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Flight simulation fatigue crack growth guidelines

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FLIGHT SIMULATION FATIGUE CRACK GROWTH GUIDELINES

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Flight simulation fatigue crack growth tests are used to evaluate fatigue-critical areas and details in aerospace structures, compare candidate materials, joint designs and surface treatments, and provide data for checking crack growth prediction methods. However, such tests evoke complicating issues that need to be addressed by guidelines. This paper gives a number of guidelines obtained from NLR research on test specimens and, more recently, aircraft pressure cabins.

INTRODUCTION

Flight simulation fatigue tests on aluminium alloys and structures were begun at the NLR in the 1960s and are still being done, albeit less intensively than during the 1970s and 1980s. These earlier tests revealed complicating issues requiring guidelines for further testing, the theme of this paper. The issues themselves have been discussed and reviewed in Wanhill [1, 2].

Since 1994 we have also investigated Multiple Site Damage (MSD) fatigue in aircraft pressure cabins [3, 4], and the results are significant for MSD fatigue crack growth tests and test guidelines.

In general terms the guideline topics to be considered are:

(1) Simple and realistic specimens.

(2) Flight simulation loading.

(3) Specimen dimensions, types of fatigue loading and stress levels.

(4) Fatigue cycle frequencies and environmental effects.

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SIMPLE AND REALISTIC SPECIMENS

An appropriate starting point for this topic is the schematic in figure 1. This shows a fatigue crack growth curve labelled according to aircraft Damage Tolerance (DT) concepts. Remarkably, the curve shows a “missing link” regime corresponding to non-inspectable slow fatigue crack growth in aircraft structures. The reason for this gap lies in the endeavour to use simple pre-cracked/starter notched sheet specimens for spectrum loading tests. The sizes of feasible pre-cracks and starter notches do not permit stabilised flight simulation fatigue crack growth data to be obtained in the non-inspectable slow crack growth regime [1, 2, 5]. We proposed further investigation of this problem in 1995 [5], but it has not been given priority.

However, it is possible to cover the non-inspectable slow fatigue crack growth regime in realistic specimens where natural cracks occur and when using flight simulation spectra that mark the fatigue fracture surfaces in a traceable way. Examples include the Fokker 100 horizontal stabilizer gust + manoeuvre spectrum [6] and marker loads in the Boeing 747-400 forward fuselage full-scale test [7].

Guidelines for simple specimens

Starter notch geometry. For short crack growth tests use the Single Edge Notch Tension (SENT) specimen [8, 9]. For tests in the non-inspectable slow crack growth regime no guidelines are presently available, see above. For tests in the in-service inspectable crack growth regime use a Centre Cracked Tension/Middle-Tension (CCT/M-T) specimen whose starter notch consists of Electric Discharge Machining (EDM) slits either side of a central hole. The hole diameter should be representative for structural fasteners, e.g. rivets.

Specimen thickness. This should be representative of service applications, and is especially important for thin sheet gauges up to 5 mm. The reason is crack tip constraint. In thinner specimens the constraint is less and there is a change to a more plane stress condition, notably during peak loads in severe simulated flights. The crack tip plastic zones are therefore larger, especially the overload monotonic plastic zones associated with peak loads. In turn, the larger overload plastic zones cause more crack growth retardation and an improvement in the crack growth life.

It is worth noting here that modern fatigue crack growth models must be able to cope with constraint changes [10, 11].

Guidelines for realistic specimen simplification

As stated previously [2], flight simulation fatigue crack growth data for realistic specimens, mainly stiffened panels, are in short supply. The obvious reason is the high cost of making and testing the specimens. Figure 2 shows some test results which compare flight simulation fatigue crack growth rates for simple, simplified and realistic specimens. There are three main points to be made:

(1) The simple (CCT) and simplified (OBSCC) specimens show similar trends in crack growth rates until the sheet cracks approached the fictitious (CCT) and

actual (OBSCC) stiffeners. The OBSCC specimen crack growth rates then *increased*, the opposite of what would be expected. This was found to be caused by strip-stiffener yielding due to peak loads in severe flights [12], and is an artifact of replacing realistic Z-stiffeners by simple strips.

(2) Although the CCT specimen crack growth rates decreased rapidly as the cracks approached the fictitious stiffeners, as was the case for the realistic (F100) specimen, the load-shedding that enabled the CCT specimens to simulate the OBSCC specimens resulted in crack closure *remote* from the crack tips [12]. Thus the actual values of the CCT crack growth rates became increasingly unreliable.

