Nationaal Lucht- en Ruimtevaartlaboratorium
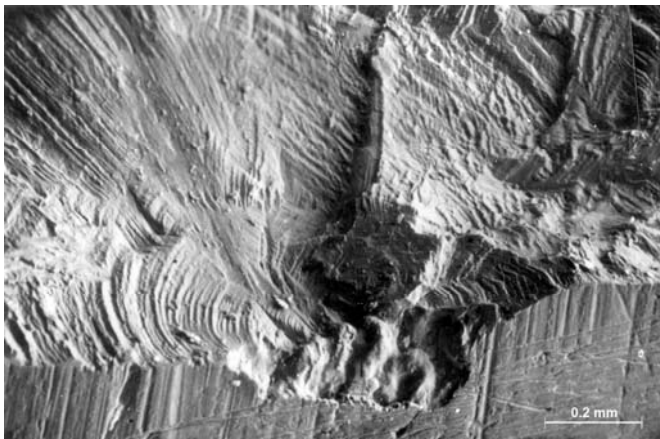
National Aerospace Laboratory NLR

Executive summary

Fatigue crack initiation in aerospace aluminium alloys, components and structures

Crack initiation from a corrosion pit on a propeller blade

Problem area

Self-healing of fatigue cracks in aluminium alloys.

Description of work

This report surveys fatigue crack initiation in aerospace aluminium alloys, components and structures.

Results and conclusions

It self-healing of fatigue cracks occurs in underaged aluminium alloys, it is limited to internal slip band cracks ~ 1µm.

Self-healing should be considered inapplicable in practice to aerospace aluminium alloys, components and structures.
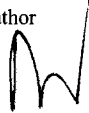
This report is based on a paper submitted to the First International Conference on Self Healing Materials, Noordwijk, the Netherlands, 18-20 April 2007.

Fatigue crack initiation in aerospace aluminium alloys, components and structures

NLR-TP-2006-751

Fatigue crack initiation in aerospace aluminium alloys, components and structures

R.J.H. Wanhill

This publication has been refereed by the Advisory Committee AEROSPACE VEHICLES.

Customer	National Aerospace Laboratory NLR
Contract number	----
Owner	National Aerospace Laboratory NLR
Division	Aerospace Vehicles
Distribution	Unlimited
Classification of title	Unclassified
	September 2007

Approved by:

Author	Reviewer	Managing department
7/09/2007	16/9/07	19/09'07

Summary

The concept of self-healing fatigue cracks in aluminium alloys has aroused much interest due to a recent paper by Lumley *et al.* in the journal Materials Forum, Vol. 29, pp. 256-261 (2005). The results of fatigue tests, fractography, and microstructural analysis for an underaged (UA) and peak aged (PA) experimental Al-Cu-Mg-Ag alloy were interpreted as evidence for possible self-healing of small internal fatigue cracks in the UA material. The present paper reviews some fatigue studies on UA, PA and overaged (OA) aluminium alloys, and surveys fatigue crack initiation in aerospace aluminium alloys, components and structures. It is concluded that whether or not self-healing of fatigue cracks actually occurs in some aluminium alloys, it should be considered inapplicable in practice.

Contents

FATIGUE CRACK INITIATION IN AEROSPACE ALUMINIUM ALLOYS, COMPONENTS AND STRUCTURES

R.J.H. Wanhill
National Aerospace Laboratory NLR
P.O. Box 153, 8300 AD Emmeloord
The Netherlands
e-mail:wanhill@nlr.nl

Abstract

The concept of self-healing fatigue cracks in aluminium alloys has aroused much interest due to a recent paper by Lumley *et al.* [1]. The results of fatigue tests, fractography, and microstructural analysis for an underaged (UA) and peak aged (PA) experimental Al-Cu-Mg-Ag alloy were interpreted as evidence for possible self-healing of small internal fatigue cracks in the UA material. The present paper reviews some fatigue studies on UA, PA and overaged (OA) aluminium alloys, and surveys fatigue crack initiation in aerospace aluminium alloys, components and structures. It is concluded that whether or not self-healing of fatigue cracks actually occurs in some aluminium alloys, it should be considered inapplicable in practice.

Keywords: aluminium alloys, aerospace, fatigue, self-healing

1   Introduction

There is currently much interest in the concept of self-healing fatigue cracks in aluminium alloys, owing to a recent paper by Lumley *et al.* [1]. The results of fatigue tests, fractography and microstructural analysis for an experimental Al-Cu-Mg-Ag alloy in an underaged (UA) and peak aged (PA) condition were interpreted as evidence for possible self-healing of small internal fatigue cracks in the UA material.

The present paper first considers fatigue studies of UA, PA and also overaged (OA) aluminium alloys, particularly the work of Lumley *et al.* [1] and Finney [2]. Then there are surveys of fatigue crack initiation in aerospace aluminium alloys, components and structures. The subsequent discussion shows that self-healing of small internal fatigue cracks, whether or not it occurs in some aluminium alloys, should be considered inapplicable in practice to aerospace aluminium alloys, components and structures.

2   The fatigue study by Lumley *et al.* [1]

Lumley *et al.* [1] conducted high-cycle reversed-stress unnotched fatigue tests on extruded bars of an experimental silver-containing aluminium alloy with the composition Al-5.6Cu-0.45Mg-0.45Ag-0.3Mn-0.18Zr by weight. The alloy was in two heat-treatment conditions: underaged (UA) and T6 peak aged (PA). The fatigue results are shown in figure 1 and demonstrate generally longer fatigue lives for the UA material.

Scanning Electron Microscope fractography showed that fatigue crack initiation was internal [1, 3], which is unusual for aluminium alloys. Microstructural analysis by Transmission Electron Microscopy led to the conclusion that during fatigue the dislocations in the UA material became saturated with free solute copper atoms. This would be expected to reduce the general mobility of dislocations, but some might transport solute to small initiating fatigue cracks and close them. This self-healing concept is illustrated schematically in figure 2.

Lumley *et al.* [1] proposed that one or both effects, i.e. a general reduction in dislocation mobility and the closing of small internal fatigue cracks could delay crack initiation and result in longer fatigue lives for the UA material. They also suggested a third possibility, that crack initiation might be delayed by localised matrix hardening due to dynamic precipitation. However, it is the self-healing concept that has gained the most attention.
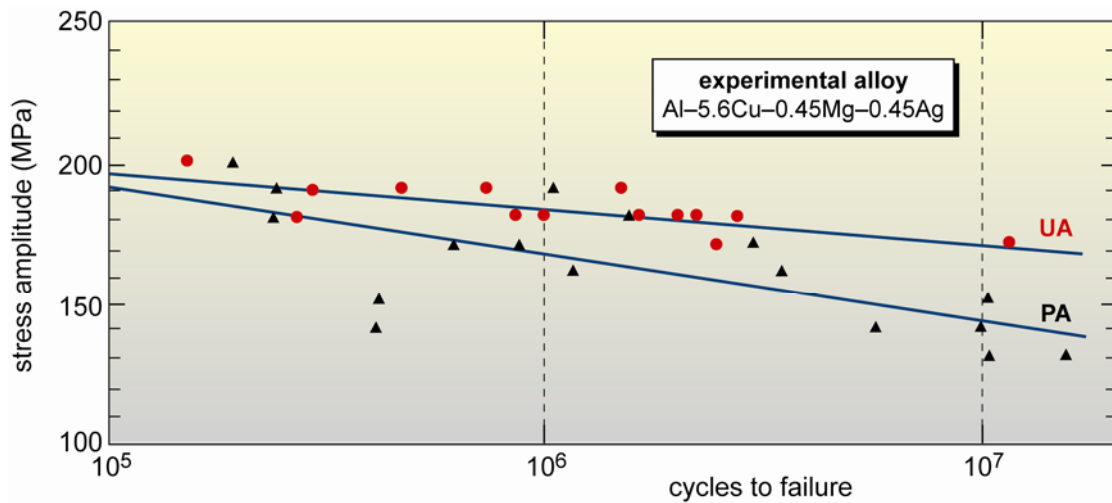
Fig. 1   Fatigue life data for the experimental Al–Cu–Mg–Ag alloy [1]
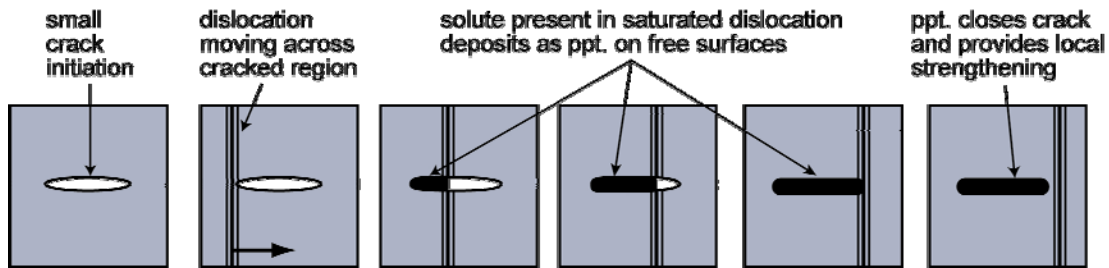
Fig. 2   Proposed self-healing mechanism for the UA experimental Al–Cu–Mg–Ag alloy [1]

3   The fatigue study by Finney [2]

Information on the effect of ageing on aluminium alloy fatigue properties was limited at the time of Finney's study [2], and is summarised in table 1. The only consistency is that OA materials never had the best fatigue properties.

Table 1 Summary of ageing effects on aluminium alloy fatigue known before 1969

Alloy type	Fatigue life ranking*	Reference
D.T.D. 683: commercial AlZnMgCu alloy	PA > OA >ST	Broom *et al.* [4]
Al-7Mg: experimental alloy	ST = UA = PA	Stubbington [5]
2014: commercial AlCuMg alloy	ST = UA > PA & OA	Form [6]
2014: commercial AlCuMg alloy	UA > PA	Fricke [7]
Al-7.5Zn-2.5Mg: experimental alloy	ST = PA > OA	Stubbington [8]

* ST: solution treated; UA: underaged; PA: peak aged; OA: overaged

Owing to the limited and inconsistent prior data, Finney set up a study of UA, PA and OA experimental and commercial variations of two AlCuMg alloys. The experimental alloys were Al-2.35Cu-1.3Mg and Al-4.18Cu-0.69Mg by weight. The commercial alloys were D.T.D. 5014 (equivalent to AA 2618) and B.S. 2L.65 (similar to AA 2014). Their compositions were respectively Al-2.4Cu-1.51Mg-0.87Fe-0.86Ni-0.24Si-0.03Mn-0.02Zn and Al-4.0Cu-0.72Mg-0.2Fe-0.67Si-0.77Mn-0.06Zn by weight. The main differences between the experimental and commercial alloys were the presence of iron, nickel and silicon in D.T.D. 5014, and iron, silicon and manganese in 2L.65.

