the fatigue crack initiation location is different in combined interference fitted-bolt clamped specimens where the crack initiation location varies from the entrance plane to the mid plane in different load ranges. Also in a number of specimens, the cracks nucleate far from the hole edge which is due to occurrence of fretting wear and fatigue. The numerical results show that the maximum longitudinal stress occurs at the hole edge in a depth confirming the experimental fatigue crack initiation location.

II. Experiments

Fatigue test results were available for similar configurations and loading conditions for different specimen types of clearance fitted (CF), interference fitted (IF, pin interference fitted with the configuration of Figure1.a), bolt clamped (BC) specimens which were torque tightened according to the configuration of Figure 1.b and finally interference fitted-bolt clamped (IF-BC) specimens which were interference fitted and then torque tightened. Consequently, fracture sections of the different specimen types were visual examined to determine the crack initiation location of different specimen types under various cyclic loading ranges. The detailed preparation processes of specimen can be found in Refs. [8-10].

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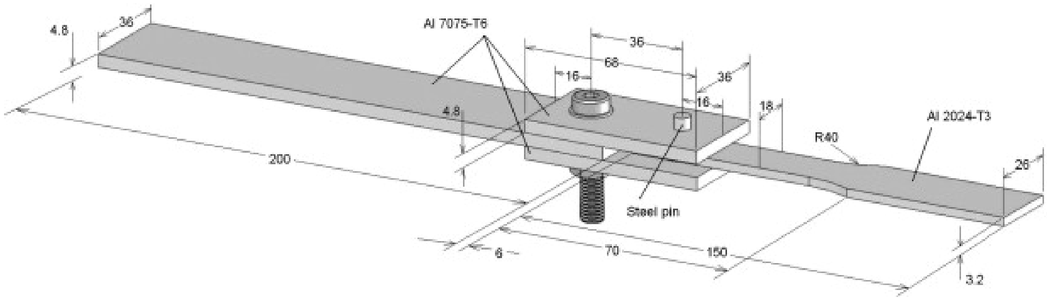
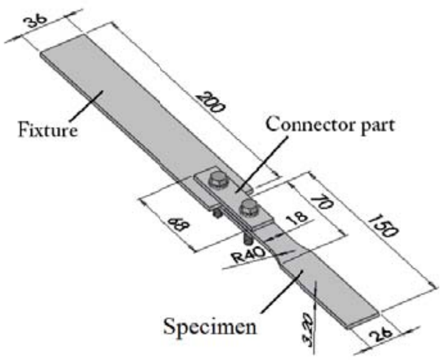
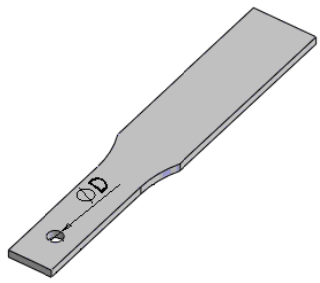


a. Configuration and dimensions of the CF and IF specimens [8]



b. Configuration and dimensions of the BC and IF-BC specimens.



c. The specimen (D differs for different levels of interference fit)

Fig. 1 Dimensions of the experimental test specimens (mm) [9]

As shown in Fig. 1 the joint consists of five parts, the specimen, two connectors, a fixture and the pin for CF and IF specimens or the bolt and nut for BC and IF-BC specimens. The fastener holes of the fixtures and connectors were prepared to achieve the proper diameter for CF and two pre-defined 1.5% and 4.7% levels of interference fit which were D=5.90, 5.81 and 5.63 mm respectively. It is worth mentioning that the outer diameter of the pin (bolt shank) was 5.90 mm.

For the IF-BC specimens, special M6 bolts with modified thread diameter were machined. Then the prepared bolts were press-fitted into the hole of the specimens using a pre-designed hollow steel cylinder support located under the plate. The same support was used for IF specimens. Then, a number of specimens were torque tightened with 2 N.m and the rest with 4 N.m (the same torques of BC specimens). After preparating the specimens, fatigue tests were carried out at different load levels (cyclic load range from 10 kN to 18 kN) by applying sinusoidal cyclic loads with zero load ratio ($R=P_{min}/P_{max}=0$) at a frequency of 12 Hz. The experimental fatigue tests results consisted of recorded lifetimes until specimen failure and are given in a semi-log S-N diagram in Figure 2.