(3) The F100 specimen's crack growth rate curve does not have an initial dip, unlike the CCT and OBSCC specimen curves. The reason is the broken central stiffener in the F100 specimen. This configuration cannot be simulated, in terms of K-a relationships, by the CCT and OBSCC specimens [2, 12].

This third point leads to a more recently discovered problem, namely the inability of sub-scale specimens to simulate early MSD fatigue crack growth rates in aircraft pressure cabins [3, 4]. Early MSD fatigue crack growth rates, accounting for 80-90 % of the crack growth life, are much higher in actual pressure cabins [3, 4] than in sub-scale specimens [13]. It may not be possible to remove this discrepancy by improved specimen design: the reduced size of sub-scale specimens is unfavourable to simulating the eccentricities and complex stress distributions in actual pressure cabins and full-scale panels.

The foregoing remarks show that realistic specimen simplification is neither easy nor ecumenical. On the other hand, the relatively low costs of simplified specimens and testing them enable more extensive studies of candidate materials, design concepts, load spectrum and environmental effects, and the capabilities of fatigue crack growth models.

Thus it seems one can give no more than a broad guideline that the *informed* use of simplified specimens to simulate realistic specimens is feasible and worthwhile. In other words, simplified specimens are acceptable when sufficient analytical, experimental and practical knowledge is available for setting up, doing and assessing the tests.

FLIGHT SIMULATION LOADING

Types of fatigue loading

These should be representative of service applications. With modern test equipment there is no blanket excuse for drastic simplifications, and there are many reference spectra available, latterly on CD-ROM [14].

However, manoeuvre spectra and other spectra that result in quasi-stationary fatigue crack growth behaviour, i.e. a regular process of crack growth, seem to tolerate considerable simplification. The snag is that tests must include both the more realistic and simplified spectrum loadings before the latter can be used with confidence. Also, the credibility of fatigue crack growth models is enhanced by verification with more realistic spectrum tests.

Spectrum simplifications and variations

Despite the foregoing remarks, some spectrum simplifications, and variations, can be very useful. Two examples will be given here, referring to figures 3 and 4 respectively:

(1) For gust spectrum loading the omission of low gust loads (Mini-TWIST *versus* TWIST in figure 3) and all but the most negative taxi load in each flight results in significant saving of testing time without changing the spectrum fatigue crack growth characteristics.

(2) Semi-random positioning of severe flights to provide characteristic markers on fatigue fracture surfaces is possible, as noted near the beginning of the previous main section of this paper. Figure 4 gives a striking example, whereby the fatigue crack front can be traced back to depths less than 20 μm and crack growth rates less than 10^{-10} m/flight [1].

It is also worth noting that fractographic work on early MSD fatigue crack growth in aircraft pressure cabins [3, 4] shows evidence only of the pressurization cycles. Thus constant amplitude loading, albeit with an orthogonal 50 % counter-part for biaxial simulation, is most probably sufficient for full-scale panel tests (and sub-scale specimen tests, though such specimens are as yet unsatisfactory, see the previous main section of this paper).

Peak load clipping

Severe flights have an evident influence on fatigue crack growth, especially for gust spectrum load histories, since the severe flights and corresponding peak loads are infrequent. The peak loads result in crack growth retardation, and to avoid their overly favourable influence it is common practice to clip the highest peak loads. Nevertheless, the choice of peak load clipping level is one of the most controversial basic problems in flight simulation fatigue.

Clipping levels must always be carefully considered, especially for thin-gauge damage-tolerant materials like the aluminium alloy 2024-T3. The clipping level is less critical for specimen thicknesses beyond 5 mm and materials with higher yield strengths, owing to increased constraint and therefore less tendency towards crack tip plane stress during peak loads. The clipping level is also less important for materials like 7000 series aluminium alloys. These have basically higher crack growth rates which imply (a) that retardation after peak loads is less, and (b) that between severe flights the crack is likely to grow well beyond the peak load monotonic plastic zone associated with the previous severe flight: in other words, more of the crack growth life is spent in growing a crack through material uninfluenced by the peak loads in severe flights.

Keeping the foregoing remarks in mind, the following two guidelines are available for gust spectrum loading:

(1) For long-life crack growth testing, for example short-to-long crack growth [1], the peak loads expected to occur less than 10 times in the target life should be clipped [15].

(2) For tests in the in-service inspectable crack growth regime the peak loads should be clipped to about 10 occurrences per estimated inspection interval.