Finney conducted high-cycle rotating cantilever unnotched fatigue tests on the four alloys in UA, PA and OA conditions. Figure 3 shows the fatigue results from 10^5 cycles onward. There are several points to note:

(1)   The fatigue rankings for the experimental alloys were UA > PA > OA.
(2)   The fatigue rankings for the commercial alloys were different:
-    The Al-2.4Cu-1.51Mg (D.T.D. 5014) alloy fatigue rankings were PA > UA > OA out to 10^7 cycles. From 10^7 to 10^8 cycles the differences gradually vanished.
-    The Al-4.0Cu-0.72Mg (2L.65) alloy fatigue rankings were UA = PA > OA.
(3)   The fatigue strengths at 10^8 cycles are given in the following table.

Table 2 Summary of fatigue strengths from Finney's test data [2]

Alloy type	Fatigue strength at 10^8 cycles (MPa)		
	UA	PA	OA
Al-2.35Cu-1.3Mg : experimental	166	133	93
Al-2.4Cu-1.51Mg : commercial	135	137	135
Al-4.18Cu-0.69Mg : experimental	169	~ 140	88
Al-4.0Cu-0.72Mg : commercial	220	220	171

From table 2 it is seen that:
-    The experimental alloys had similar fatigue strengths in all three conditions.
-    The commercial Al-4.0Cu-0.72Mg (2L.65) alloy had significantly higher fatigue strengths than the commercial Al-2.4Cu-1.51Mg (D.T.D. 5014) alloy in all three conditions.
-    In the UA condition the Al-2.35Cu-1.3Mg experimental alloy had a higher fatigue strength than its commercial equivalent, but the reverse held for the experimental Al-4.18Cu-0.69Mg and its commercial equivalent.
-    As for the previous investigations, table 1, the only overall consistency is that OA materials never had the best fatigue properties.

Finney used optical fractography to qualitatively determine the fatigue fracture modes. He found a good correlation, not entirely consistent, with the fatigue rankings at 10^7 cycles, see table 3. From this correlation he proposed that slip band (Stage I) fatigue is a slower cracking process than tensile mode (Stage II) fatigue, since the plastic deformation is dispersed and not concentrated at a single crack tip. Consequently, conditions resulting in slip band fatigue should lead to better fatigue resistance [2].

Table 3 Fatigue fracture modes and rankings at 10^7 cycles: Stage I = slip band cracking

Al-2.35Cu-1.3Mg : experimental Al-4.18Cu-0.69Mg : experimental	UA > mainly Stage I	PA > small Stage I	OA little/no Stage I
Al-2.4Cu-1.51Mg : commercial	PA > small Stage I	UA > mainly Stage I	OA little/no Stage I
Al-4.0Cu-0.72Mg : commercial	UA = mainly Stage I	PA > mainly Stage I	OA little/no Stage I

However, Finney's data extend beyond 10^7 cycles, where one would expect the fatigue lives and strengths to be dominated by crack initiation and possibly a small amount of microcrack growth [9, 10]. Other work, to be discussed in section 5 of this paper, showed that inclusions and dispersoids in commercial alloys can affect crack initiation, and it was noted above that Finney's commercial alloys contained iron, nickel, silicon and manganese, which are inclusion- and dispersoid-forming elements.

Finally, Forsyth [11] commented briefly on the UA > PA > OA ranking of one of Finney's experimental alloys. He suggested – somewhat indirectly – that the superior fatigue strength of the UA material could be due to S' precipitation on dislocations, resulting in dislocation pinning.
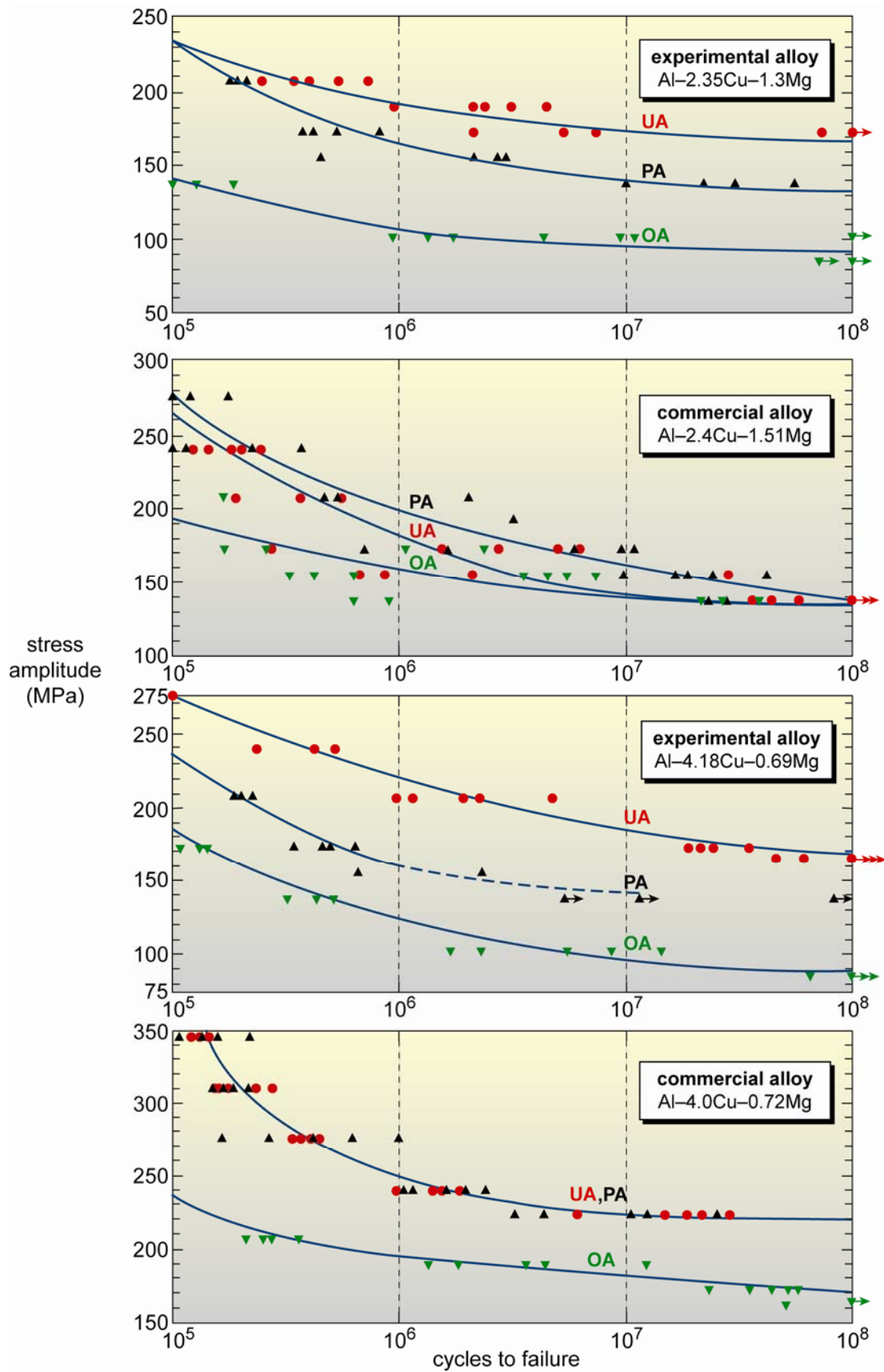
Fig. 3 Finney's [2] fatigue life data from 10^5 cycles onward

4   Comparison of the data of Lumley et al. [1] and Finney [2]

Figure 4 compares the UA and PA experimental alloy data points from Lumley *et al.* [1] with the appropriate fatigue life curves from Finney [2]:

(1)   Beyond 10^6 cycles Lumley's UA data points agree well with Finney's UA curve for the Al-2.35Cu-1.3Mg alloy.

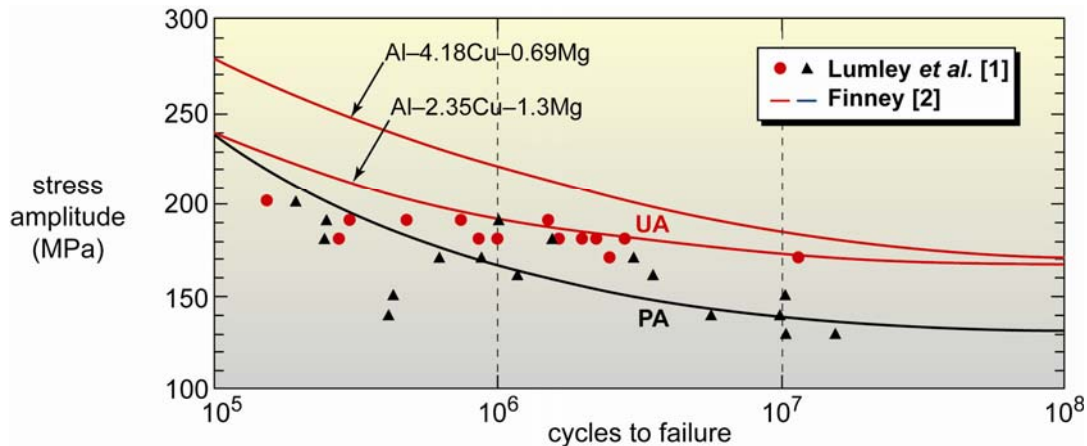(2)   Over the whole range of fatigue lives, Lumley's PA data agree with the PA curve for both of Finney's alloys.

Fig. 4   *Comparison of the fatigue properties of the UA and PA experimental alloys of Lumley* et al. *[1] and Finney [2]*

The agreements shown in figure 4 are in the first instance remarkable, since the alloys had relatively large differences in copper contents, and the alloy of Lumley *et al.* contained silver, which is a potent age-hardening element when added to AlCuMg alloys [12]. On the other hand, the solid solution content of copper in the UA alloys may have been similar [13]. In any event, it seems that the high-cycle fatigue properties were not strongly determined by differences between the alloys in the amount of precipitation hardening up to peak strength.

5   Fatigue crack initiation in aerospace aluminium alloy specimens

5.1   External or internal initiation
Fatigue cracks in high-strength aerospace aluminium alloy specimens nearly always initiate at external surfaces. This is the case even in gigacycle fatigue, where internal crack initiation is otherwise the rule for high strength steels and titanium and nickel alloys [14]. One practical exception is when the aluminium alloy surfaces have been shot-peened [15], see subsection 5.4.

