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# OUTCOMES OF RESEARCH INTO SMALL FATIGUE CRACK NUCLEATION AND GROWTH IN AA7085-T7452

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**Abstract:** Aluminium alloy (AA) 7085-T7452 is a recent addition to the 7XXX series of aluminium (Al), zinc (Zn), magnesium (Mg) and copper (Cu) high strength aerospace alloys which has applications in primary airframe structure of the Airbus A380 and Lockheed Martin F-35. AA7085-T7452 was developed for large unitized, lightweight airframe structures since its low quench sensitivity and good through-thickness fracture toughness enables forgings of up to 12 inches (305mm) thick. The Defence Science and Technology Group (DSTG), working with RMIT University, have completed several studies concerning small fatigue crack nucleation and growth in this material using specimens with representative production surface finishes and loaded with service representative spectra.

This paper presents an overview of observations concerning fatigue crack nucleation and small fatigue crack growth rates (FCGR) in AA7085-T7X in contrast with other 7XXX-T7X alloys. Two influences on the fatigue durability of this alloy were investigated. Firstly, the 'fatigue crack like effectiveness' of surface etch pitting arising from the commonly used Type 1C anodising process was assessed by deriving equivalent initial discontinuity size (EIDS) values via a fractography-based method. This work showed etch pitting associated with Type 1C anodising surface treatments is less effective in nucleating fatigue cracks in AA7085-T7X compared to AA7050-T7X. Secondly, FCGRs for physically small or near-threshold fatigue cracks were quantified for AA7085 using fractography-based measurements and these were compared with equivalent measurements for AA7050 and AA7075 in the T7X condition. Here, small crack and near-threshold FCGRs in AA7085 were largely consistent with those for AA7050 and AA7075 T7X materials. These results highlight the authors' current progress toward their goal of understanding the fatigue properties of AA7085-T7452 well enough to allow accurate fatigue life predictions for structural certification and sustainment of AA7085-T7452 airframe components.

**Keywords:** Fatigue crack nucleation, small fatigue crack growth, aluminium alloys.

## INTRODUCTION

Aluminium alloy (AA) 7085-T7452 is a recent addition to the 7XXX series of aluminium (Al), zinc (Zn), magnesium (Mg), and copper (Cu) high strength aerospace alloys, which has applications in primary airframe structure of the Airbus A380 and Lockheed Martin F-35. AA7085-T7452 was developed for large unitized, lightweight airframe structures since its low quench sensitivity and good

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through-thickness fracture toughness enables forging applications of up to 12 inches (305mm) thick [1]-[4].

The Defence Science and Technology Group (DSTG), working with RMIT University, have completed and are continuing several studies of fatigue crack nucleation and small crack growth in AA7085-T7452 [5]-[7] using specimens with production representative surface finishes and loaded with service representative spectra. This work aims to enable improved accuracy for fatigue life analysis of AA7085-T7452 airframe components. This paper presents an overview of the observations concerning fatigue crack nucleation and small fatigue crack growth rates (FCGRs) in AA7085-T7452 that have been made so far.

## BACKGROUND

Many previous works highlight the importance for aircraft certification and sustainment of thoroughly characterising common sources of fatigue crack nucleation in production aircraft structures, including the development of equivalent initial discontinuity sizes (EIDS) distributions [8]-[15]. Standards such as MIL-STD-1530Dc1 [16], which outlines the requirements of an Aircraft Structural Integrity Program (ASIP), prescribe such assessments. The importance of thoroughly characterising small crack and near-threshold FGCRs for the certification and sustainment of metallic airframe components has also been highlighted in the literature [17]-[20]. Realistic EIDS and small FCGRs are essential inputs for correlating linear elastic fracture mechanics (LEFM) based durability and damage tolerance (DaDT) tools with the outcomes of certification durability tests. Accurate DaDT predictions for fleet airframes directly underpin safe and efficient airframe sustainment and structural risk assessments.

As a relatively new commercial 7XXX series aerospace alloy with some significant aircraft applications since 2000 (Figure 1), there is limited research into these two topics in the open literature for AA7085. Instead, AA7085 research has focussed on either the alloys susceptibility to intergranular corrosion or how to account for forging induced residual stresses during structural analysis. Neither of these topics shall be covered here.

