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My Doc ID: MAC 3b Mar22[1]

Attention: Dr M. Fox NTSB

Piper PA-28R-201 Spar Cracking: Preliminary Observations and Comments

Ref:

1. Fox M. MATERIALS LABORATORY FACTUAL REPORT NTSB Report No. 21-091, January 3, 2022
2. Epperson J, METALLURGIST'S FACTUAL REPORT, Materials laboratory, NTSB Report No. 87-89, August 17, 1987. [N8191U]
3. Fox M. MATERIALS LABORATORY FACTUAL REPORT NTSB Report No. 18-061, March 15, 2019 [N106ER]
4. Epperson J, METALLURGIST'S FACTUAL REPORT, Materials laboratory, NTSB Report No 94-34, December 15, 1993. [N2093]
5. Molent L, Barter SA and Wanhill RJH. The Lead Crack Fatigue Lifing Framework, Int Fatigue; 33 (2011) 323–331.
6. Gallagher JP and Molent L. Effect of load spectra and stress magnitude on crack growth behaviour variability from typical manufacturing defects. Advanced Materials Research Vols. 891-892 (2014) pp 100-105.
7. Molent, L, Q. Sun and A. Green, Charcterisation of Equivalent Initial Flaw Sizes in 7050 aluminium alloy, J. Fatigue and Fracture of Engineering Materials and Structures 29 (2006); 916-937.
8. Molent, L. and Wanhill, R. Management of Airframe In-Service Pitting Corrosion by Decoupling Fatigue and Environment. Corros. Mater. Degrad. 2021, 2, 493–511.
9. Wanhill RJH, Barter SA et al., Fractography-assisted Observations on Fatigue Thresholds in an Aerospace Aluminium Alloy, NLR-TP-2009-596, Nov 2010.

The following is a summary of some observations primarily based on data from Ref 1. From these a preliminary estimate of the crack growth rate of Spar B is made.

Pertinent Observations SPAR B:

1. Fig. B9: many striations/progression markings – possibly indicating high-cycle fatigue close to origin. Ground-Air-Ground (GAG) cycles may be cause of these. The heavy progression marking in image B9 (outlined by black arrows and called 'prominent arrest line') has a definite width in image B11 with two demarcations. It is possible that this was a hard landing whereby a small amount of tensile crack extension occurred between the two demarcations, the first one being a crack 'jump' and the second an 'arrest' (the resolution in the report is insufficient to check/evaluate this hypothesis).

[1] Updated following Fox comments 16 Mar 2022

2. There does not appear to be a systematic increase in striation or progression spacings with increasing crack length (depth). There is almost a uniform progression along the fracture surface. I think that we have a unique case of decreasing ΔK fatigue, whereby the striation spacings remain fairly uniform and appear to be "constant amplitude" in nature*. (e.g. The fine striations going back to O.114 mm from the origin look predominantly CA). Measuring batches of striations at different locations could prove this. Load shedding into the doubler or adjacent fasteners as the crack grows may explain this behaviour.

*This appears consistent with your (Fox) striation density chart.

3. You can see separate crack fronts, especially along the front indicated by the black arrows in the overall view. This is the reverse of what usually happens during ΔK-increasing FCG, but typical for near-threshold ΔK-decreasing FCG (see RJH Wanhill and SA Barter, Ref 9).

4. Crack 'arrest' markings are most probably simply progression markings, owing to local peak loads: see observation (1) above.

5. In Fig. B10 the 'hairpin' features (loops pointing back to the origin are typical of topographical interference of low stress intensity FCG by constituent particles.

6. It appears that for all 3 spars (A-C) the source of fatigue nucleation is corrosion pits. Corrosion pits are generally time-dependant (i.e. it generally takes some in-service time to produce a pit that will nucleate fatigue). However: "However, the area near the origin was obscured by oxidation and paint deposits." This may indicate the corrosion pit was present from the time of manufacturing. Given that, and the common nucleation source for Spars A-B, I would argue that fatigue commenced near day one. Establishing the fatigue nucleation time is critical in determining a CG curve.