5.2   Large inclusions
Over the last 50 years there have been numerous investigations of fatigue crack initiation in high-strength aluminium alloys, e.g. Refs. [2, 9, 11, 16-24]. In some of the earlier work there was an understandable tendency to focus on crack initiation and development along slip bands [2, 9], and it was not recognised that fatigue cracks could initiate at large intermetallic particles (inclusions) unless they were already cracked [9]. However, further studies showed that fatigue cracks nucleate at both cracked and uncracked inclusions, and that these are the predominant sites of fatigue crack initiation in commercial alloys [16-18, 20-24].

Figure 5 gives examples of fatigue crack initiation at cracked and uncracked inclusions in two commercial alloy specimens, tested under widely different conditions (unnotched *versus* notched, constant amplitude loading *versus* flight simulation loading). Note that figure 5a refers to the same alloy specification, D.T.D. 5014, of one of the commercial alloys studied by Finney [2]. The inclusions

11

in figure 5a are FeNiAl$_9$, and are characteristic of this alloy, though they need not always be cracked [11].
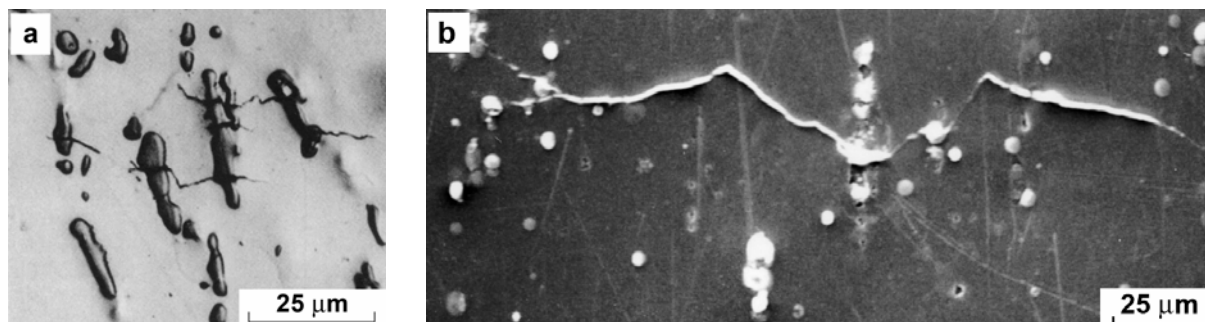

Fig. 5   Fatigue crack initiation at (a) cracked inclusions in a smooth specimen of D.T.D. 5014 tested presumably under constant amplitude loading, and (b) uncracked inclusions in a notched ($K_t = 3.2$) specimen of 2024-T3 tested under gust spectrum loading [11, 25]

The sizes of the inclusions in figure 5 are typical. FeNiAl$_9$ is specific to iron- and nickel-containing alloys, but there are several kinds of large inclusions that commonly occur in commercial alloys, including Al$_7$Cu$_2$(Fe,Cr), (Fe,Mn)Al$_6$, Mg$_2$Si and Al$_2$CuMg [23, 24, 26, 27]. Recent quantification of the sizes of inclusions associated with fatigue crack initiation shows that they often reach depths of 10 – 20 µm into the specimen surface [23], but their overall dimensions can be much larger [23], see figure 6.

Although inclusions are evidently associated with fatigue crack initiation, and there is general agreement that the cracks initially follow the inclusion/matrix interfaces [11, 16-18, 20-23, 25], opinions differ as to whether interfacial debonding is involved [18, 20-23]. Also, it appears that some cracks may start from processing voids between closely-spaced inclusions [21].

Figure 7 suggests that interfacial debonding could well be involved in fatigue crack initiation. Several inclusion/matrix interfaces in an inclusion cluster have debonded during (R = 0.7) near-threshold fatigue crack growth [28], where there is a minimum of possible crack closure and cyclic plasticity to disturb the appearance of debonding. Note the magnification: optical and low-magnification SEM microscopy, as used in Refs. [16, 18, 20-23], will not resolve such details, if present and TEM of replicas [16-18] appears generally unsuitable. The interfacial debonding is most likely due to dislocation pile-ups at the inclusions.

Owing to the importance of inclusions in nucleating fatigue cracks, Grosskreutz and Shaw investigated the effect of reduced inclusion content on high-cycle reversed-stress notched fatigue of the AlCuMg alloy 2024 [17]. An experimental alloy, X2024-T4, was obtained with more than ten times fewer inclusions larger than 10 µm. Figure 8 shows that a relative *absence* of large inclusions has a beneficial effect on fatigue compared with commercial 2024 alloys, but the improvement is not large.

5.3   Dispersoids and small inclusions
There are some data on the effects of dispersoids, about 1µm in size, and small inclusions in the 0.1 – 0.2 µm size range, on high-cycle fatigue of high-strength aluminium alloys [11, 19, 29]. Unlike large inclusions, the *presence* of these smaller particles can have a beneficial influence on fatigue. This is shown in figure 9, which may be compared with figure 8.

The effects of dispersoids in figure 9a may be due partly to preventing recrystallization and retention of a fine grain size [11, 29], which would have prevented long dislocation pile-ups along fatigue-induced slip bands, thereby reducing the stress concentrations leading to crack nucleation. However, the dispersoids would also have helped to prevent cyclic slip concentration in narrow bands, as did the small inclusions in the commercial 2024 alloy of figure 9b [19].
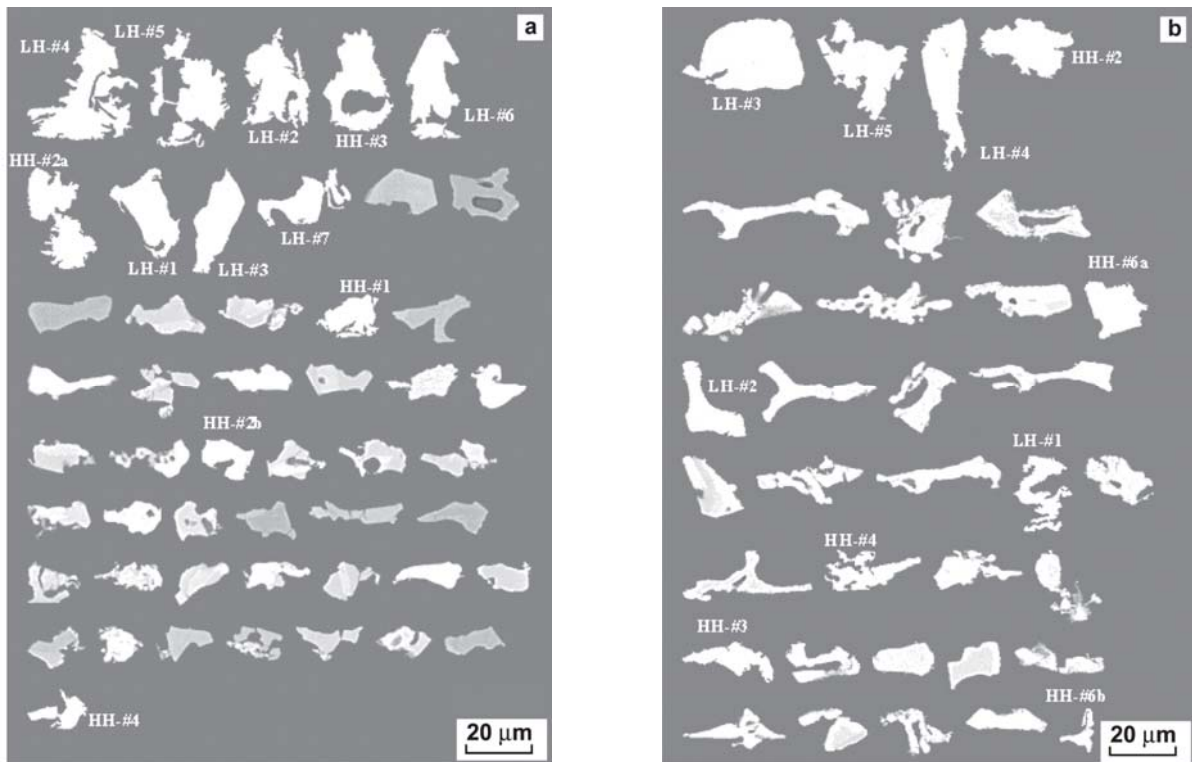
Fig 6   Comparison between fatigue-initiating inclusions and those obtained from metallographic sectioning of the short-transverse planes of (a) thin and (b) thick 2024-T3 [23].
The fatigue-initiating inclusions are indicated by specimen numbers. The inclusions are arranged from left to right and from top to bottom in descending order of size (area)
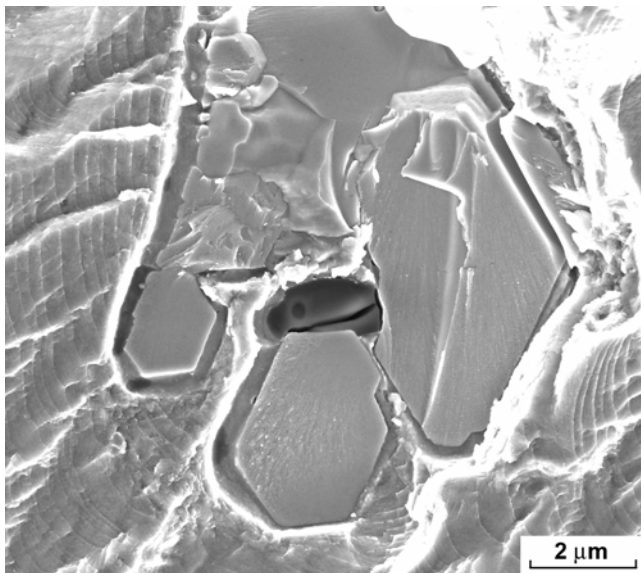
Fig. 7   Inclusion/matrix debonding during near-threshold fatigue crack growth in OA 7075-T7351 plate [28]. The crack front markings are due to low-frequency growth measurements every 10,000 cycles
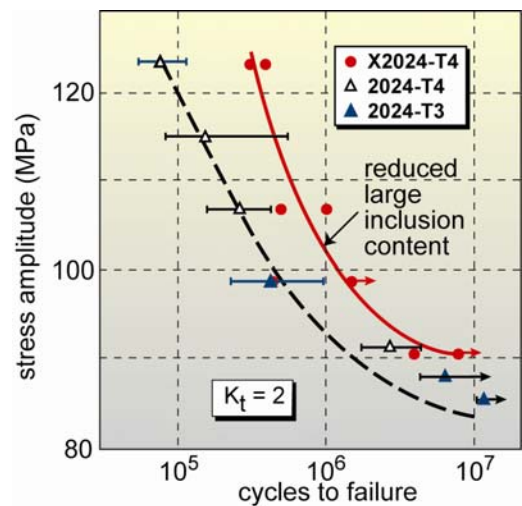
Fig. 8   Effect of reduced inclusions content on notched fatigue of experimental (X) and commercial UA 2024 alloys [17]
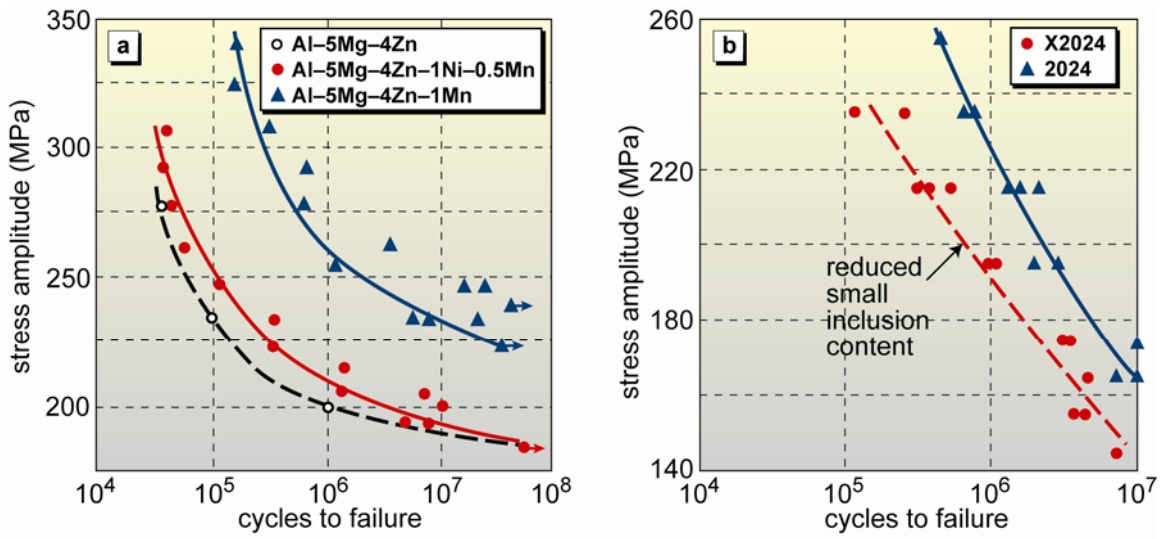
Fig. 9   Effects of (a) adding Mn- and Ni-containing dispersoids to a ternary PA AlMgZn alloy
[11, 29] and (b) reducing the small inclusion content of UA 2024 [19] on the unnotched
fatigue properties
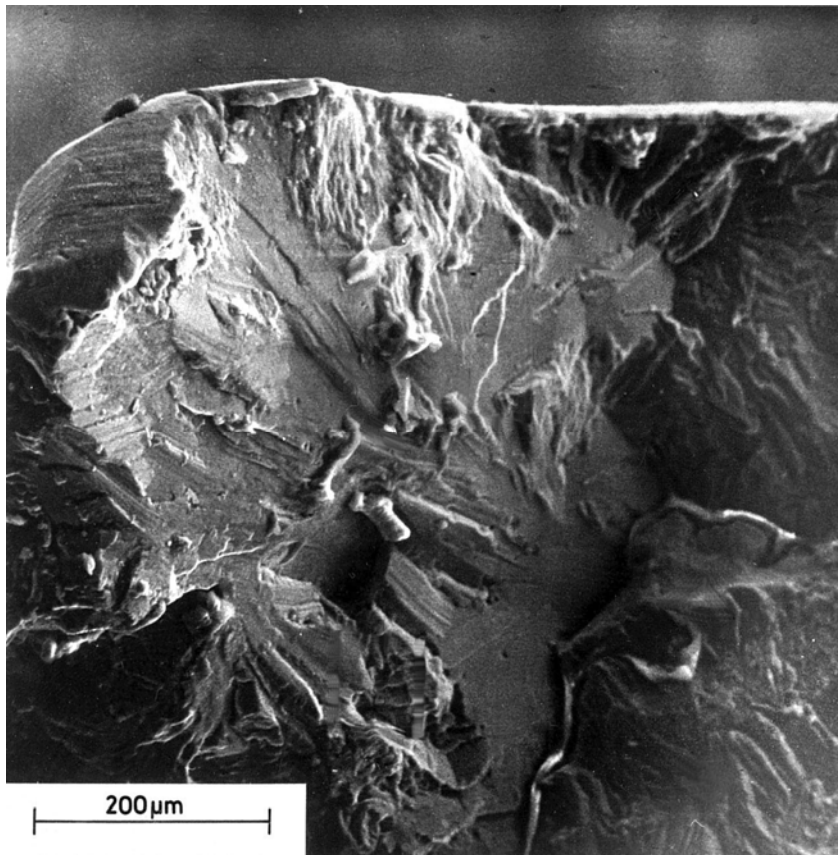
Fig. 10   Internal high-cycle fatigue crack initiation in a shot-peened
unnotched specimen from a 7079-T652 (PA) forging, tested
under axial loading [15]