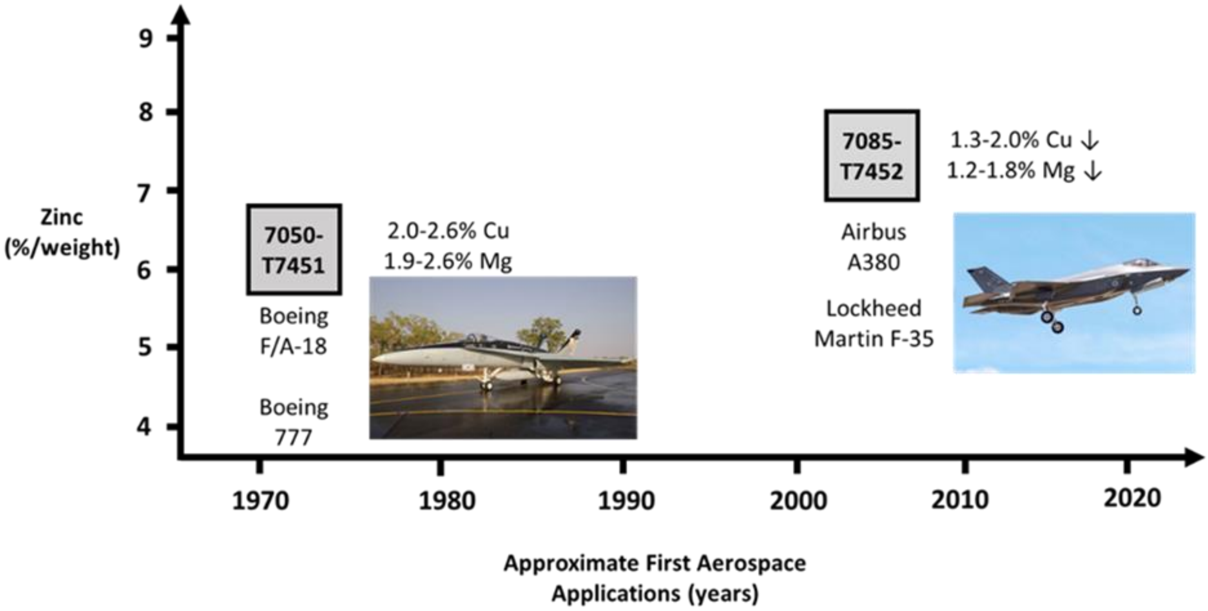

Figure 1: Chemical composition and approximate timeframe of significant aircraft structural applications of AA7050 vs AA7085.

## FATIGUE CRACK NUCLEATION IN AA7085-T7452

### Etch pitting from the Type 1C anodising process

Along with production fastener hole quality, surface etch pitting associated with preparatory steps in the aluminium anodising process is a significant source of fatigue crack nucleation in aircraft structures [8]-[15],[21]. Type 1C anodising [22], specifically thin-film sulphuric acid anodising (TFSAA), is a common surface protection scheme applied to AA7085-T7452 components by the major aircraft manufacturers to reduce the susceptibility to corrosion. To apply an anodised layer post part machining, corrosive cleaning and deoxidising preparatory steps are necessary. In the case discussed here, these steps involved nitric acid and ammonium bi-fluoride, which leads to surface etch pitting beneath the final anodised aluminium layer. Other similar protection treatments such as ion-vapour deposition (IVD) typically involve similar etching [12], since etching provides the clean surface needed for effective application of the protective layer. This etch pitting has been demonstrated historically to be a source of fatigue crack nucleation under favourable stress and material conditions, and therefore, some degree of fatigue performance is traded for improved corrosion resistance.

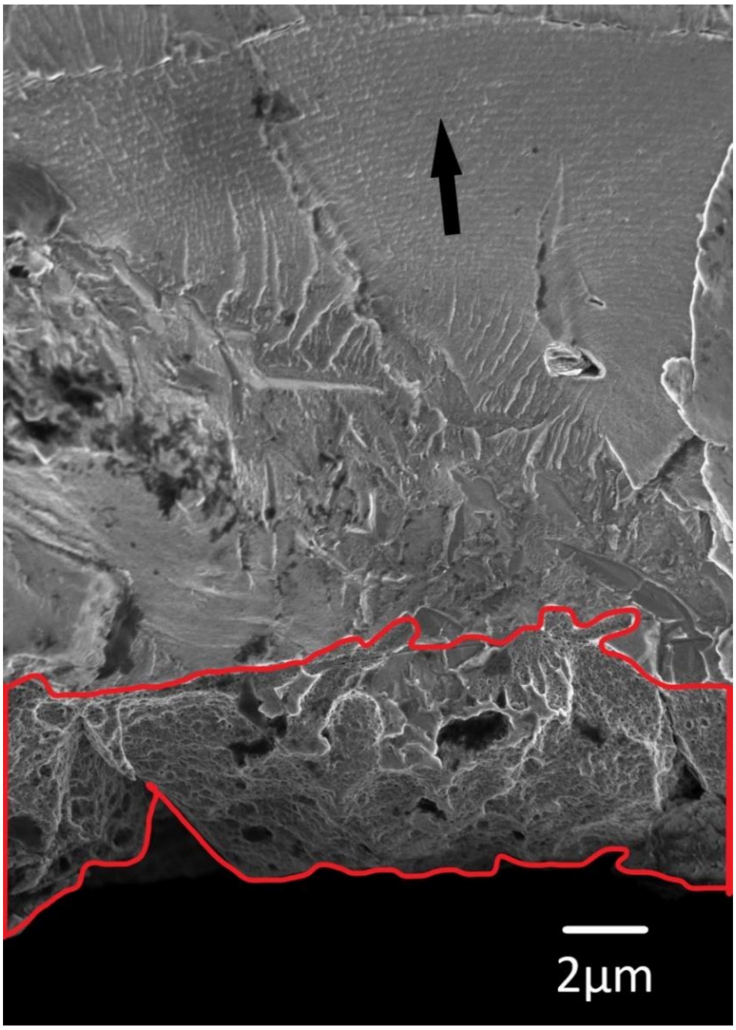

Figure 2: A fatigue crack that has nucleated from surface etch pitting (outlined in red) produced during Type 1C anodising of an AA7085-T7452 specimen. The main direction of fatigue crack growth is indicated by a black arrow. Progression marks resulting from repeated spectrum block loading can be seen beneath this arrow.