These two guidelines provide the reasons for the maximum peak load (gust level I) and the clipped peak loads (to gust level III) for the TWIST and Mini-TWIST spectra shown in figure 3. Thus gust level I is, in fact, clipped with respect to the full, continuous gust spectrum; and clipping to gust level III results in 8 occurrences per block of 4000 flights, which corresponds reasonably well to an inspection interval.

SPECIMEN DIMENSIONS, TYPES OF FATIGUE LOADING AND STRESS LEVELS

The combination of specimen dimensions, types of fatigue loading and stress levels must result in fatigue crack growth lives long enough to be quasi-independent of the positions of the severe flights. In practice this usually means that the stress levels must be carefully chosen. An obvious general guideline is that the stress levels should be fairly representative of service applications. Two further guidelines from NLR experience can be given:

(1) For gust spectrum loading too *high* stresses must be avoided. This means that the mean stress in flight (the 1-g level) should be less than 90 MPa [1, 2]. Values commonly used by the NLR are 70 MPa for thin-gauge and damage-tolerant materials, and 55 MPa for thicker-section 7000 series aluminium alloys.

(2) For manoeuvre spectrum loading too *low* stresses must be avoided for thin-gauge materials. This means that the maximum in-flight stress should not be less than about 190 MPa [1, 2].

FATIGUE CYCLE FREQUENCIES AND ENVIRONMENTAL EFFECTS

Fatigue cycle frequencies

Aircraft fatigue load cycle frequencies vary widely, table 1.

TABLE 1 Aircraft fatigue load cycle frequencies [16]

Types of load	Cycle frequencies (Hz)
Ground-air-ground	0.00003-0.001
Cabin pressurization	0.00003-0.0005
Manoeuvres	0.005-0.2
Gusts	0.1-10
Taxiing	0.5-20
Buffeting	10-100
Acoustic	100-1000

Ground-air-ground and cabin pressurization cycles are far too long to be used completely realistically in tests, as are some manoeuvre cycles. However, the full cycles are not necessary. For example, the NLR has used 0.003 Hz positive sawtooth loading to represent the cabin pressurization rate, thereby taking into account that fatigue crack growth occurs only during the upward part of the load cycle. Even so, the tests take a long time, and are practical only if the anticipated fatigue crack growth curve is “sampled” at judicious intervals.

Be that as it may, with the obvious exception of acoustic fatigue and in the absence of a need to investigate aqueous environmental effects (see below), it seems acceptable – and of course convenient – to use cycle frequencies of 10-20 Hz for most flight simulation fatigue crack growth tests [17-19].

Humidity, temperature and pressure of air environments

For most tests laboratory air is sufficient, since the results are likely to be conservative [18, 19], but not unduly so. In other words, changes in humidity, temperature and pressure to simulate flying up to and down from high altitudes or particular climatological conditions are not necessary except for special tests.

Figure 5 shows a fractograph from a special test based on, and compared with, fractographs from service aircraft [3, 4]. Whatever the cause of the “beach markings” on the fatigue fracture surfaces from the service aircraft, the specimen fatigue fracture topography was clearly influenced by changing from “dry” to “wet” air during very low frequency testing. However, whether this indicates a significant change in fatigue crack growth rates is as yet uncertain [3, 4].

Aqueous environments

There are two aspects, or rather questions, that have to be addressed here:

(1) Whether or not to test with an aqueous environment, and if so, which?

(2) If testing with an aqueous environment, which load cycle frequencies should be used?

The first aspect is the more difficult. Until recently, little was known about the corrosion environments inside aircraft structural joints. It now appears that a representative solution is condensate with small amounts of ionic contaminants, mainly sulphates, and an *alkaline* pH [20]. As argued earlier [1, 2], the use of 3.5 % aqueous NaCl is inappropriate: now in view of these recent results [20], and also because the fatigue fracture surfaces are obliterated by the build-up of corrosion products within 1-2 weeks [21]. This rapid destruction runs counter to general experience with service fatigue failures, e.g. [3, 4, 22].

In my opinion, the most that can be said about deciding to test with an aqueous environment is that the recently obtained information on contaminated condensate [20] should be considered. Any test programme should, of course, include baseline tests in laboratory air.

If it is decided to conduct flight simulation fatigue crack growth tests with an aqueous environment, then the load cycle frequencies must be carefully considered. For continuous exposure, and in the absence of stress corrosion or possible cyclic stress corrosion, it seems acceptable to use frequencies up to 20 Hz [19]. However, for intermittent wetting and drying on a flight-by-flight basis it may be necessary to reduce the cycle frequency below 5 Hz [1, 2] and also include a hold time, say at the 1-g level, to enable the cracks to be dried *internally* by a continuous stream of forced air.