14
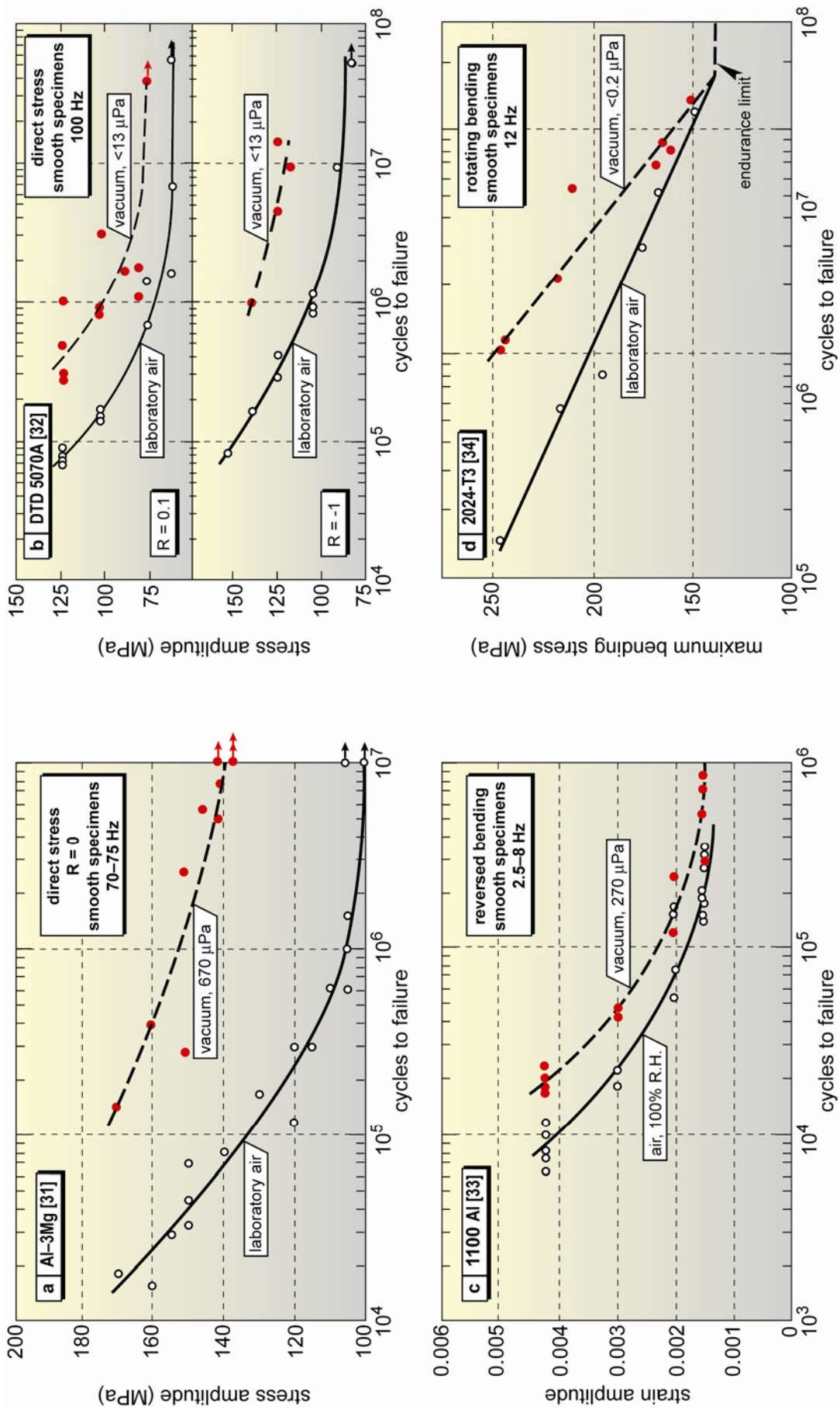
Fig. 11 Effects of vacuum fatigue, as compared to fatigue in air, for several aluminium alloys: D.T.D. 5070A is Al–2.5Cu–1.5Mg–1.0Fe–1.2Ni–0.25Si sheet in the PA condition and clad with Al–1.0Zn on the sheet faces; 1100 Al is effectively unalloyed aluminium

5.4   Initiation in air and *in vacuo*

Lumley *et al.* [1, 3] observed that the fatigue cracks in their specimens initiated internally. Since internal cracks initiate *in vacuo* [15, 30], it is appropriate to compare the effects of vacuum and air environments on the fatigue of aluminium alloys. Figure 10 shows subsurface fatigue crack initiation in a shot-peened specimen [15]. The faceted appearance of the initiation site is typical for vacuum fatigue [31], and is due to extensive slip band (Stage I) cracking [15].

Several investigations have shown that the high-cycle unnotched fatigue lives of aluminium alloys can be longer *in vacuo* than in air. Some results show life differences for up to $10^7 - 10^8$ cycles [31, 32, 35, 36], e.g. figures 11a and 11b. Other data indicate little or no effect at long lives [32-34, 37], see figures 11c and 11d.

Fatigue cracks initiate at the same time [31, 36, 38] or later [33, 39] *in vacuo* than in air. However, even in the latter case it appears that the major environmental effect is on crack growth, which is much slower *in vacuo* than in air, e.g. Refs. [31, 40-42].

6   Fatigue crack initiation in aerospace aluminium alloy components and structures

Probably the most widespread, though not the most frequent, source of fatigue cracking in aerospace aluminium alloy components and structures is corrosion, which has led to failures in all types of aircraft and a variety of components [24, 43-49]. Corrosion pitting causing fatigue failures of propellers and rotor blades is particularly dangerous [45, 49]: only very small defects can be tolerated before rapid high-cycle fatigue initiates, e.g. figure 12, and the aircraft usually becomes uncontrollable.