## Equivalent initial discontinuity sizes (EIDS)

Studies by the authors on fatigue crack nucleation and growth from etch pits associated with Type 1C anodising (see an example in Figure 2) have measured the etch pit sizes and FCGRs in the vicinities of crack nucleating etch pits using quantitative fractography (QF). The EIDS framework [16] was used to characterise the effectiveness of Type 1C anodising associated etch pit populations in nucleating and growing fatigue cracks. Importantly, QF measurements of FCGRs were taken as close to the interface between the pit and the surrounding material as possible [6], [7], often within approximately 100µm of the pitted surface. This approach allows direct observation of the effect of the nucleating discontinuity on early crack growth and a comparison of this early growth to that occurring once the fatigue crack grows relatively independent of the influence of the nucleating discontinuity. These observations are considered advantageous compared to traditional applications of the EIDS concept where a fatigue crack growth prediction is used to back-project from the time and crack depth at failure. As etch pits are not fatigue cracks, the EIDS process attributes a surrogate fatigue crack size to each crack nucleating discontinuity. It does so by estimating the size of fatigue crack that would produce FCGRs equivalent to that observed near the nucleating discontinuity.

A summary of Type 1C AA7085 etch pit depths ‘a’ and EIDS values are presented in Figure 3, alongside similar estimates that were made for AA7050-T7451 with the same surface treatment, applied spectrum loading and a similar test stress level. The etch pits quantified here were associated with the fatigue crack that caused failure of each specimen, also known as the ‘lead’ fatigue crack [23]. Such pits are considered to be the most important because they are the primary influence on fatigue durability. As illustrated in Figure 3, etch pits associated with pre-Type 1C anodising tend to be deeper, but also significantly more effective in nucleating and growing fatigue cracks in AA7050 as measured by the EIDS process [6], [7]. The geometric mean EIDS value for Type 1C anodised AA7050 was estimated to be approximately 30 times larger than the corresponding value for AA7085 (0.015 mm versus 0.0005 mm depth). The physical mechanisms of etch pit formation is similar for both materials and typically involves the dissolution of surface breaking intermetallic particles, including iron rich $Al_7Cu_2Fe$ (see Figure 4). Notably, AA7050 tends to have significantly more of such intermetallic particles, both by number and size, and this is thought to be a key influence on it producing an etch pit population that tends to nucleate more fatigue cracks and have larger pits associated with lead cracks [6], [7]. Both the larger on-average sizes and greater prevalence of crack nucleation sites are thought to contribute to the tendency for significantly higher EIDS for AA7050-T7451 compared to AA7085-T7452. This data shows that under equivalent cyclic stress conditions, AA7085-T7452 airframe components would tend to have slower early crack growth and therefore longer fatigue lives compared to identical AA7050-T7451 components, if the underlying resistance to fatigue crack growth for each alloy was the same. Such information, as well as accurate estimates of EIDS values, are valuable for airframe designers, as well as operators seeking to efficiently manage the fatigue lives of airframe components using LEFM tools.

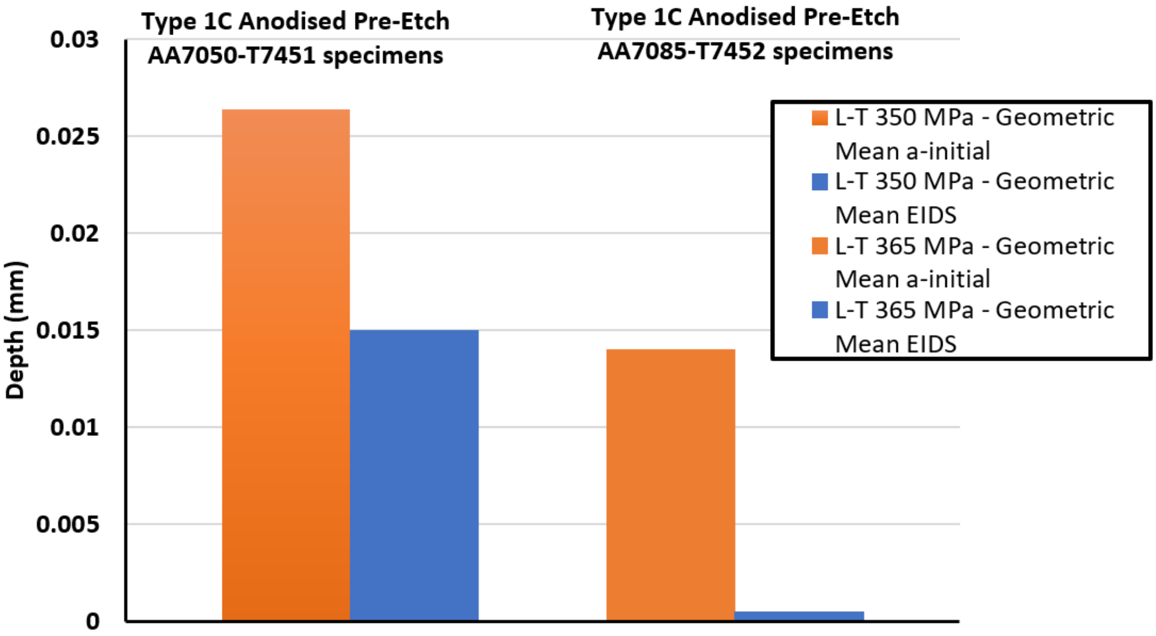

Figure 3: Geometric mean discontinuity depth and equivalent initial damage size (EIDS) depths for AA7050 and AA7085 pre-Type 1C etched specimens. The stresses noted were present at the etched surface of each specimen.