Analyses of other aircraft incidents (Ref 2 to 4) do not always specifically identify the source of nucleation and corrosion pits are not specifically mentioned.

7. There is almost no final rupture (i.e. quasi static failure) on the image B9, indicating that the overall stress levels during FCG were probably low. The critical crack size appears to be approximately 10mm deep.

8. No observable corrosion band marks within the crack surface. Thus, no correlation with extended periods of down-time etc.

9. There appears to be no sign of anomalous or rogue flaws or material deficiencies.

10. The following maximum crack depths and flight hours were estimated from the figures in the stated references:

	maximum crack depth (mm)	Flight Hours
Spar A Ref 1	3.4	5959
Spar B Ref 1	11.79	9378
Spar C Ref 1	4.5 Over-stress	5240
N8191U Left Ref 2	12.5	7488
N104ER Left Ref 3 Fig 20	3.02	7660.7
N106ER Right Ref 3 Fig 16	1.19	7690.6
N106ER Left Ref 3 Fig 5	22	7690.6
N2093 Right Ref 4	6.7	11600

11. The crack growth analyses conducted so far (as available in the public domain) have provided classic Damage Tolerance and Durability analyses. These are not failure analyses. We now know classical da/DN data under-estimates the growth of small cracks near the origin and over-estimates growth close to rupture.

    The best estimates of usage spectra used in the publicly available analyses may not apply to some/all aircraft and will thus not be considered further.

12. Relevant flight data or weight records or history are unavailable.

Considerations:

a. It appears unlikely that more flight data histories will become available. Efforts should continue to relate prominent surface markings to calendar dates. Considering this, further quantitative fractography may not be of benefit.
b. The crack growth for Spar B appears relatively constant over the entire depth.
c. In light of a. the one known means of estimating the crack growth (and rate) for the cracked spars is the Lead Crack Framework, Ref 5. Whilst training for the NTSB on this method is highly desirable, it should be noted that the method is highly peered reviewed and applied to several airframes most notable for the Royal Australian Air Force.
d. With a regulator's perspective the method used to estimate crack growth curves must be conservative.
e. Despite the nucleating source (many of which require further determination) the crack-like effectiveness of the nucleating source is significant.
f. It is acknowledged that reported flight hours are at best estimates and whether the usage of each aircraft can be considered approximately uniform across their flight histories cannot be established with certainty.

Caveats:

i. Despite the nucleation source it is assumed that the cracks grew from near entry into service.
ii. It is assumed that the usage is approximately uniform across the aircraft's flight history.
iii. Flight hours are used in the following assessment, but other cyclic load sources may be important e.g. GAG cycles.

iv. The estimating of a typical nucleating discontinuity effectiveness for a specific material and surface finish is a work in progress. The author's main activities have involved AA7050 e.g. Ref 6 & 7. The effectiveness of a limited number of corrosion pit nucleated fatigue has also been considered (e.g Ref 7 & 8). AA2024 has not been specifically considered by the author. It is the author's opinion that considering the limited statistically-sound analyses, a typical nucleating size for aerospace AA materials and surface finish is 0.01 mm deep. This will be used in the preliminary assessment below including for a corrosion pit. I note that Ref 1. estimated the pit depth as 0.015mm.

v. The critical crack size can be taken as 10mm deep.

Analyses:

The Ref 1 related analyses of striation spacing supports the premise of exponential crack growth, see Figure 1. However, a linear growth curve is also possible in this case (see Figure 1) given some of the observations reported above. For the purposes of conservatism an exponential growth model is used below.