Another common initiator of fatigue is fretting [47], notably at faying surfaces and in fastener and pin-loaded holes [50]. Fretting fatigue cracks initiate very early in the fatigue life [51-53]. For example, figure 13 shows a fretting-initiated fatigue crack in a fastener hole from a window frame of a transport aircraft full-scale test article [54]. This crack had initiated and grown during 45,402 simulated flights. Fractographic analysis enabled tracing crack growth back to 0.15 mm from the origin, and back-extrapolation to the origin indicated that fatigue effectively began immediately, as if there were an initial defect about 0.06 mm in size.

Other surface-related damages that act as fatigue initiation sites include manufacturing defects in fastener holes [55, 56], etch pits from anodising and other surface treatments [24, 46, 55, 57, 58], and fatigue cracking in cladding layers [23, 58-61]. Crack initiation from large inclusions, clusters of inclusions, porosity and other material discontinuities has also been observed [46, 55, 62].

Besides all these sources of fatigue, crack initiation can also occur owing to the stress concentrations at fastener-filled and open holes; double stress concentrations, e.g. knife-edges at fastener holes; fillet and blend radii; more or less abrupt changes in section thickness; cutouts; and higher than anticipated service stresses owing, for example, to secondary bending and excessive load transfer [63-70].

Some "milestone case history" examples of aircraft accidents involving fatigue in aluminium alloys are shown in figures 14-16 [71]. These, and others, notably the General Dynamics F-111 crash in 1969 [69, 71], have led to adoption of the Damage Tolerance design philosophy for military and transport fixed-wing aircraft, and Aviation Regulations requiring its use. This is also likely to be the case for helicopters [72].

There are some essential points to be made about the Damage Tolerance philosophy in the context of the present paper:

(1)   The concept of an initial crack-free fatigue life is abandoned. Instead it is assumed that defects (cracks and flaws) are already present at critical locations in new aerospace components and structures, and that these assumed defects must be treated as cracks that are immediately capable of growing by fatigue, albeit slowly.

(2)   The assumed defects are all surface-connected, for example table 4. When designing for *safety* the assumed defects are all larger than 0.5 mm. When designing for *durability* the

assumed defects are generally larger than 0.1 mm [73, 74] and unlikely to be smaller than 0.03 mm [25].

(3)   The assumed defects will be mostly at fastener holes. A large majority of fatigue cracks in aluminium alloy aircraft structures initiate at fastener holes in joints [70].

From the above information and remarks we may conclude that both actual and assumed initial damage and fatigue cracks in aerospace aluminium alloy components and structures are surface-related. The assumed initial defects are also much larger than actual ones, reflecting the necessary conservatism when designing safety-critical structural elements.
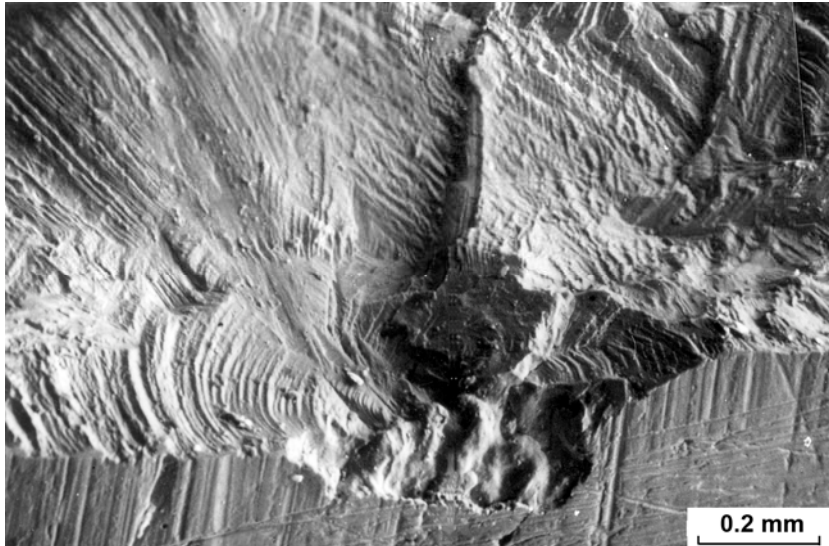
Fig. 12   Fatigue crack initiation from a corrosion pit on a 2014-T651 (PA) forged propeller blade [44]
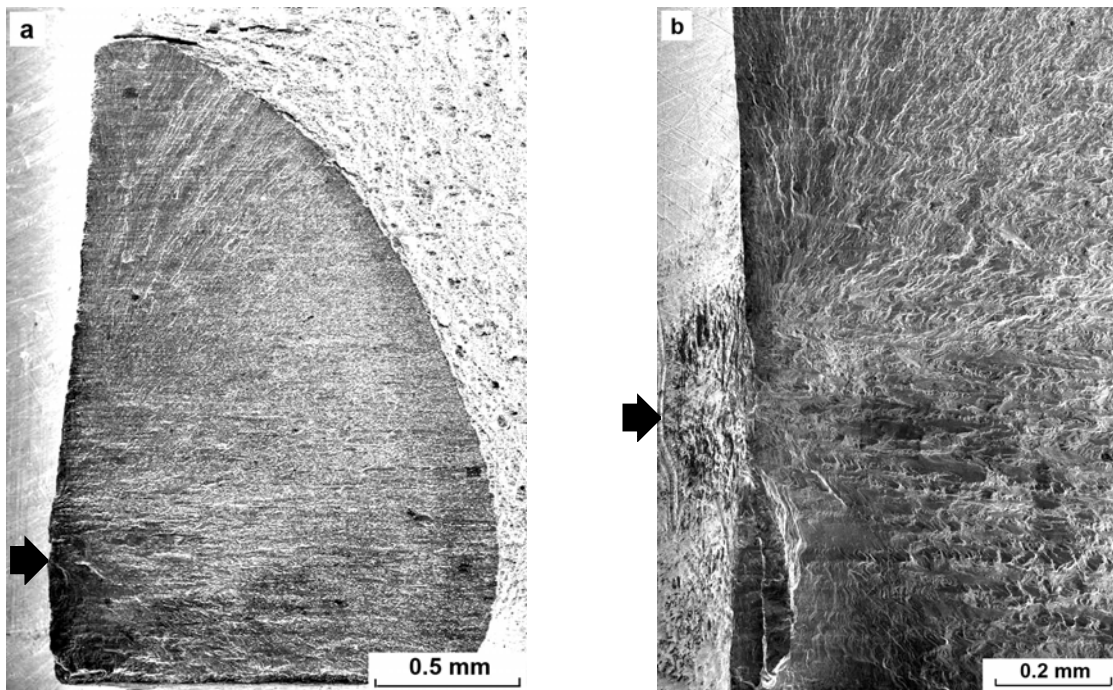
Fig. 13   Fatigue crack initiation owing to fretting in the bore of a fastener hole in a 7175-T73 (OA) forged window frame [54]. The arrows point to (a) the fatigue origin and (b) a detail showing the fretting scar
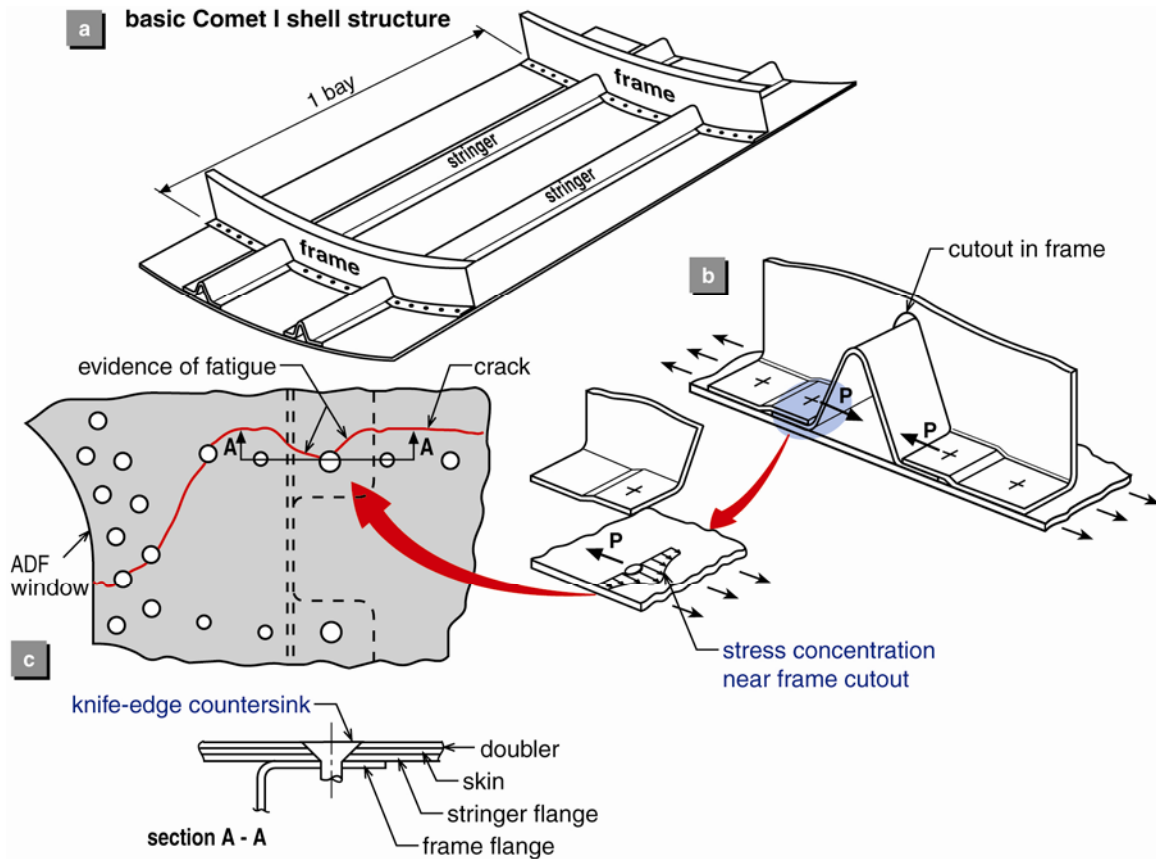
Fig. 14   Details of the probable failure origin in the pressure cabin of DeHavilland Comet
G-ALYP [64, 71], which was lost in January 1954. Figures 14a and 14b show the frame
cutouts to accommodate the stringers, and the resulting stress concentration at the first
fastener joining the frame and stringer flanges to the skin (and an outside doubler).
Figure 14c shows that the first fastener was a countersunk bolt, creating knife-edges in
both the skin and outside doubler. There was thus a double stress-concentration.
This combined with local unanticipated secondary bending to cause early fatigue failure
[64, 71]
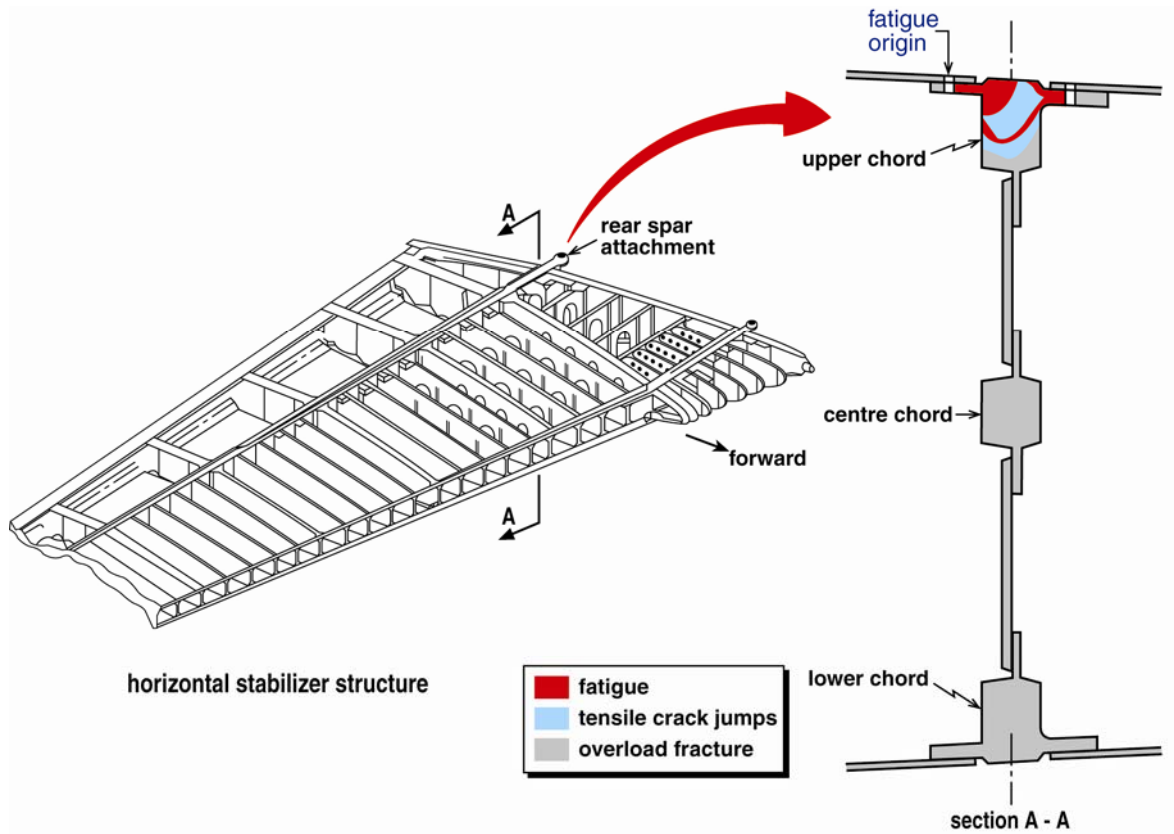
Fig. 15 Failure origin in the right-hand horizontal stabilizer of a Boeing 707-321C freighter [68, 71].
which was lost in May 1977. Fatigue initiated at a fastener hole in the upper chord of the
rear spar attachment to the skin, owing to higher loads than those anticipated in the design
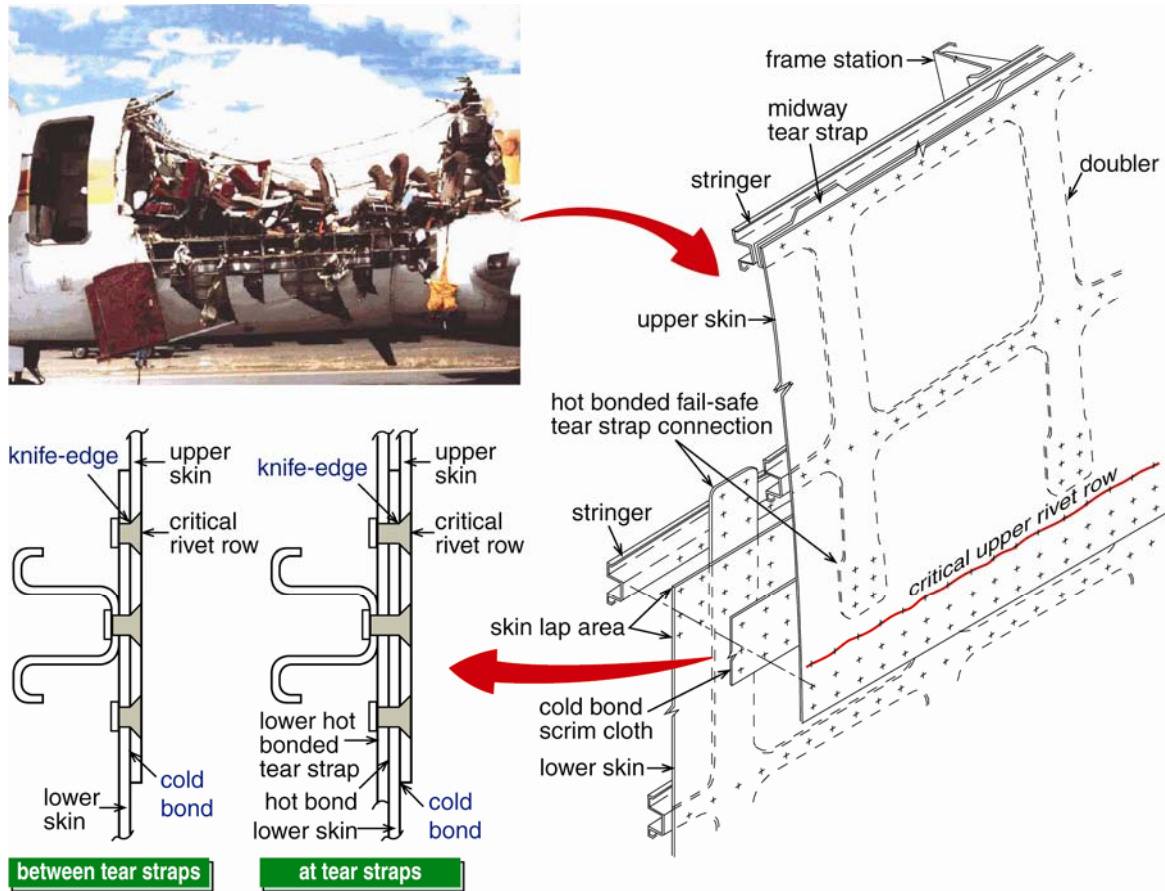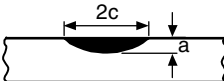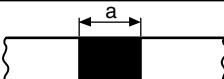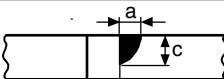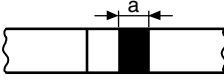
Fig. 16   *Structural aspects of the Boeing 737-200 accident in April 1988 (the famous Aloha Airlines case) [65, 71]. Defective cold bonding allowed moisture to enter the skin lap area. This led to corrosion-induced disbonding, both in the cold-bonded skin splice and the associated hot-bonded tear straps. The loss of skin splice integrity caused the pressure cabin loads to be transferred through the rivets. These had countersunk heads causing knife-edges in the upper skin, and the knife-edges caused stress-induced Multiple Site fatigue Damage (MSD) in the upper skin along the upper rivet row of the skin lap area [65, 71]*