## EIDS discussion

Several factors, including the characteristics of the discontinuity population (e.g. sizes, numbers, morphologies and orientations), local stress conditions and the properties at the interface of the discontinuities with the surrounding material, are thought to influence how effectively etch pits associated with lead cracks nucleate and grow fatigue cracks. Studies concerning the influence of such factors are ongoing. However, secondary nucleation sites appear to be far more prevalent at the fracture surface and in close proximity to the fracture surface where the material was plastically deformed during failure (see examples in Figure 5) for AA7050 specimens compared to AA7085 specimens, under equivalent test conditions. This points to a larger or more uniformly distributed population of iron rich surface breaking intermetallic particles in AA7050 versus AA7085, which allows more crack nucleation. This means the ‘lead’ crack is more likely to occur at a location with an etch pit and microstructural conditions suitable for early crack nucleation and crack growth.

This work suggests that the EIDS populations for Type 1C anodised AA7085 are not the same as for AA7050 and this should be taken into consideration in fleet structural risk assessments for fatigue cracks in these materials with these surface finishes in the absence of other crack nucleating features such as fastener holes, corrosion, fretting or mechanical damage.

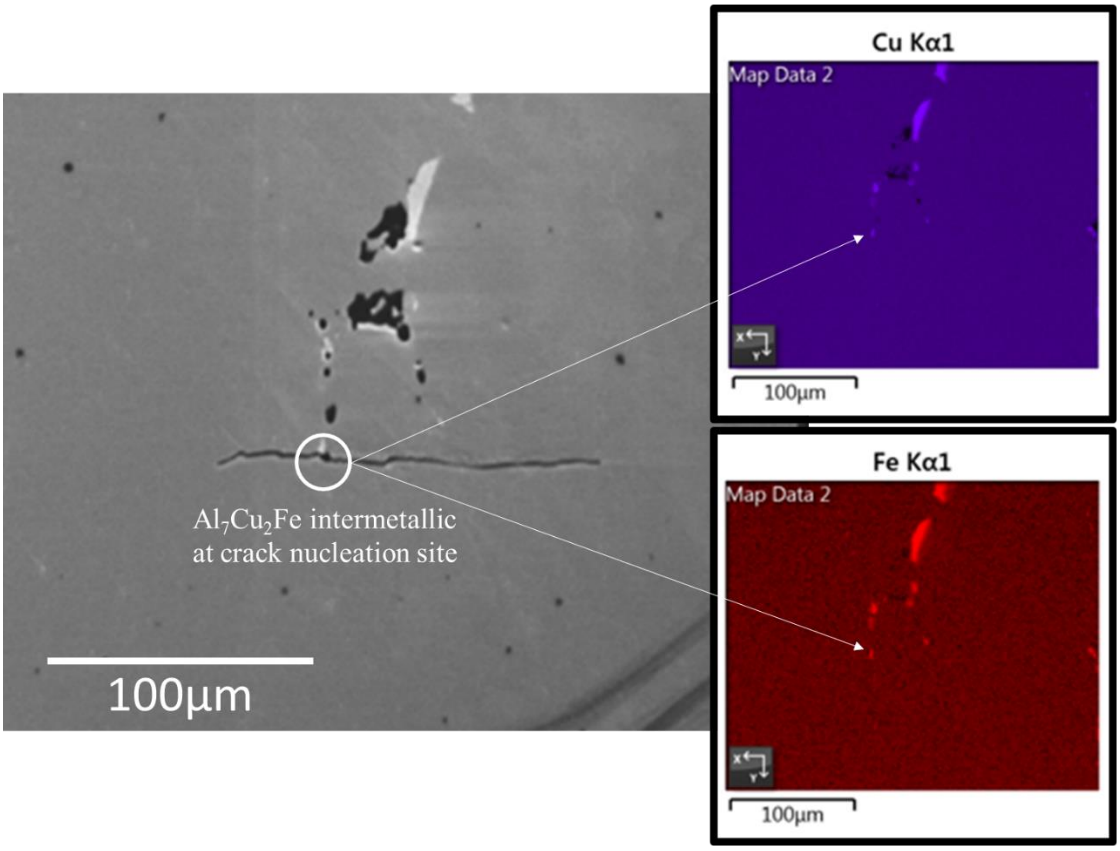

Figure 4: Scanning electron microscop (SEM) and energy-dispersive x-ray spectroscopy (EDS) images of etched $Al_7Cu_2Fe$ intermetallics at, and adjacent to, fatigue crack nucleation sites in a Type 1C anodised AA7050 specimen.