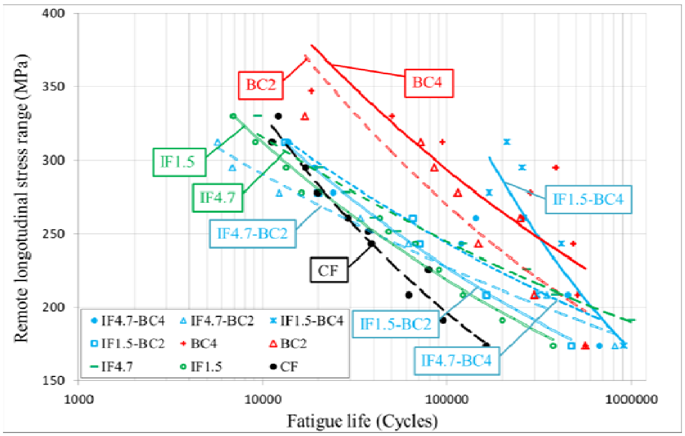
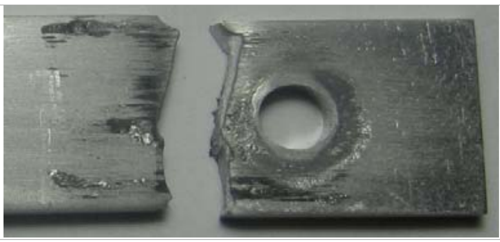


Fig. 2 S-N curve of experimental fatigue tests [9]

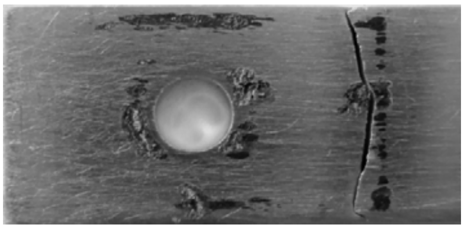
III. Examination of the Fractured Surfaces

Preceding performed studies [8] have shown that the fatigue crack initiation location is affected by interference fitting the hole. The fatigue crack initiates from the pin entrance plane at lower cyclic load ranges (10-12 kN) while at higher cyclic load range (16-18 kN), the fatigue crack initiation location tends to the middle plane of the plate (specimen) in the hole edge. Besides, the contacted surfaces between the connector parts and the plate in bolt clamped specimens (entrance and exit planes) behave stronger than the middle plane due to the presence of the frictional shear force and thus, the fatigue cracks initiation starts from the middle plane [3, 4].

In order to investigate the fatigue crack initiation location in the different specimen types (levels of interference fit, tightening torques and combined IF-BC) at different load levels, the fractured surfaces were examined visually and compared with each other. The results show that in BC specimens, the cracks nucleate and propagate from the mid plane and in IF specimens, the cracks are initiated from the entrance plane at low load levels and from the mid plane at the high load levels. In IF-BC specimens the cracks nucleate and propagate mostly somewhere between the middle plane and the entrance plane at the hole edge regardless of interference fit level and tightening torque. This means that the clamping affects (strengthens) the hole entrance region and counterbalances the unfavorable effect of interference fit on this region. However, as shown in Figure 3, at low ranges of the applied cyclic loads (i.e. 10 kN) both the BC and IF-BC specimen's fatigue failure occurs somewhere far from the hole edge. When the load range increases (i.e. 12 and 14 kN), the fatigue crack is initiated from the hole edge near the pin entrance plane and at the higher load ranges (i.e. more than 14 kN), the crack nucleates from the middle plane of the hole edge in IF and IF-BC specimens.