Table 4   Example of Damage Tolerance safety requirements for assumed initial damage [73]

types of flaw		aspect ratio (a/c)	flaw size a (mm) to be assumed immediately after inspection		
description	geometry		pre-service inspection with high standard NDI		in-service inspection with special NDI
			fail-safe	slow flaw growth	
surface flaw		1.0 0.2	1.27	3.18	6.35
through crack			2.54	6.35	12.7
corner flaw at a hole		1.0 0.2	0.51	1.27	6.35 mm beyond fastener head or nut
through crack at a hole			0.51	1.27	6.35 mm beyond fastener head or nut

7   Discussion

7.1   The self-healing concept

The possible self-healing of fatigue cracks in UA aluminium alloys is subject to some constraints. Its occurrence should be limited to internal cracks, since cracks initiating at an external surface in an air environment will be contaminated by adsorption of water vapour and oxygen onto the crack surfaces [41]. This would likely prevent self-healing, and certainly promotes crack growth compared to fatigue *in vacuo* [31, 40-42].

There is also the question of crack size. If internal cracks were to nucleate at large inclusions, e.g. from dislocation pile-ups at the inclusion/matrix interfaces, then they would be expected to rapidly assume dimensions larger than 10 µm. This makes the idea of self-healing less feasible. On the other hand, internal cracks can initiate from slip band cracking [15], with no lower-bound restriction on the initial crack size.

However, there appears to be another problem. Slip band crack initiation and self-healing would both have to occur via the movement of dislocations, even if the self-healing dislocations do not actually cross the crack, as sketched in figure 2, but only deliver solute by pipe diffusion to the crack vicinity [75]. Lumley *et al.* [1] obtained evidence to suggest that the dislocations in their UA alloy became saturated with free solute copper atoms relatively early in the fatigue process. Since high-cycle fatigue crack initiation usually occurs late in life, there does not seem to be a reason why there should be two types of dislocation (unsaturated and saturated) that compete in initiating and self-healing events.

Be that as it may, there will be an upper-bound to the size of slip band crack that can be self-healed. This upper-bound could be when the crack becomes capable of generating dislocations from its tips. An analysis to this effect has been given by Tanaka and Akiniwa [76]. They considered a Stage I slip band crack in aluminium, and calculated that it can emit dislocations when the total length reaches 1.4 µm. This seems entirely reasonable for the upper-bound size of a self-healing crack.

21

7.2   High-cycle fatigue of UA and PA experimental aluminium alloy specimens

At the beginning of section 3 of this paper it was stated that the only consistency from pre-1969 studies of ageing effects on aluminium alloy fatigue is that overaged (OA) materials never had the best fatigue properties, see table 1. Finney's 1969 study [2] reinforces this conclusion, as may be seen from figure 3.

However, Finney's study and that of Lumley *et al.* [1] show a similar result, namely that their experimental alloys had better underaged (UA) high-cycle fatigue properties than the equivalent peak aged (PA) alloys, see figures 1, 3 and 4. The significance of this result in the present context is as follows:

(1)   Because these alloys were experimental, they were relatively large-grained owing to recrystallization during solution treatment [2] and grain growth [77]. They would also have been relatively free from large inclusions, and Finney's alloys would have had few dispersoids in the 0.1 – 0.2 μm size range. In the UA condition such relatively clean microstructures should favour the development of long slip bands during fatigue, and extensive and long Stage I fatigue cracks, as found for Finney's alloys [2], see table 3 also.

(2)   While Lumley *et al.* reported internal fatigue crack initiation for their reversed-stress UA and PA specimens [1, 3], Finney reported surface initiation for rotating cantilever specimens [2]. (This would be expected anyway, since the maximum fatigue stresses for rotating cantilever specimens are at the surface.)

