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Predicting the likely causes of early crack initiation for extruded aircraft components containing intergranular corrosion

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ABSTRACT

This paper details an experimental and finite element (FE) analysis of the atypical form of intergranular corrosion (IGC) observed in the wing skins of the RAAF and RNZAF P-3 Orion to determine if its presence is likely to cause atypical fatigue crack initiation. An investigation of the local stress concentration of IGC-related features found that it was not the IGC fissure itself that can lead to early fatigue crack initiation, but the pits and corroded inclusions associated with its presence. It was also found that fatigue can initiate sub-surface, however this is limited to a depth of approximately 650 μm.

1. Introduction

Intergranular corrosion (IGC) is currently an issue for the Royal Australian Air Force (RAAF) and Royal New Zealand Air Force (RNZAF) AP-3C Orion fleets with a number of aircraft having increased maintenance work to remove all traces of IGC found around the dome-nut holes near the engine nacelles [1]. This form of IGC is not a typical IGC morphology – in the thin, highly extruded 7075-T6511 wing skins, IGC forms long, straight fissures parallel to the surface (and thus loading direction). Fig. 1 shows a representation of the IGC found in the AP-3C Orion wing skin material.

Conventional analyses using fracture mechanics cannot determine the effect of the IGC fissure as it is parallel to the applied loading. This means that the mode I stress intensity factor (K_I) will be zero according to fracture mechanics. As a consequence of the failure of conventional fracture mechanics to describe the system, the fatigue implications of the form of IGC seen at these locations are unknown. Maintenance practices, which must remain conservative require removal of all IGC found around the dome-nut holes (which are located near the engine nacelles), leading to a significant increase in aircraft maintenance time and cost.

This paper sets out to determine the structural integrity implications of the dome-nut hole IGC for the aircraft by investigating the stress concentration caused by IGC and its associated features. Surface pits down the bore of the hole and corroded inclusions along the path of the IGC fissure, have been found in metallographic teardowns of actual AP-3C dome nut holes containing IGC [2] and simulated IGC in the same material [3,4]. These investigations did not include the presence of fatigue cracking and its interactions with these features.

The investigation performed here used an automated computer model that creates an ABAQUS input file of a hole with IGC, surface pits and corroded inclusions placed within a centre hole system with finite width corresponding to the fatigue coupon geometry. A Monte-Carlo analysis of differing IGC fissure lengths, pit sizes and inclusion sizes and locations was conducted to determine their effects on local stress concentrations (both magnitude and location of the maximum stress concentration).

2. Background

There are numerous causes of fatigue crack initiation in the materials used in structural applications, such as aircraft, and each of these must be accounted for in order to minimise the chance of unexpected failure. Some of these initiators include material porosity [5], machining marks from assembly [6], mechanical

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Nomenclature

CID	critical inclusion distance
K_t	stress concentration factor
IGC	intergranular corrosion
L	longitudinal (i.e. extrusion) direction as per ASTM E399
T	long-transverse direction as per ASTM E399
S	short-transverse direction as per ASTM E399
RAAF	Royal Australian Air Force
RNZAF	Royal New Zealand Air Force

damage during maintenance and various forms of localised corrosion, such as pitting [7–9] and exfoliation [10–12].

Corrosion can be more complicated to manage than other forms of initiators due to its insidious nature-stemming from the fact that what is visible on the surface (and thus inspectable) does not necessarily show the full extent of what lies beneath. Pitting, for instance, can be varied in both size and shape, particularly in aluminium. Whilst pits can be quite smooth and hemi-spherical in shape in some steels (e.g. D6ac steel [13]), pits in aluminium tend to have an irregular shape and rough inner surface [14]. It is possible to create a predictive fatigue model by treating pits as an equivalent sized crack [8,14], however the scatter in these models is seemingly proportional to the irregularity in pit shape. In previous work conducted at DST Group, the smooth pits found in D6ac steel used in the F-111 led to accurate in fatigue life predictions with minimal scatter [13], whilst for 7050 [14] and 7010 [8] the corrosion pits were much more irregular in shape and the scatter in observed fatigue lives was much greater.