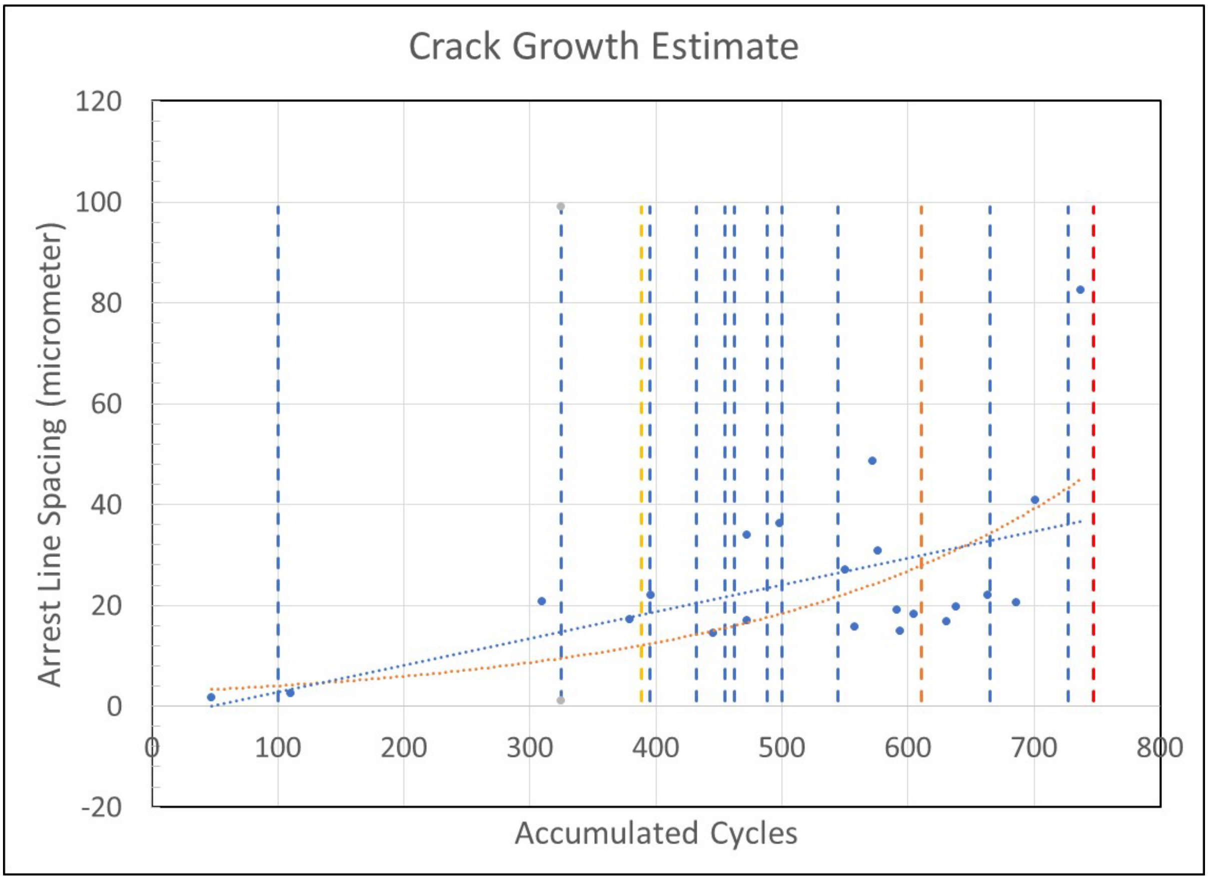

Figure 1: Striation spacing versus accumulated cycles on the fracture surface of Spar B, from Fox, Ref 1. The red line represents the best fit exponential curve and the blue dashed line the best fit linear line.

Using the available estimated flight hours versus maximum crack depth (See Table above), the lead crack framework has been applied (with caveats as outlined above) to produce Figure 2.

Discussion:

Given the uncertainties in the load/stress/weight history of the aircraft considered, in this author's opinion the level of scatter in the crack growth is low. It is instructive to note the similar crack growth estimated behaviour of Spar B and Aircraft N104ER left wing, and Spar A, N8191U and N106ER left.

It is important to note that there may be a faster crack growth rate in the fleet of aircraft in service. However, given the view on scatter, the crack growth curve for Spar A may be appropriate for in-service actions.

Conclusions

The lack of in-service histories of the subject aircraft may mean that further quantitative fractography may be of limited value. Efforts may be best spent in better defining the type and size of the nucleating discontinuities.

Given the availability of maximum crack depth versus estimated flight hours and subject to the caveats and assumptions listed above, the lead crack framework has been applied to estimate the crack growth curves for the subject aircraft.

It is noted that Spar B appears not to be the fastest growing crack found to-date.