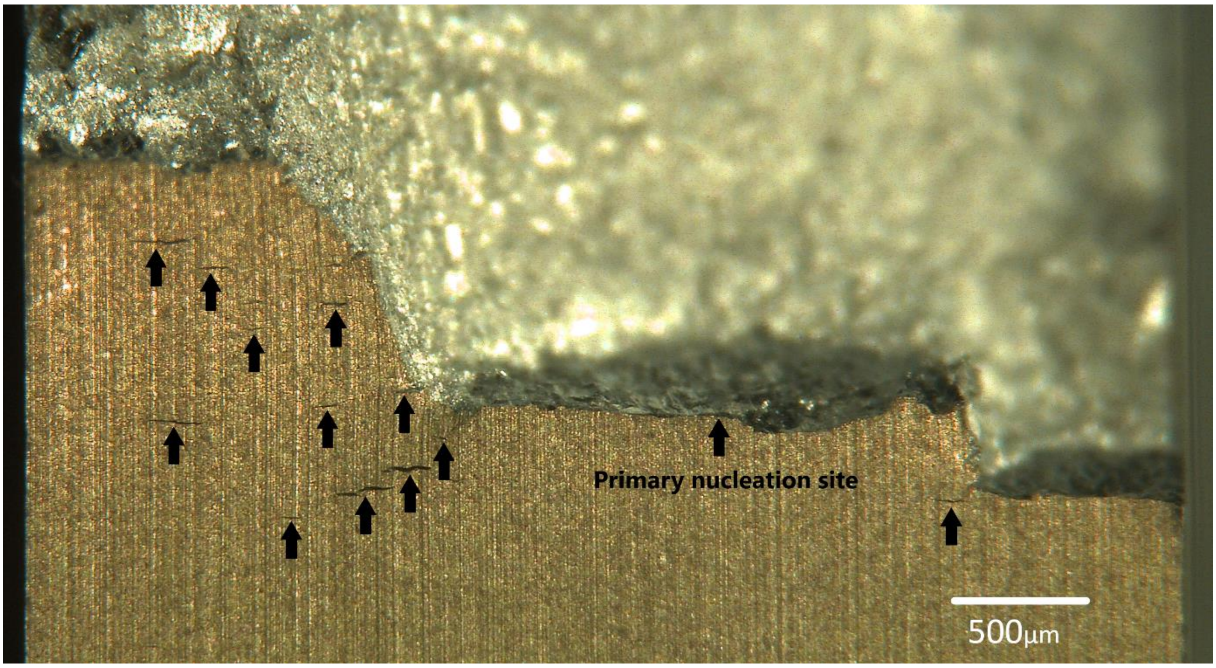

Figure 5: Secondary fatigue cracks nucleating from etch pits associated with Type 1C anodised AA7050, adjacent to the primary crack nucleation site. Cracks are identified with black arrows.

# SMALL FATIGUE CRACK GROWTH RATES IN AA7085-T7452

## Fractographic measurements of small FCGRs

Small crack and near-threshold FCGRs for airframe materials are another critical input to accurate LEFM-based fatigue analysis of airframe structures [17]-[20]. A review of open literature sources of small FCGR data for AA7085-T7452 (Figure 6) [5] revealed an absence of data below FCGRs of approximately $1x10^{-9}$ m/cycle and cyclic stress intensity factors ($\Delta K$) of approximately 3 MPa√m. Accurate FCGR data is needed for fatigue analysts to correlate DaDT tools to full-scale durability tests or in-service instances of fatigue cracking in highly optimised aircraft structures loaded with combat aircraft loading spectra [15],[20].

To address this, DSTG and RMIT developed a comprehensive small FCGR data set using DSTG’s fractography method [24],[25]. Over 5000 measurements were taken from 27 fatigue tested AA7085 specimens that were loaded in either the L-T or T-L material direction. FCGRs were measured for four different load ratios (R= 0.1, 0.5, 0.8 and -0.5) and the quality of the resulting data set was established by using the resulting curves to predict an independent set of fatigue specimens tested to a combat aircraft variable amplitude (VA) loading sequence [5]. This data is shown in Figure 7. It can be seen that FCGRs were measured well below the lower limit of data previously available in the literature. Such data allow prediction of considerably faster and more realistic early life FCGRs for airframe components.

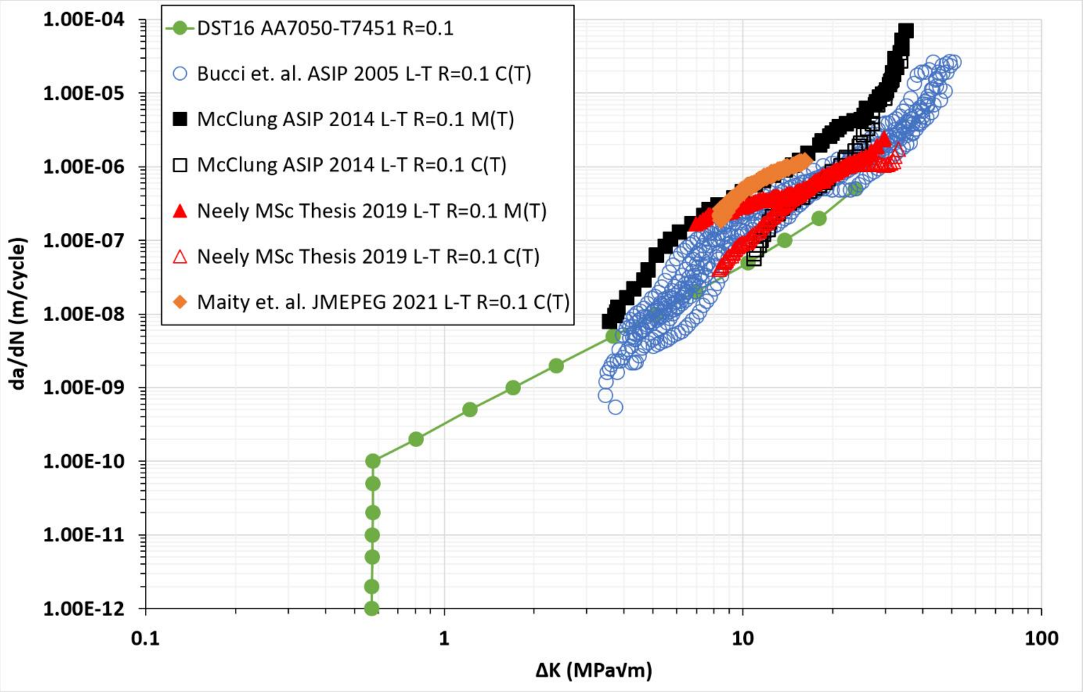

Figure 6: The FCGR data currently available in the open literature. The lower limit of these data are considered inadequate for characterising physically small and near-threshold FCGRs, as illustrated by the range of data previously dervived from small cracks for AA7050 (green) [5].