Developing a predictive fatigue model for IGC is more difficult. In this material, the IGC forms long, straight fissures parallel with the surface, up to 5 mm long [4]. These fissures also have a complex shape as they progress into the material, with the corrosion fissures changing direction up and down as they grow along grain boundaries [3]. The IGC fissures are also generally quite thin, meaning little overall thickness loss from the component. This combination of IGC growing parallel to a surface (shown in Fig. 1) with a thin cross section raises the question of whether IGC poses a threat to the fatigue life of components, particularly investigating the location of fatigue initiation.

Fatigue initiation, from any of the sources mentioned above, can be attributed to the stress concentrations each of the features cause; the resulting stress concentration, particularly its location, will be the likely point of fatigue initiation [8]. Strain-life based certification of aircraft using the notch factor at design features and applying variations of Neuber's rule is common amongst military aircraft and is used for the P-3 Orion [15]. The RAAF uses a combination of a strain-life phase, followed by a linear elastic fracture mechanics phase from a crack length of 1.27 mm to failure to determine total life at critical locations. The second phase uses a plasticity induced closure (i.e. ΔK_{eff}) crack growth method implemented using the software package FASTRAN [16]. The work presented in this paper will focus on the effect of IGC on the first stage of lifeing and will determine if any change in the fatigue initiation location can be predicted by analysing the stress concentration factors of various IGC-related features. The analysis will concentrate on pits on the bore of the hole that IGC grows from and any corroded inclusions that can form along the IGC fissure.

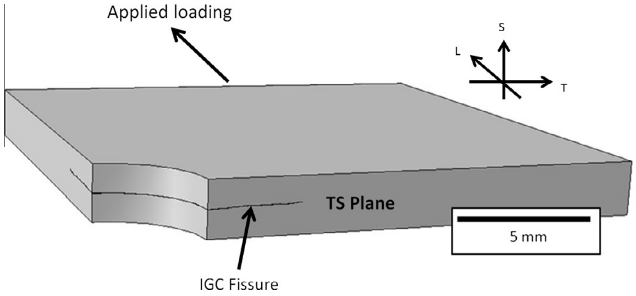

Fig. 1. Representation this atypical form of IGC found in the P-3 Orion. The IGC fissure is located on the LT plane and a typical fatigue crack grows on the TS plane in the T direction.

3. Experimental material

The material used in the study was taken from the wing of an ex-service Royal New Zealand Air Force P-3 Orion. Table 1 compares the compositions of the experimental material with the SAE AMS-QQ-A-2250 standard for the alloy [17]. The composition of the ex-service material was determined using inductively coupled plasma atomic emission spectroscopy. The material complied with its composition specification.

The microstructure of the material was studied by cutting samples from the bulk material, cold-mounting these samples and then polishing them to a sub-micron finish. The samples were then etched with Keller's Reagent. The material's microstructure consisted of grains that were elongated and pancaked in the extrusion

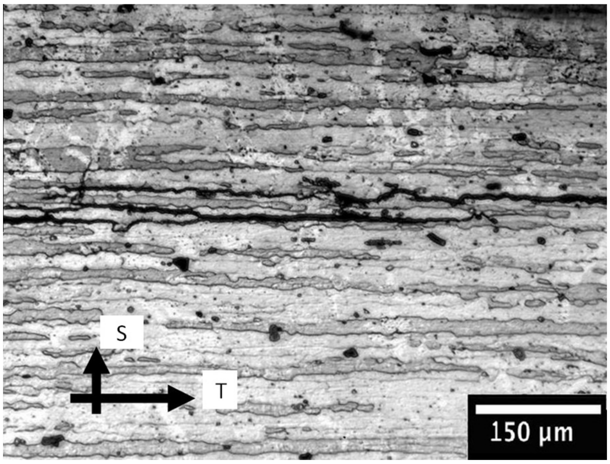

Fig. 2. Grain structure of the TS plane of the 7075-T651 extruded aluminium alloy used in this work.

Table 1
Composition in weight percentage of 7075-T651 extruded aluminium alloy.

Material	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
Experimental	0.34	0.30	1.93	0.22	2.47	0.23	5.98	0.11	0.09	Bal.
Nominal	<0.4	<0.5	1.2–2.0	<0.3	2.1–2.9	0.18–0.28	5.1–6.1	<0.2	<0.15	Bal.