Further recommendations will follow separately.

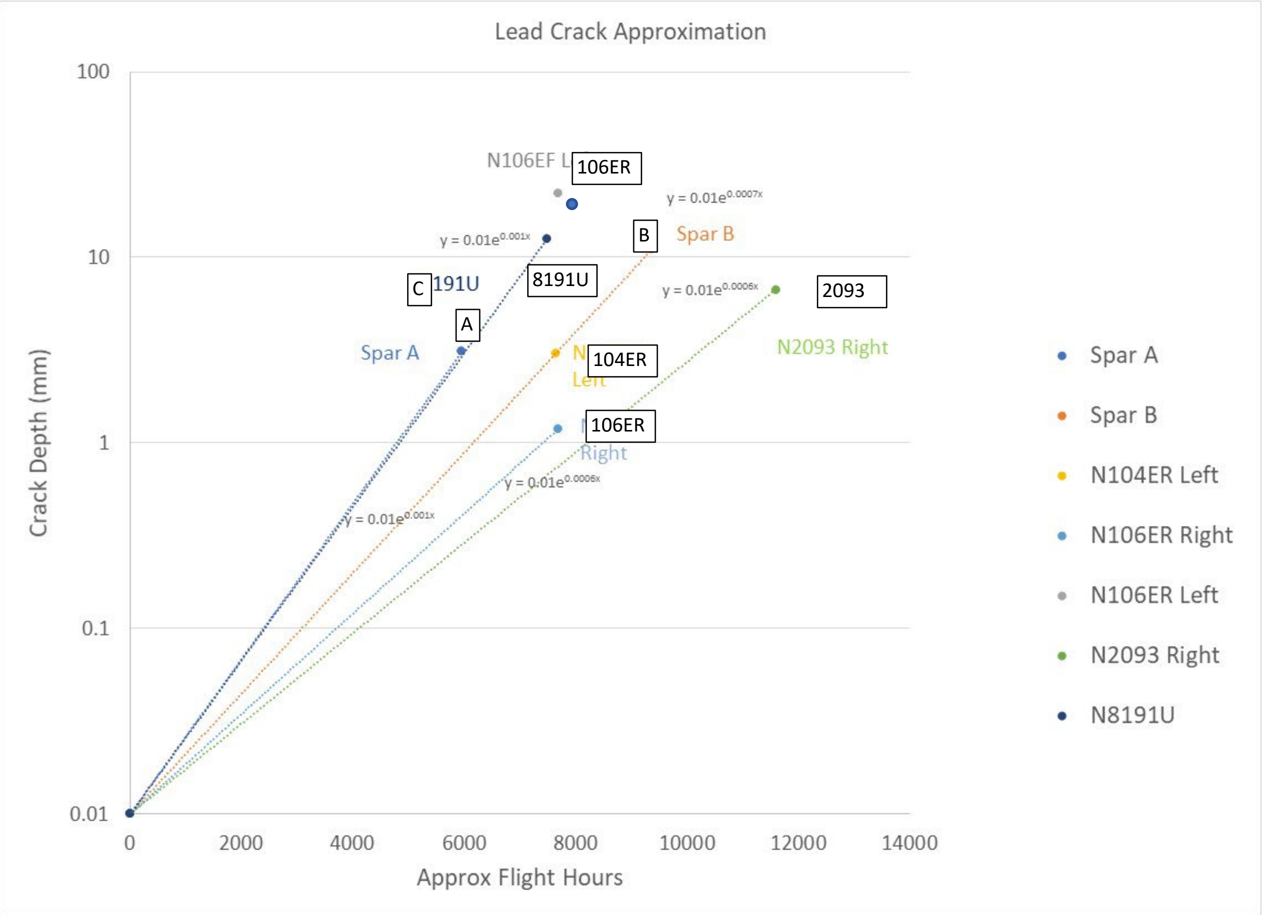

Figure 2: Preliminary estimates of crack growth curves for available cases.

L. Molent
16 March 2022

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Loris Molent AM – Director
ABN 655464494
Phone: +61 413 474 318
E: clanmolent@bigpond.com