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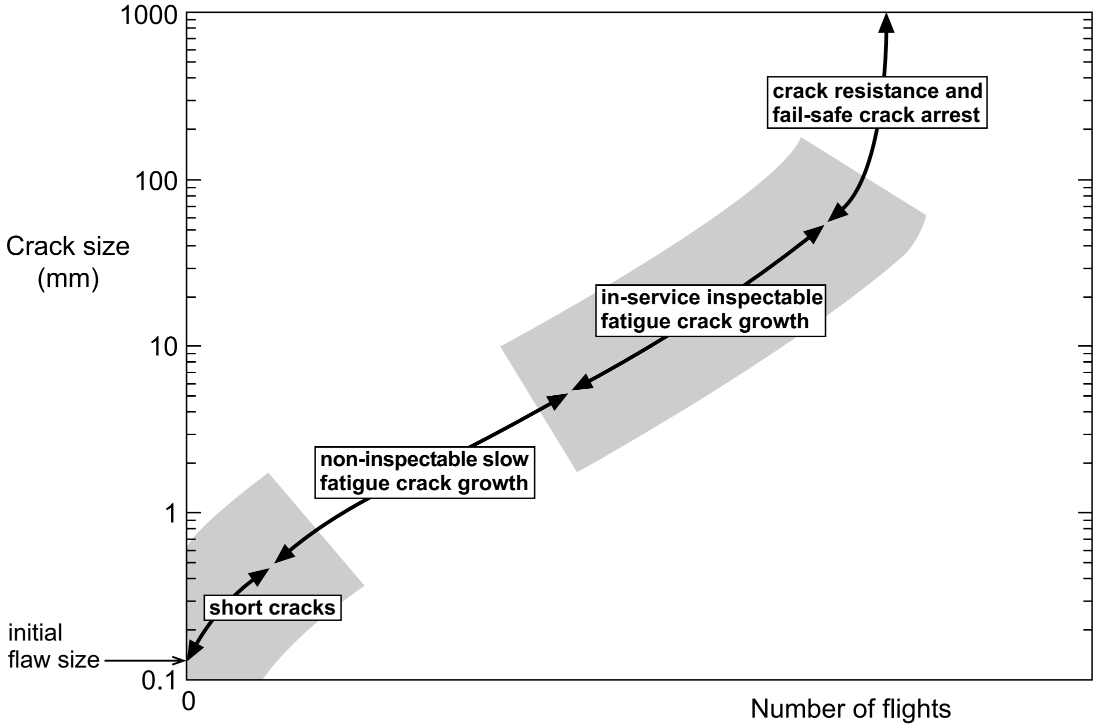

FIGURE 1 Schematic fatigue crack growth curve in Damage Tolerance terms for aircraft structures. [grey shading] indicates regimes accessible to simple sheet specimen flight simulation tests [1]