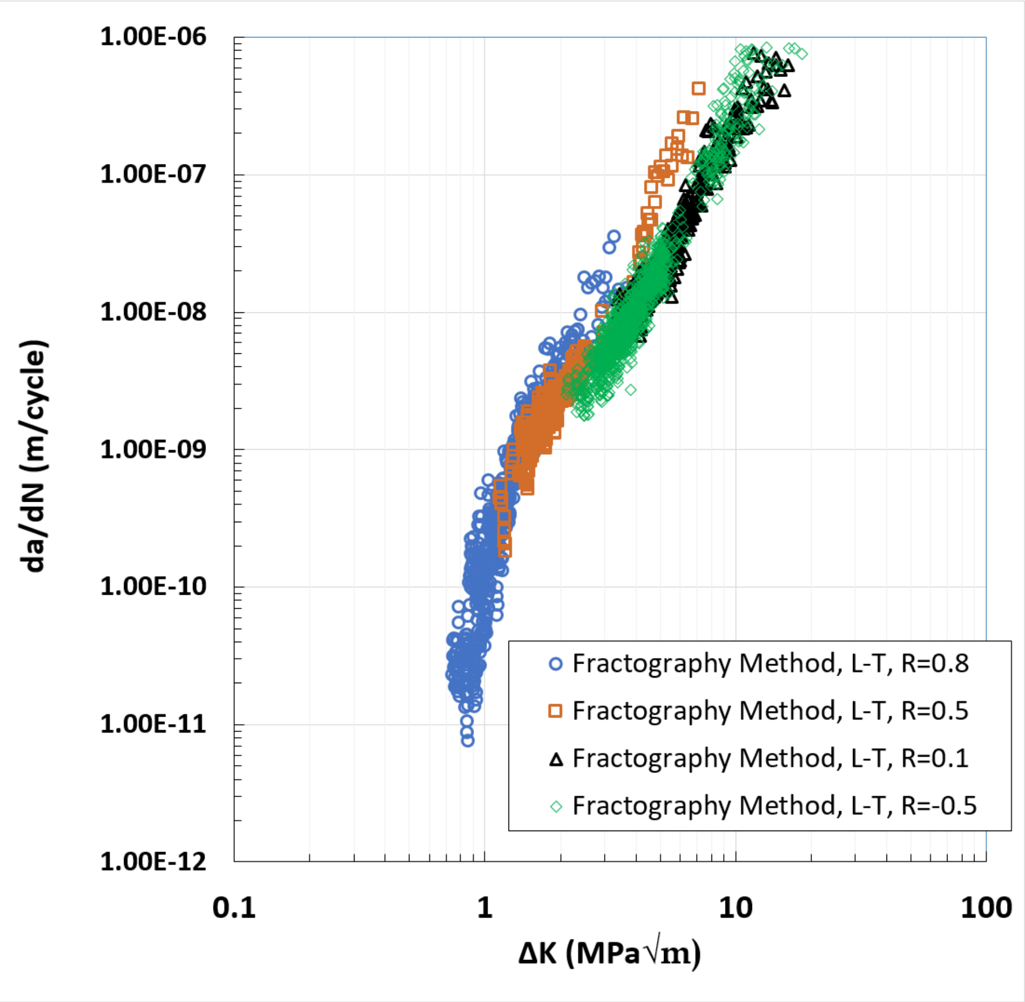

Figure 7: AA7085-T7452 small FCGR data set developed using the fractography method [5].

## Impact of microstructure on small FCGRs

The microstructure of AA7085-T7452 can vary throughout forgings due to the local thermo-mechanical processing history. The research discussed earlier suggests that the local microstructure impacts the EIDS of etch pits: e.g. the EIDS for specimens from quarter-thickness of a forging tended to be larger than for those from mid-thickness [7]. However, the influence of microstructure on FCGRs is less clear [26]. Small FCGR measurements taken below approximately 0.2 mm were therefore segregated, based on a qualitative assessments of material grain size, as illustrated in Figure 8. It can be seen that the FCGRs for both fine and coarse materials grains were quite variable, but generally similar. The scatter in FCGRs would likely be at least in part related to crack growth resistance variability due to factors such as material grain property and orientation variations. As suggested earlier, such variations are thought to also influence the EIDS derived for etch-pits that nucleated lead cracks.