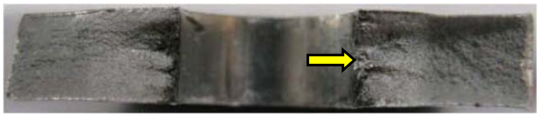


a. Fatigue crack initiation and fracture far from the hole edge (IF1.5-BC4, P=10kN)

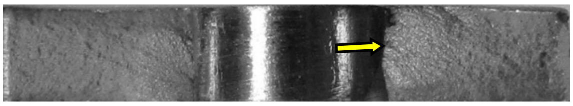


b. Fatigue crack initiation and fracture far from the hole edge (BC2, P=10kN)

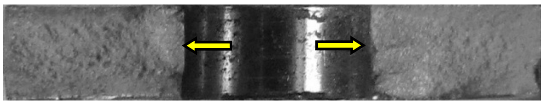
c. Fatigue crack initiation from the entrance plane at the hole edge, IF1.5, P=10kN.



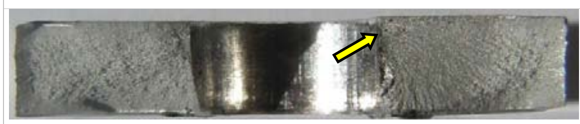
d. Fatigue crack initiation from the mid plane at the hole edge, IF1.5, P=13kN.



e. Fatigue crack initiation from the mid plane at the hole edge BC2, P=15kN.



f. Fatigue crack initiation from the mid plane at the hole edge BC2, P=18kN.



g. Fatigue crack initiation from near the entrance plane at the hole edge IF1.5-BC4, P=12kN.

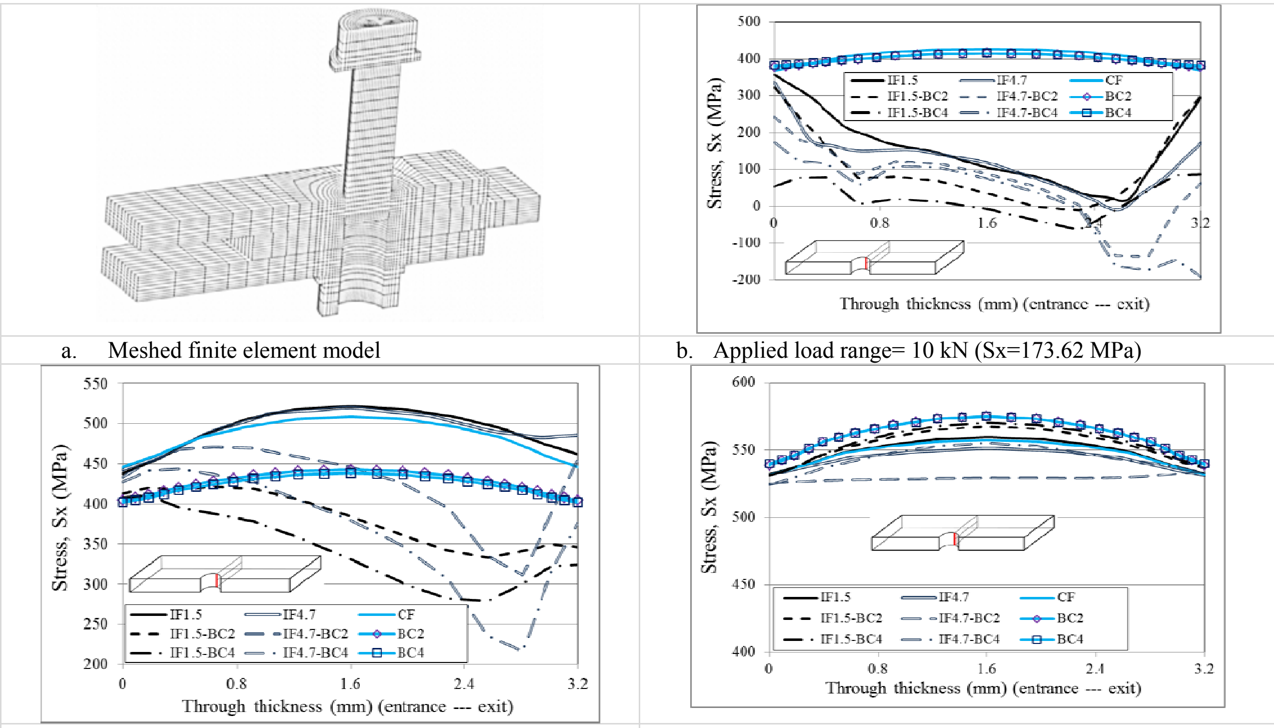
h. Fatigue crack initiation from near the mid plane at the hole edge IF4.7-BC4, P=18kN.

