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The effect of interference-fit on fretting fatigue crack initiation and ΔK of a single pinned plate in 7075 Al-alloy

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ABSTRACT

The effect of interference-fit on fretting fatigue crack initiation and ΔK was studied numerically for available experimental results in a single pinned plate in Al-alloy 7075-T6. The role of interference ratio was investigated alongside friction coefficient through finite element. Cyclic stress distributions in the plate ligament and fretting stresses on the contact interface were evaluated using 3-D elastic–plastic finite element models. Additionally a 3-D elastic finite element model was utilized to discuss ΔK of cracks emanating from interference fitted holes. Results demonstrate that fretting was the main reason for crack nucleation, and furthermore, the location was precisely predicted and fatigue life enhancement was explained.

1. Introduction

Mechanical joints, such as bolts, rivets or pins are used numerously in metallic structures, specifically in aircraft constructions. These joints require a hole which makes them inherently vulnerable to failure via fatigue. Nevertheless, various techniques exist which can be used to enhance the fatigue life of such joints profoundly including the use of cold expansion [1,2], bolt clamping [3] and using an interference fitted pin [4–6].

An IF is accomplished when inserting an oversized item into a hole. Effectively there is negative clearance and in the case of circular items, the fastener diameter will be larger than the hole diameter it is to fit inside. In practice, achieving an IF can be carried out either by forcing one into the other or through utilizing temperature difference performed either by heating and expanding the hole or by cooling and contracting the inserted item, which they are allowed to return to a common ambient temperature afterwards.

The IF has been used to prolong the fatigue life of bolted joints owing to the fact that a beneficial tensile tangential pre-stress is induced at the hole edge. This pre-stress diminishes the effective magnitude of local cyclic stress due to remote applied cyclic load. Although the produced tensile stress may cause a mean stress rise, it considerably reduces the alternating stress which is far more detrimental in terms of fatigue [7]. The reduction of stress amplitude will postpone the onset of fatigue crack initiation and propagation, hence will extend fatigue life. Furthermore, it is believed that when a pin is interference fitted in a fastener hole, it will open the existing crack (i.e. pre-crack or fatigue crack), creating a non-zero SIF in the absence of an externally applied load. While the maximum SIF will be elevated on account of presence of the

Abbreviations: DCT, Displacement Correlation Technique; DOF, degree of freedom; DIF, Degree of interference fit (%); FE, finite element; FCG, fatigue crack growth; LEFM, linear elastic fracture mechanics; IF, interference fit; SEM, scanning electron microscopy; SIF, stress intensity factor; 2-D, two dimensional; 3-D, three dimensional.

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pin, the SIF range ($\Delta K = K_{max} - K_{min}$) will be lower than that in the case of no IF (open hole) under cyclic loading resulting in diminished crack growth rates [8].

For the most part, recognition of the advantages to be gained using an IF remains qualitative, coming from practical experience and experimentation, nevertheless, quantifying the magnitude of fatigue life improvement by detailed analysis is limited [4,9]. By contrast, in [9] the IF effect on fatigue life improvement of joints was studied both experimentally and numerically using 2-D finite-element plane stress models. More recently, the effect of IF on the fatigue life of double shear lap joints with empirical fatigue testes and numerical FE simulation was investigated by the authors [6,7]. The fatigue tests were carried out on the specimens made from Al 2024-T3 and the results demonstrated that IF could only enhance fatigue life at the lower load levels. Moreover, the authors studied the effect of IF on fatigue life improvement [4] and fatigue crack growth and life prediction of IF in a holed single plate [5]. Surprisingly, findings unfolded that unlike the interference fitted double shear lap joints, fatigue life improvement of a single plate including a force fitted pin is notable at the higher load levels.

On the other hand, fretting commonly takes place in pinned or bolted joints and has an adverse effect on fatigue life and alarmingly reduces the positive effect of life improvement techniques such as IF. Recently there have been a number of studies investigating the application of titanium coating using IBED technique and shot peening methods [10], the influence that fretting has on stress distribution, fatigue crack origination site and life reduction [11–15]. Nonetheless, generally these studies are concerned with specific geometries. The authors' findings [16] reveals that fretting fatigue occurring between the pin and hole surfaces at joints lessened fatigue life significantly. In fact, all of these studies illustrated that the friction coefficient plays an influential role at the crack nucleation stage thereby declining fretting fatigue life. Despite mentioned works, there is still the scarcity of research on practical joints in the presence of pre-stress field effects.

In this paper fretting fatigue crack nucleation and ΔK were studied for interference fitted hole in a single plate based on preceding experimentally conducted study on fatigue performance of the interference fitted hole in a plate. This research was carried out experimentally using SEM of the hole surface, and also numerically, using 3-D FE models for 1%, 1.5%, 2% and 4% DIF. The fatigue fractured specimens were studied to characterize the crack initiation location and viable diverse modes of failure. In the FE part, friction coefficient between the force fitted pin and hole attained through a trial and error procedure. Finally, fatigue cracks were included in new FE models to investigate the IF effect on FCG by obtaining SIF and its range during cyclic loading using LEFM.

2. Test procedure and fractured section examination

The details of the experimental fatigue test programme were previously reported in [4] and have just briefly explained here. Fatigue specimens were made from 4.5 mm thick aluminium alloy (grade 7075-T6) with planar dimensions as depicted in Fig. 1a. The steel pin which was used in IF process is also shown in Fig. 1b. Furthermore, during the IF, the pin fitting forces were recorded by testing machine (see Section 3.2).

To achieve different DIF, the pins were manufactured with special diameters in their cylindrical part, the largest diameter of the pins were D = 5.05, 5.075, 5.10 and 5.20 mm of which created interference fits 1%, 1.5%, 2% and 4% respectively (according to Eq. (1)) when they entered the hole. The fatigue results for the tests are displayed in the form of linear-log S–N data in Fig. 2.

$$\text{Degree of interference fit } (\%),\ \text{DIF} = \frac{D-d}{d} \times 100 \quad (1)$$

To investigate whether there was any difference in the crack initiation locations and propagation regions in the 'open hole' and 'interference fitted' specimens, fractured surfaces of the specimens were examined (see Fig. 3). The examinations demonstrate that fatigue crack initiates on the mid-plane (Z = 2.25 mm and about $\theta = 90°$) in all cyclic loads for the open hole specimens because of the big stress concentration (see Fig. 3a). On the contrary, the fatigue crack initiates around the entrance face for interference fitted specimens at the hole edge (see Fig. 3b and c).

The fractured section of test specimens proves that while fatigue cracks initiate at about $\theta = 90°$ for the open hole specimens, at the interference fitted specimens, they initiate and propagate from about θ = 50–60° at the hole edge on the entrance face (Z = 4.5 mm) as shown in Fig. 3. Moreover, failed IF specimens illustrate that the final crack shape is a quarter elliptical and in most cases it is located just at one side of the hole. To characterize the effect of interference fitted pin (and friction stresses value) on the hole surface abrasion, the crack initiation region at the hole surface was examined using the SEM method typically for 2% DIF specimen with peak load of 35 kN (see Fig. 3d and e). The figure demonstrates that the combination of contact normal stress and frictional stress produce a stress concentration at the contact interface which results in nucleation of surface fretting damages.

3. Numerical stress analyses

3.1. Finite element modeling

In the present study the FE simulation was used directly from the previous research and part of needed results obtained from the extension of former simulations. Nonetheless, the entire details can be found in Ref. [4]. In the FE simulation 3-D models were generated according to the dimensions of the fatigue specimens. The 3-D FE models were conducted using ANSYS code [17] to simulate the IF process and obtain stress distributions.