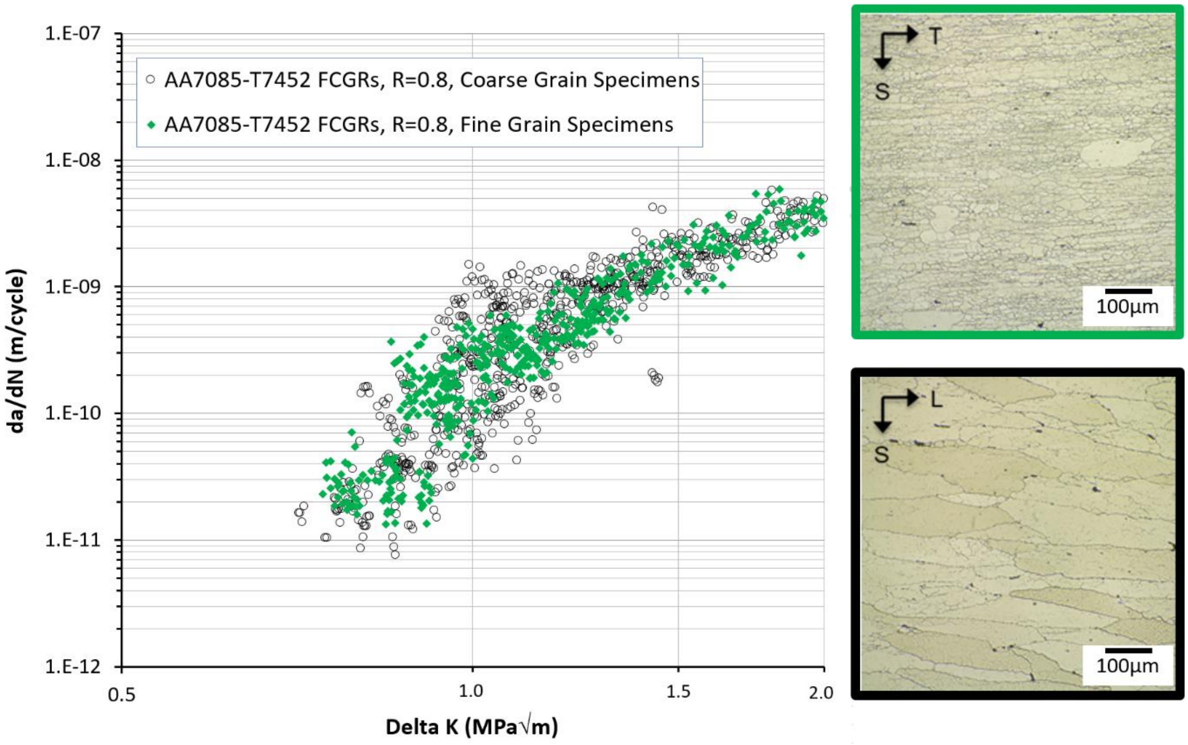

Figure 8: AA7085-T7452 QF-based FCGRs taken for crack depths below 0.2 mm for specimens tested with R = 0.8 constant amplitude loading. The data are separated on the basis of microstructure present at the test section of each specimen. Coarse-grain microstructure, which is characteristic of surface and quarter-thickness forging material, is plotted in black. Fine-grain material, which tends to occur mid-thickness, is plotted in green.

## Comparison of small FCGRs with other 7XXX-T7X alloys

The small FCGR data for AA7085-T7452 were compared with equivalent data sets developed for AA7050-T7451 [27] and AA7075-T7351 [28] using the same experimental approach (as illustrated in Figure 9 and Figure 10). The small FCGRs were observed to be similar across the materials for all crack growth rates and ΔK ranges. Studied closely per Figure 10, it is possible to discern very small differences in the near-threshold FCGRs of these materials below the knee in the FCGR curve at approximately $1x10^{-9}$ m/cycle. For R=0.8 FCGRs a polynomial best-fit curve was fitted to each material dataset in the near-threshold regions to estimate the average rates for each. These curves suggest AA7050-T7451 has the fastest near-threshold FCGRs, AA7085-T7452 has the slowest and AA7075-T7351 is midway between the two. However, these estimated differences are very small considering the scatter in the FCGRs, which suggests that grain-to-grain or even component-to-component differences for a single material could be greater than the differences between the average behaviours of the respective alloys. It is also worth noting that these near-threshold FCGRs are associated with constant amplitude loading and recent studies indicate that spectrum effects, such as underloads, can increase FCGRs in the near threshold region [29].