Fig. 3 Fatigue crack initiation location in different types of specimens [10]

IV. Finite Element Simulation

To explain the trends observed in the experimental tests, the stress distribution around the hole of the specimen was investigated. For this purpose, 3D models were generated using ANSYS finite element package. The FE analyses of the tested specimens were reported in detail in [8, 10, 11] and only a brief discussion of IF-BC specimens (as the most complex model) is included here. The developed FE models were built according to the dimensions of the specimens (see Figs. 1 and 4.a).

The simulation process consists of simulating force fitting the tapered bolt (introducing the interference fit) and applying the clamping force. Finally, by implementing longitudinal tensile cyclic loads (at different amplitudes) for at least two cycles, the stress resultant distribution was obtained. In fact, the cyclic loading of the specimens was simulated to determine the stress and strain at different defined paths (around the hole) during the experimental cyclic loading of the specimens and to compare the numerical results of the different specimen types.



a. Meshed finite element model

b. Applied load range= 10 kN (Sx=173.62 MPa)

c. Applied load range= 14 kN (Sx=243.056 MPa)

d. Applied load range= 18kN (Sx=312.5 MPa)

Fig. 4 Stress distribution results of finite element simulation [10]

To represent the aluminum alloy 2024-T3 stress-strain behavior, an elastic-plastic multi-linear kinematic hardening material model was used. The elastic modulus and Poisson's ratio were measured to be E=71.5 GPa and ν=0.33 respectively [8]. For the steel bolt however, a simple elastic material model was defined with E= 207 GPa and ν=0.3, because loading of the steel bolt and washer was observed to remain within the materials elastic range [10]. The friction coefficients of 0.5 between the plates and 0.15 between the bolt shank and the hole surface were defined in accordance with experimental test results [10].

As shown in Fig. 4, results of the finite element simulations were used to compare the calculated longitudinal stress (Sx) of different types of specimens at the smallest cross section. The results show that the maximum longitudinal stress in BC specimens occurs in the mid plane while in the IF specimens, the maximum stress occurs in the top plane where the pin enters the hole. The stress distribution results of IF-BC specimens are different from IF and BC specimens. It is shown that in low applied load amplitudes (in IF-BC specimens), the stress on the top plane has its maximum amount while in medium load amplitudes (14 kN) the critical region tends to mid plane and the maximum longitudinal stress occurs at a depth about 0.8 mm from the top plane. When the applied load amplitude increases, the effect of interference fitting decreases and thus the fatigue crack initiation location inclines to mid plane.

V. Discussion

The experimental fatigue tests results showed that the fatigue cracks are initiated from different depths at the hole edge for IF, BC and IF-BC double shear lap joint specimens. It was also shown that in low amplitude loaded specimens the cracks are initiated of somewhere far from the hole edge. The results of finite element simulation showed that the location of maximum longitudinal stress is same with the crack nucleation location in experimental samples where the maximum stress occurs in the pin entrance plane in the IF specimens and in the mid plane in BC specimens. Also in the IF-BC specimens, the maximum stress occurrence location tends from the entrance plane to the mid plane when the applied load amplitude increases which is confirmed with the experimental test results. The only difference is in the specimens which are failed far from the hole edge. In these specimens, the crack are initiated because of occurrence of fretting fatigue which can't be predicted using longitudinal stress distribution and other criteria are required which are not the subject of this paper.

The fatigue crack initiation location can affect the fatigue life of the specimen and thus predicting it can be used in the design process of such specimens.

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