From (1) and (2) one may conclude that the better fatigue properties of the UA experimental alloys cannot depend only on the delay of crack initiation by self-healing of small internal fatigue cracks. There are other possible mechanisms, already mentioned in sections 2 and 3. These are (a) reductions in dislocation mobility owing to their becoming saturated by free solute [1]; (b) dislocation pinning by precipitates [11]; and (c) localised matrix hardening due to dynamic precipitation [1]. Note that these mechanisms could apply to all the experimental alloy results, i.e. self-healing is not required.

7.3   High-cycle fatigue of UA and PA commercial aluminium alloy specimens

Depending on the alloy, and to some extent on the fatigue lifetimes between 10^6 and 10^8 cycles, see figure 3, the underaged (UA) commercial alloys had better [6, 7], similar [2] or worse [2, 4] high-cycle fatigue properties than their peak aged (PA) equivalents.

This lack of consistency suggests that the high-cycle fatigue properties of commercial alloys can be determined more by differences in grain size and inclusion and dispersoid contents than by the ageing condition up to peak strength. Also, the surveys in subsections 5.1 and 5.2 indicate that the predominant sites of fatigue crack initiation are large surface-connected inclusions. All in all, there seems to be little scope for the self-healing of small internal cracks to influence the basic fatigue properties of commercial alloys.

7.4   Aerospace aluminium alloy components and structures

The survey in section 6 of this paper shows that actual initial damage and fatigue cracks in aerospace aluminium alloy components and structures are surface-related, and a large majority will be at fastener holes in joints. Inevitably, this is also the case for the assumed defects when designing according to Damage Tolerance requirements. The minimum size of the assumed initial defects is at least 0.03 mm, and generally more than 0.1 mm.

The actual initial damages and fatigue cracks and Damage Tolerance requirements show that the concept of self-healing of small internal fatigue cracks is inappropriate to aerospace aluminium alloy components and structures.

8 Conclusions

The possible self-healing of fatigue cracks in underaged (UA) aluminium alloys is

(1) Limited to internal slip band cracks probably shorter than about 1.4 μm.

(2) Not capable of explaining the similar high cycle fatigue behaviour and/or rankings of UA and peak aged (PA) experimental alloys tested by Lumley *et al.* [1] and Finney [2]. Nor is it required for explaining why any UA experimental alloys can have better high-cycle fatigue properties than their PA equivalents.

(3) Unlikely to influence the basic fatigue properties of commercial alloys.

(4) Inapplicable in practice to aerospace aluminium alloy components and structures.

Acknowledgements

References

[1] R.N. Lumley, R.G. O'Donnell, I.J. Polmear and J.R. Griffiths, Enhanced fatigue resistance by underageing an Al-Cu-Mg-Ag alloy, Materials Forum, Vol. **29**, 256-261, 2005.

[2] J.M. Finney, The relationship between aged structure and the fatigue behaviour of aluminium alloys. Part II: experimental results of aluminium-copper-magnesium alloys, Aeronautical Research Laboratories Structures and Materials Report 325, Melbourne, Australia, July 1969.

[3] R.N. Lumley, Personal communication from CSIRO Manufacturing and Infrastructure Technology, Melbourne, Australia, 6th March 2006.

[4] T. Broom, J.H. Molineux and V.N. Whittaker, Structural changes during the fatigue of some aluminium alloys, Journal of the Institute of Metals, Vol. **84,** 357-363, 1955-56.

[5] C.A. Stubbington, Some observations on the fatigue behaviour of aluminium 7 per cent magnesium in various conditions of heat treatment, Royal Aircraft Establishment Technical Note No: Met.279, Farnborough, UK, November 1957.

[6] G.W. Form, A study on the relationship between state of aging and notch-fatigue performance of a high strength aluminum alloy, Transactions of the ASM, Vol. **52**, 514-527, 1960.

[7] W.G. Fricke, Jr., Written discussion to Ref. [6], Transactions of the ASM, Vol. **52**, 527-529, 1960.

[8] C.A. Stubbington, Some observations on air and corrosion fatigue of an aluminium–7.5% zinc–2.5% magnesium alloy, Metallurgia, Vol. **68**, 109-121, 1963.

[9] M.S. Hunter and W.G. Fricke, Jr., Metallographic aspects of fatigue behavior of aluminum, Proceedings, American Society for Testing and Materials, Vol. **54**, 717-732, 1954.

[10] J. Schijve, Significance of fatigue cracks in micro-range and macro-range, Fatigue Crack Propagation, ASTM STP 415, 415-457, American Society for Testing and Materials, Philadelphia, USA, 1967.

[11] P.J.E. Forsyth, The metallurgical aspects of fatigue and fracture toughness, AGARD Report No. 610, Metallurgical aspects of Fatigue and Fracture Toughness, 1-22, Advisory Group for Aerospace Research and Development, Neuilly sur Seine, France, December 1973.

[12] B.C. Muddle and I.J. Polmear, The precipitate Ω phase in Al-Cu-Mg-Ag alloys, Acta Metallurgica, Vol. **37**, 777-789, 1989.

[13] R.N. Lumley, Personal Communication from CSIRO Manufacturing and Infrastructure Technology, Melbourne, Australia, 15th November 2006.

[14] C. Bathias, Designing components against gigacycle fatigue, Proceedings of the International Conference on Fatigue in the Very High Cycle Regime, (editors S. E. Stanzl-Tschegg and H.M. Mayer), 97-109, Institute of Meteorology and Physics, University of Agricultural Sciences, Vienna, Austria, 2001.

[15] E.A.B. de Graaf, R.J.H. Wanhill and A.U. de Koning, Einfluß von Kugelstrahlen und Bohrungsaufweitung auf das Ermüdungsverhalten von AlZnMgCu-Proben, Aluminium, Vol. **51**, 514-519, 1975.

[16] J.C. Grosskreutz and G.G. Shaw, Mechanisms of fatigue in 1100-0 and 2024-T4 aluminum, Air Force Materials Laboratory Technical Report AFML-TR-65-127, Wright-Patterson Air Force Base, Ohio, USA, July 1965.

[17] J.C. Grosskreutz, G.G. Shaw and D.K. Benson, The effect of inclusion size and distribution on fatigue of 2024-T4 aluminum, Air Force Materials Laboratory Technical Report AFML-TR-69-121, Wright-Patterson Air Force Base, Ohio, USA, June 1969.

[18] J.C. Grosskreutz and G.G. Shaw, Critical mechanisms in the development of fatigue cracks in 2024-T4 aluminum, Fracture 1969, (Editors P.L. Pratt, E.H. Andrews, R.L. Bell, N.E. Frost, R.W. Nichols and E.Smith), 620-629, Chapman and Hall Ltd., London, UK, 1969.

[19] G. Lütjering, H. Döker and D. Munz, Microstructure and fatigue behavior of Al-alloys, Proceedings of the Third International Conference on the Strength of Metals and Alloys, 427-431, Institute of Metals, London, UK, 1973.

[20] C.Y. Kung and M.E. Fine, Fatigue-crack initiation and microcrack growth in 2024-T4 and 2124-T4 aluminum alloys, Metallurgical Transactions A, Vol. **10A**, 603-610, 1979.

[21] D.R. Sigler, M.C. Montpetit and W.L. Haworth, Metallography of fatigue crack initiation in an overaged high-strength aluminum alloy, Metallurgical Transactions A, Vol. **14A**, 931-938, 1983.

[22] J.C. Newman, Jr. and P.R. Edwards, Short-crack growth behaviour in an aluminum alloy – An AGARD cooperative test programme, AGARD Report No. 732, Advisory Group for Aerospace Research and Development, Neuilly sur Seine, France, December 1988.

[23] A. Merati, A study of nucleation and fatigue behavior of an aerospace aluminum alloy 2024-T3, International Journal of Fatigue, Vol. **27**, 33-44, 2005.

[24]   S.A. Barter, P.K. Sharp, G. Holden and G.Clark, Initiation and early growth of fatigue cracks in an aerospace aluminium alloy, Fatigue and Fracture of Engineering Materials and Structures, Vol. **25**, 111-125, 2002.

[25]   R.J.H. Wanhill, Damage tolerance engineering property evaluations of aerospace aluminium alloys with emphasis on fatigue crack growth, National Aerospace Laboratory NLR Technical Publication NLR TP 94177 U, Amsterdam, the Netherlands, December 1994.

[26]   J.T. Staley, Microstructure and toughness of high-strength aluminum alloys, Properties Related to Fracture Toughness, ASTM STP 605, 71-103, American Society for Testing and Materials, Philadelphia, USA, 1976.

[27]   J.G. Kaufman, Design of aluminum alloys for high toughness and high fatigue strength, Specialists Meeting on Alloy Design for Fatigue and Fracture Toughness, AGARD Conference Proceedings No. 185, 2-1 – 2-26, Advisory Group for Aerospace Research and Development, Neuilly sur Seine, France, January 1976.

[28]   R.J.H. Wanhill, In-house research, National Aerospace Laboratory NLR, Amsterdam, the Netherlands, 2005/6.

[29]   R.W. George and P.J.E. Forsyth, The influence of nickel and manganese on the fatigue properties and microstructures of three Al-Mg-Zn alloys, Royal Aircraft Establishment Technical Note No. Met.Phys. 352, Farnborough, UK, January 1962.

[30]   J. Schijve, Internal fatigue cracks are growing in vacuum, Engineering Fracture Mechanics, Vol. **10**, 359-370, 1978.

[31]   M.Böhmer, Die Beeinflussung des Ermüdungsverhaltens einer Aluminiumlegierung durch den Druck der Luft und ihrer Bestandteile zwischen 760 und 10^{-7} Torr, Deutsche Luft- und Raumfahrt Forschungsbericht 74-19, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt Institut für Werkstoff-Forschung, Porz-Wahn, Germany, February 1974.

[32]   F.J. Bradshaw and C. Wheeler, The effect of environment on fatigue crack growth in aluminium and some aluminium alloys, Applied Materials Research, Vol. **5**, 112-120, 1966.

[33]   G.A. Beitel, An ultrasonic device for the study of fatigue crack initiation in anodized aluminum alloys, Corrosion Fatigue: Chemistry, Mechanics and Microstructure, (editors O.F. Devereux, A.J. McEvily and R.W. Staehle), 512-517, National Association of Corrosion Engineers, Houston, USA, 1972.

[34]   W. Engelmaier, Fatigue behavior and crack propagation in 2024-T3 aluminum alloy in ultrahigh vacuum and air, Transactions of the Metallurgical Society of AIME, Vol. **242**, 1713-1718, 1968.

