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The influence of burr formation and feed rate on the fatigue life of drilled titanium and aluminium alloys used in aircraft manufacture

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ABSTRACT

Following drilling, fatigue life trials were performed on as-drilled and deburred specimens made from Ti–6Al–4V, AA7010 and AA2024, with feed rates varied at 2 levels. Deburring dramatically increased the fatigue performance of the Ti–6Al–4V and AA7010 samples by 69% and 283% respectively, but there was no significant effect on the AA2024 alloy. Fractography showed failure initiated near the exit burrs in Ti–6Al–4V and AA7010 specimens but not in the AA2024 workpieces. Correlation (R^2) of fatigue notch factor against the sum of entrance and exit burr height was 0.68 and 0.79 for Ti–6Al–4V and AA7010 respectively, compared to 0.54 for AA2024.

1. Introduction

Carbon fibre reinforced plastic (CFRP) composites now account for the majority of weight in modern civil aircraft structures (~50% of Boeing 787), with more traditional titanium and aluminium alloys liable for ~35% of the overall weight [1]. Many of the critical load bearing sections of the fuselage and wings consist of hybrid composite-metallic assemblies which require the drilling of high tolerance holes for mechanical joining [2]. The integrity of such joints is a critical consideration and substantial research has been undertaken relating to the effect of drilling operations on fatigue performance. The majority of work has focussed on the influence of hole machining marks/scoring, surface roughness and residual stress [3–6], with only limited studies devoted to evaluating burr formation on fatigue behaviour. Results from comprehensive trials performed by Koster et al. [7] involving 7.93 mm diameter tapered interference-fit fastener holes in AA7175-T73511 aluminium alloy, indicated that the presence of exit burrs up to ~0.5 mm high had no detrimental influence on the fatigue life of the joint, as none of the associated failures initiated in the burred region. Work by Noronha et al. [8] to assess the fatigue performance of drilled and reamed fastener holes (6.35 mm diameter) in AA7475-T7351, similarly concluded that burrs had no discernible impact on specimen fatigue behaviour, as no cracks were observed to originate from the burrs.

Nishimura [9] investigated the effect of burrs (fabricated by milling) on the fatigue performance of Ti–6Al–4V specimens having holes drilled at diameters of 1, 2, 5 and 10 mm. The burrs were found to significantly reduce fatigue life by up to two orders of magnitude compared with corresponding non burred specimens, but only in test pieces with small diameter holes (1 and 2 mm). For specimens with larger holes (5 and 10 mm diameter), no major degradation in fatigue life was observed as peak stress caused by the burr decreased with increasing hole size. In an evaluation of drilled and reamed AA2024-T3 open hole specimens (4 mm diameter), Lanciotti and Polese [10] showed that deburring enhanced the workpiece run-out fatigue strength by ~34%. Work by Barter et al. [11] provides reinforcement for this stance based on inspection of a wide range of post service metallic airframe components from both commercial and military aircraft, to ascertain the types of manufacturing induced discontinuities/defects that initiated fatigue failure. One of the examples highlighted included a poorly deburred fastener hole, which was identified as the source of fatigue cracks in a decommissioned AA7075-T6 wing spar.

It is likely that the conflicting results detailed in the literature regarding the effect of burrs on the fatigue life of drilled components is in part due to the large variation in workpiece surface integrity and operating test conditions employed by the different researchers. The current work aimed to examine the influence of burr formation and feed rate on the fatigue performance of drilled titanium and aluminium alloy specimens.

2. Experimental work

Fatigue testing was performed on a Phoenix twin-column servo-hydraulic machine having a load capacity of 100 kN with a maximum head stroke and loading frequency of 50 mm and 50 Hz respectively; see Fig. 1a. The 3 aerospace grade materials assessed

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were Ti–6Al–4V annealed at 800 °C for 1 h, together with 2 aluminium alloys; AA7010-T7451 and AA2024-T351 in the solution treated, water quenched and aged condition. Both of these alloys were subsequently stress relieved by controlled stretching (1.5–3%). The rectangular fatigue specimen blanks were cut from a single slab/billet of each alloy along a consistent alignment to avoid any directionality effects in the workpieces. Each side of the test samples was finish face milled (depth of cut of 0.125 mm) symmetrically to final dimensions of 150 × 17 × 7 mm (L × W × H) in order to ensure flatness and equilibrium of residual stresses. A single through hole was subsequently drilled at the centre of each test specimen on a 3-axis machining centre using 6.35 mm diameter solid WC twist drills, see Fig. 1b for sample fatigue specimens. This resulted in a theoretical stress concentration factor K_t of 2.26 for the open hole specimens. Two different feed rates were used; 0.07 and 0.14 mm/rev for the Ti–6Al–4V and 0.08 and 0.24 mm/rev for both the AA7010 and AA2024 workpieces, while cutting speed was kept constant at 10 and 50 m/min for the Ti and Al alloys respectively. The low and high feed rate levels were selected to generate large and small exit burr heights respectively based on results from a previous publication [12], which also details the drill geometries used in the present work. All holes were drilled with cutting fluid supplied externally at a flow rate of 52 l/min.