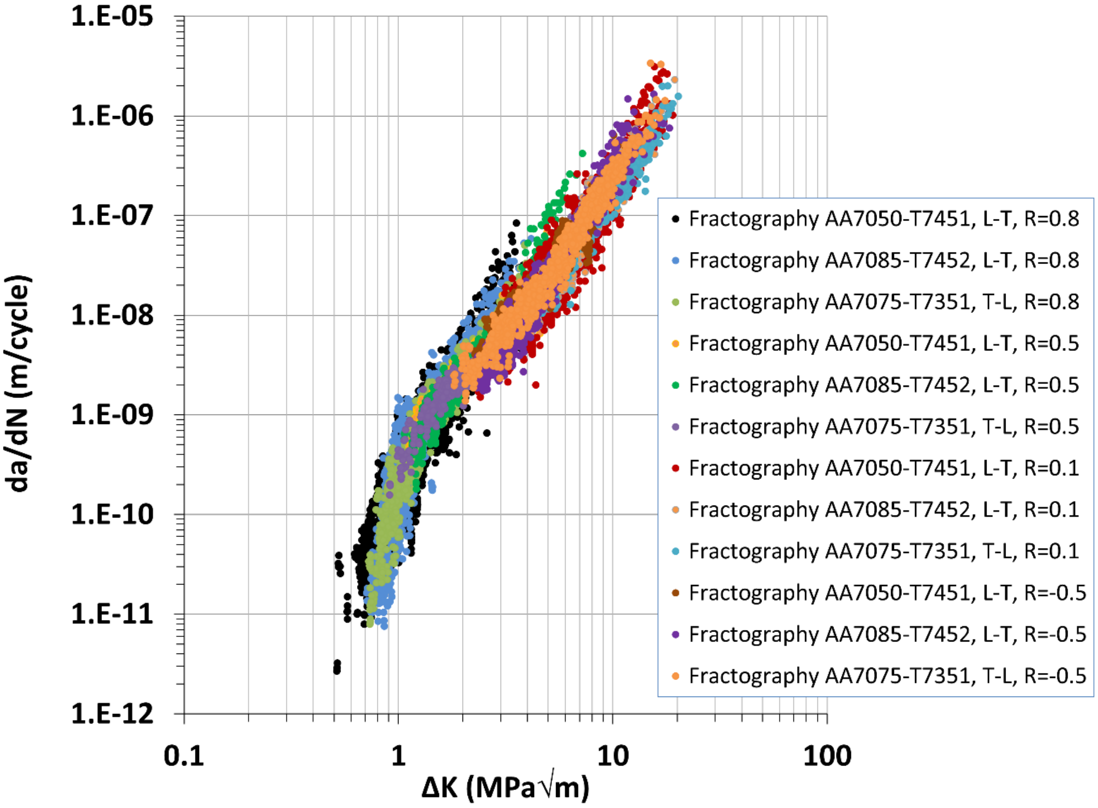

Figure 9: Small FCGR data sets developed for AA7050-T7451 [27], AA7085-T7452 [5] and AA7075-T351 [28].

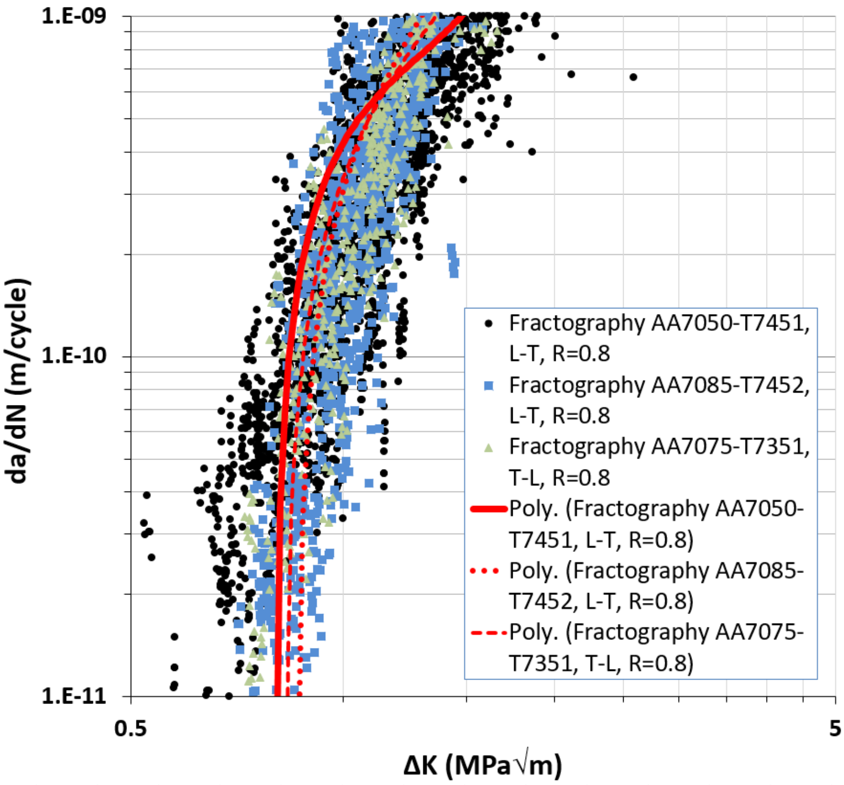

Figure 10: A subset of the small FCGR data for AA7050-T7451 [27], AA7085-T7452 [5] and AA7075-T351 [28] focussing on R=0.8 constant amplitude loading and the near-threshold region.

## CONCLUSIONS AND RECOMMENDATIONS

This paper presents an overview of the current observations and outcomes from an ongoing DSTG and RMIT University research program concerning fatigue crack nucleation and small fatigue crack growth rates (FCGRs) in AA7085-T7452. The goal of this work is to enable improvements in LEFM based fatigue lifing for AA7085-T7452 airframe components subjected to service-representative loading conditions.

To this aim, the authors have made a number of key contributions and observations including:

1. The development of EIDS data for crack nucleating etch pits associated with Type 1C anodising of AA7085-T7452.
2. Providing evidence that Type 1C anodising of AA7085-T7452 is less effective in nucleating fatigue cracks than it is for AA7050-T7451. This, at least in part, appears to be due to a lesser prevalence of surface breaking intermetallic particles in AA7085-T7452.
3. The development of a small FCGR data set for AA7085-T7452, which allows the prediction of faster and more realistic early fatigue life FCGRs compared to pre-existing data available from open literature sources.
4. Showing the small FCGR behaviour of AA7085-T7452 is similar to that of two materials commonly used for airframe components, AA7050-T7451 and AA7075-T7351.
5. Providing evidence that microstructure variations arising from the forging process have more influence on the EIDS of etch pits in AA7085-T7452 than they do on small FCGRs.

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