[35]   H. Shen, S.E. Podlaseck and I.R. Kramer, Effect of vacuum on the fatigue life of aluminum, Acta Metallurgica, Vol. **14**, 341-345, 1966.

[36]   M.J. Hordon, Fatigue behavior of aluminum in vacuum, Acta Metallurgica, Vol. **14**, 1173-1178, 1966.

[37]   H.J. Gough and D.G. Sopwith, Atmospheric action as a factor in fatigue of metals, Journal of the Institute of Metals, Vol. **49**, 93-112, 1932.

[38]   N.J. Wadsworth and J. Hutchings, The effect of atmospheric corrosion on metal fatigue, Philosophical Magazine, Vol. **3**, 1154-1166, 1958.

[39]   T. Broom and A. Nicholson, Atmospheric corrosion-fatigue of age-hardened aluminium alloys, Journal of the Institute of Metals, Vol. **89**, 183-190, 1960-61.

[40]   D.A. Meyn, The nature of fatigue-crack propagation in air and vacuum for 2024 aluminum, Transactions of the ASM Quarterly, Vol. **61**, 52-61, 1968.

[41]   F.J. Bradshaw and C. Wheeler, The influence of gaseous environment and fatigue frequency on the growth of fatigue cracks in some aluminum alloys, International Journal of Fracture Mechanics, Vol. **5**, 255-268, 1969.

[42]   R.J.H. Wanhill, Fractography of fatigue crack propagation in 2024-T3 and 7075-T6 aluminum alloys in air and vacuum, Metallurgical Transactions A, Vol. **6A**, 1587-1596, 1975.

[43]   B. Cohen, Corrosion fatigue in the aerospace industry, Corrosion Fatigue: Chemistry, Mechanics and Microstructure, (editors O.F. Devereux, A.J. McEvily and R.W. Staehle), 65-83, National Association of Corrosion Engineers, Houston, USA, 1972.

[44]   G.F.J.A. van Gestel, Investigation into the cause of failure of a McCauley propeller blade, National Aerospace Laboratory NLR Technical Report NLR TR 77086 C, Amsterdam, the Netherlands, July 1977.

[45]   R.J.H. Wanhill, E.A.B. de Graaf and A.A.M Delil, Significance of a rotor blade failure for fleet operation, inspection, maintenance, design and certification, Paper Nr.: 38, Fifth European Rotorcraft and Powered Lift Aircraft Forum, Amsterdam, the Netherlands, September 1979.

[46]   P.J.E. Forsyth, The fatigue performance of service aircraft and the relevance of laboratory data, Journal of the Society of Environmental Engineers, Vol. **19**, 3-10, March 1980.

[47]   G.S. Campbell and R. Lahey, A survey of serious aircraft accidents involving fatigue fracture, International Journal of Fatigue, Vol. **6**, 25-30, 1984.

[48]   M.C. Latham, D.G. Harlow and R.P Wei, Nature and distribution of corrosion fatigue damage in the wingskin fastener holes of a Boeing 707, ICAF' 2001, Design for Durability in the Digital Age, (editor J. Rouchon), Vol I, 469-483, Cépaduès-Éditions, Toulouse, France, 2002.

[49]   D.W. Hoeppner, A review of corrosion fatigue and corrosion/fatigue considerations in aircraft structural design, ICAF 2003, Fatigue of Aeronautical Structures as an Engineering Challenge, (editor M. Guillaume), Vol. I, 425-438, EMAS Publishing, Sheffield, UK, 2004.

[50]   P.J.E. Forsyth, Occurrence of fretting fatigue failures in practice, Chapter 4 in: Fretting Fatigue, (editor R.B. Waterhouse), 99-125, Applied Science Publishers Ltd, London, UK, 1981.

[51]   K.Endo, H.Goto, and T. Nakamura, Effects of cycle frequency on fretting fatigue life of carbon steel, Bulletin of the Japanese Society of Mechanical Engineers, Vol. **12**, 1300-1308, 1969.

[52] P.R. Edwards, The application of fracture mechanics to predicting fretting fatigue, Chapter 3 in: Fretting Fatigue, (editor R.B. Waterhouse), 67-97, Applied Science Publishers Ltd, London, UK, 1981.

[53] K. Endo, Practical observations of initiation and propagation of fretting fatigue cracks, Chapter 5 in: Fretting Fatigue, (editor R.B. Waterhouse), 127-141, Applied Science Publishers Ltd, London, UK, 1981.

[54] R.J.H. Wanhill, T.Hattenberg, D.J. Platenkamp and A.F. Bosch, MegaLiner Barrel GLARE window area F4: Fractographic examination and analysis of fatigue cracks for the F4 window panel, National Aerospace Laboratory NLR Contract Report NLR-CR-2005-666, Amsterdam, the Netherlands, April 2006.

[55] S.A. Barter, G. Clark and N.T. Goldsmith, Influence of initial defect conditions on structural fatigue in RAAF aircraft, Durability and Structural Integrity of Airframes, (editor A.F. Blom), Vol. I, 281-304, Engineering Materials Advisory Services Ltd., Warley, UK, 1993.

[56] W.C. Ralph, W.S. Johnson, P. Toivonen, A.Makeev and J.C. Newman, Jr., Effect of various aircraft production drilling procedures on hole quality, International Journal of Fatigue, Vol. **28**, 943-950, 2006.

[57] S.D. Antolovich and A. Saxena, Fatigue Failures, Metals Handbook Ninth Edition, Volume 11 Failure Analysis and Prevention, 126-127, American Society for Metals, Metals Park, USA, 1986.

[58] A. Merati and G. Eastaugh, Determination of fatigue related discontinuity state of 7000 series of aerospace aluminum alloys, Engineering Failure Analysis, In Press.

[59] P.J.E. Forsyth, The effect of cladding condition on the stages of fatigue crack formation and growth, Problems with Fatigue in Aircraft, Proceedings of the Eighth ICAF Symposium, (editors J. Branger and F. Berger), 2.5/1-2.5/23, Swiss Federal Aircraft Establihment (F+W), Emmen, Switzerland, 1975.

[60] R.J.H. Wanhill, Effects of cladding and anodising on flight simulation fatigue of 2024-T3 and 7475-T761 aluminium alloys, Fatigue Prevention and Design, (editor J.T. Barnby), 323-332, Engineering Materials Advisory Services Ltd., Warley, UK, 1986.

[61] R.J.H. Wanhill, T. Hattenberg and W. van der Hoeven, A practical investigation of aircraft pressure cabin MSD fatigue and corrosion, National Aerospace Laboratory NLR Contract Report NLR-CR-2001-256, Amsterdam, the Netherlands, June 2001.

[62] V.J. Colangelo and P.A. Thornton, Failures of Forgings, Metals Handbook Ninth Edition, Volume 11 Failure Analysis and Prevention, 323, 325, American Society for Metals, Metals Park, USA, 1986.

[63] W.R. Elliott, J.W. Lincoln and D.C. Register, Assessment and terminating action for widespread fatigue damage in C-141 wing fuel transfer holes, ICAF 95, Estimation, Enhancement and Control of Aircraft Fatigue Performance, (editors J.M. Grandage and G.S. Jost), Vol. I, 273-291, Engineering Materials Advisory Services Ltd., Warley, UK, 1995.

[64] T. Swift, Damage tolerance in pressurized fuselages, 11th Plantema Memorial Lecture, New Materials and Fatigue Resistant Aircraft Design, (editor D.L. Simpson), 1-77, Engineering Materials Advisory Services Ltd., Warley, UK, 1987.

[65] Aircraft Accident Report, Aloha Airlines, Flight 243, Boeing 737-200, N73711, Near Maui, Hawaii, April 28, 1988, NTSB Report No. NTSB/AAR-89/03, National Transportation Safety Board, Washington, D.C., USA, 1989.

[66] M.L. Overd, EH101 airframe – the fatigue testing and resulting timely modifications for the production aircraft, ICAF 97, Fatigue in New and Ageing Aircraft, (editors R. Cook and P. Poole), Vol. I, 347-364, Engineering Materials Advisory Services Ltd, Cradley Heath, UK, 1997.

[67] S.J. Swift, The Aero Commander chronicle, ICAF 95, Estimation, Enhancement and Control of Aircraft Fatigue Performance, (editors J.M. Grandage and G.S. Jost), Vol. I, 507-530, Engineering Materials Advisory Services Ltd., Warley, UK, 1995.

[68] I.C. Howard, Fracture of an aircraft horizontal stabilizer, Case Histories Involving Fatigue and Fracture Mechanics, ASTM STP 918, (editors C.M. Hudson and T.P. Rich), 259-276, American Society for Testing and Materials, 1986.

[69] J.W. Mar, Structural integrity of aging airplanes: a perspective, Structural Integrity of Aging Airplanes, (editors S.N. Atluri, S.G. Sampath and P. Tong), 241-262, Springer-Verlag, Berlin, Germany, 1991.

[70] H.Huth and D.Schütz, The collection and analysis of fatigue damage occurring in aircraft in service, Royal Aircraft Establishment Library Translation 1934, Farnborough, UK, August 1977.

[71] R.J.H.Wanhill, Milestone case histories in aircraft structural integrity, Chapter 1.04 in: Comprehensive Structural Integrity, Volume 1 Structural Integrity Assessment – Examples and Case Studies, (editors I. Milne, R.O. Ritchie and B. Karihaloo), 61-72, Elsevier Ltd., Oxford, UK, 2003.

[72] B. Dickson, J. Roesch, D. Adams and B. Krasnowsksi, Rotorcraft fatigue and damage tolerance, Paper 10, Twentyfifth European Rotorcraft Forum, Rome, Italy, September 1999.

[73] Military Specification Airplane Damage Tolerance Requirements, MIL-A-83444 (USAF), 1974.

[74] T. Swift, Verification of methods for damage tolerance evaluation of aircraft structures to FAA requirements, Industrial Applications of Damage Tolerance Concepts, Structures of High Fatigue Performances, Proceedings of the Twelfth ICAF Symposium, 1.1/1-1.1/87, Centre d'Essais Aéronautique de Toulouse (CEAT), Toulouse, France, 1983.

[75] R.N. Lumley, Personal communication from CSIRO Manufacturing and Infrastructure Technology, Melbourne, Australia, 10th August 2006.

[76] K. Tanaka and Y. Akiniwa, Mechanics of small fatigue crack propagation, Small Fatigue Cracks: Mechanics, Mechanisms and Applications, (editors K.S. Ravichandran, R.O. Ritchie and Y. Murakami), 59-71, Elsevier Science Ltd., 1999.

[77] R.N. Lumley, A.J. Morton and I.J. Polmear, Enhanced creep performance in an Al-Cu-Mg-Ag alloy through underageing, Acta Materialia, Vol. **50**, 3597-3608, 2002.