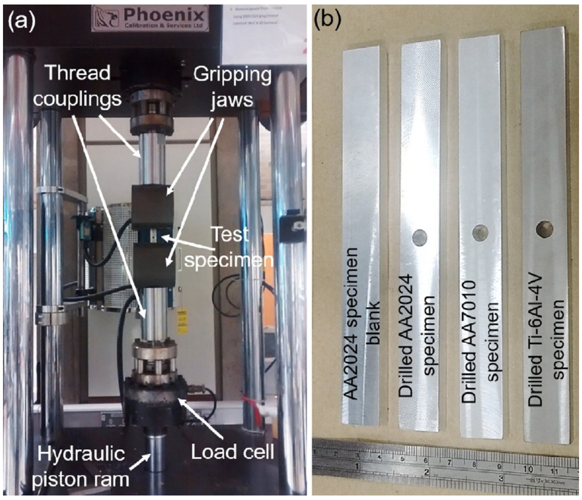

Fig. 1. (a) Fatigue test setup and (b) sample test specimens.

Tension–tension fatigue experiments were undertaken based on a standardised wing loading spectrum used by Airbus, which entailed room temperature testing at a frequency of 15 Hz and stress ratio (R) of 0.1. The free/unclamped length of the specimens held between the grips was 70 mm. Restrictions relating to fatigue machine access and workpiece material availability however precluded testing to obtain full S–N curves. As a consequence, fatigue performance in terms of the number of cycles to failure was assessed at a pre-determined load for each material based on published S–N data for a fatigue life of ~200,000 cycles (at equivalent K_t and stress ratios). The load levels utilised were 28 kN (net stress of 375.6 MPa), 14 kN (187.8 MPa) and 13 kN (174.4 MPa) for the Ti–6Al–4V [13], AA7010 [14] and AA2024 [15,16] samples respectively. All selected loads/stresses were within 97–109% of the maximum loads employed in published fatigue data derived from flight load spectra simulation [17–19]. Test specimen preparation and loading parameters were based on fatigue testing procedures utilised by Airbus in accordance with ASTM E466 standards [20].

Trials were carried out according to the full factorial experimental array outlined in Table 1 involving two replications of each run, giving a total of 12 tests for each material. The burr height and width at hole entry and exit locations of the as-drilled specimens were measured using an Alicona InfiniteFocus G5 microscope (at 10× magnification and 0.5 μm resolution) prior to fatigue testing with results shown in Table 2. Deburring was achieved by introducing a 50 × 50 μm chamfer on both ends of the hole using a 90° countersinking tool at a feed rate and cutting speed of 0.05 mm/rev and 5 m/min respectively, with cutting fluid delivered externally. Specimens were tested to failure or up to a run out of 1×10^6 cycles. Fractography analysis of the failed fatigue specimens were performed using optical and scanning electron microscopy (SEM).

Table 1
Experimental array and variable factor levels for the fatigue tests.

Test	AA2024/AA7010		Ti–6Al–4V	
	Feed rate	Hole condition	Feed rate	Hole condition
1	0.24	Deburred	0.14	Deburred
2	0.08	As-drilled	0.07	As-drilled
3	0.24	As-drilled	0.14	As-drilled
4	0.08	As-drilled	0.07	As-drilled
5	0.24	As-drilled	0.14	As-drilled
6	0.08	Deburred	0.07	Deburred
7	0.24	As-drilled	0.14	As-drilled
8	0.08	Deburred	0.07	Deburred
9	0.24	Deburred	0.14	Deburred
10	0.08	Deburred	0.07	Deburred
11	0.24	Deburred	0.14	Deburred
12	0.08	As-drilled	0.07	As-drilled

Table 2
Hole exit and entry burr height/width measurements.

Test	Exit burr height/width (μm)			Entry burr height/width (μm)		
	Ti–6Al–4V	AA7010	AA2024	Ti–6Al–4V	AA7010	AA2024
1	0/0	0/0	0/0	0/0	0/0	0/0
2	52/190	65/16	58/17	25/100	8/13	13/29
3	23/127	11/17	12/16	20/48	23/12	30/28
4	50/195	67/15	60/15	26/95	7/12	11/28
5	19/123	10/17	13/15	19/44	22/14	27/27
6	0/0	0/0	0/0	0/0	0/0	0/0
7	21/192	13/16	14/16	22/95	24/13	26/27
8	0/0	0/0	0/0	0/0	0/0	0/0
9	0/0	0/0	0/0	0/0	0/0	0/0
10	0/0	0/0	0/0	0/0	0/0	0/0
11	0/0	0/0	0/0	0/0	0/0	0/0
12	49/124	64/16	57/17	24/43	9/13	12/29

3. Results and discussion

3.1. Fatigue performance evaluation

The influence of hole condition on the number of cycles to failure at the specified stress levels for each of the workpiece materials drilled at high and low feed rates are shown in Figs. 2 and 3 respectively. Samples with deburred holes generally exhibited superior fatigue life compared to the corresponding as-drilled workpieces, although differences in performance were observed depending on the drilling feed rate and specimen material. For trials involving holes drilled at the high feed rate level, the average number of cycles to failure of the deburred Ti–6Al–4V, AA7010 and AA2024 specimens were ~69%, 190% and 8% higher respectively than the as-drilled counterparts. Similarly when drilling with the low feed rate level, deburring improved the mean number of cycles to failure of the Ti–6Al–4V, AA7010 and AA2024 open hole samples by ~48%, 283% and 93% respectively. A major factor contributing to the lower fatigue life of the as-drilled specimens was the presence of defects including microcracks and spalling/chipping at the entrance/exit regions of the holes, similar to those shown in Fig. 4, which detail sample SEM micrographs of internal hole exit burr

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