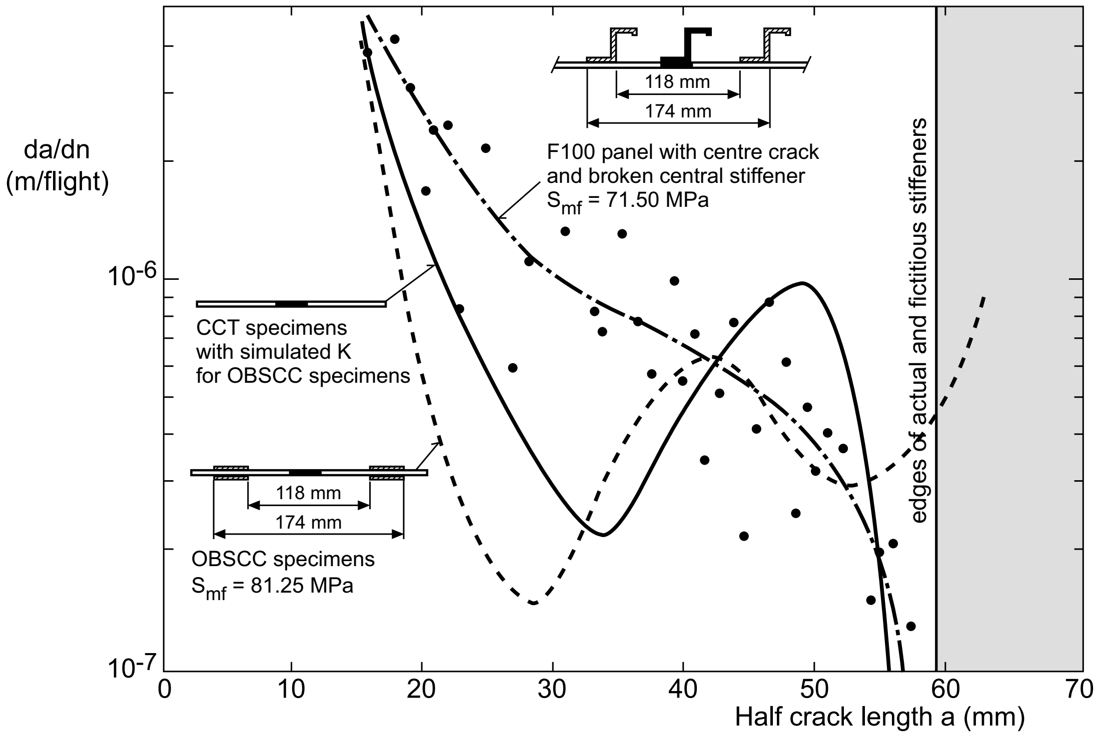

FIGURE 2 Gust spectrum fatigue crack growth rates in simple (CCT), simplified (OBSCC) and realistic (F100) specimens simulating a lower wing skin panel [2]

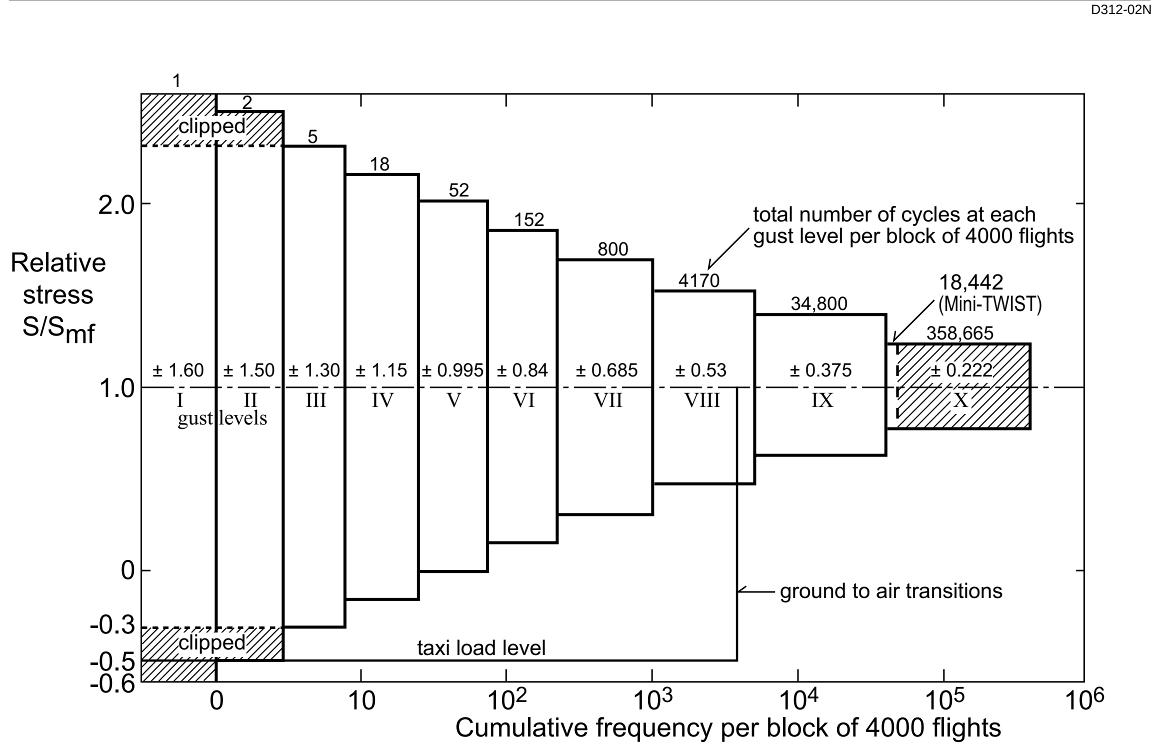

FIGURE 3 Stepped approximations to the gust spectra TWIST and Mini-TWIST, showing the omission of many low gust loads (Mini-TWIST), the simplification of taxi loads, and the clipping of peak gust loads that seldom occur

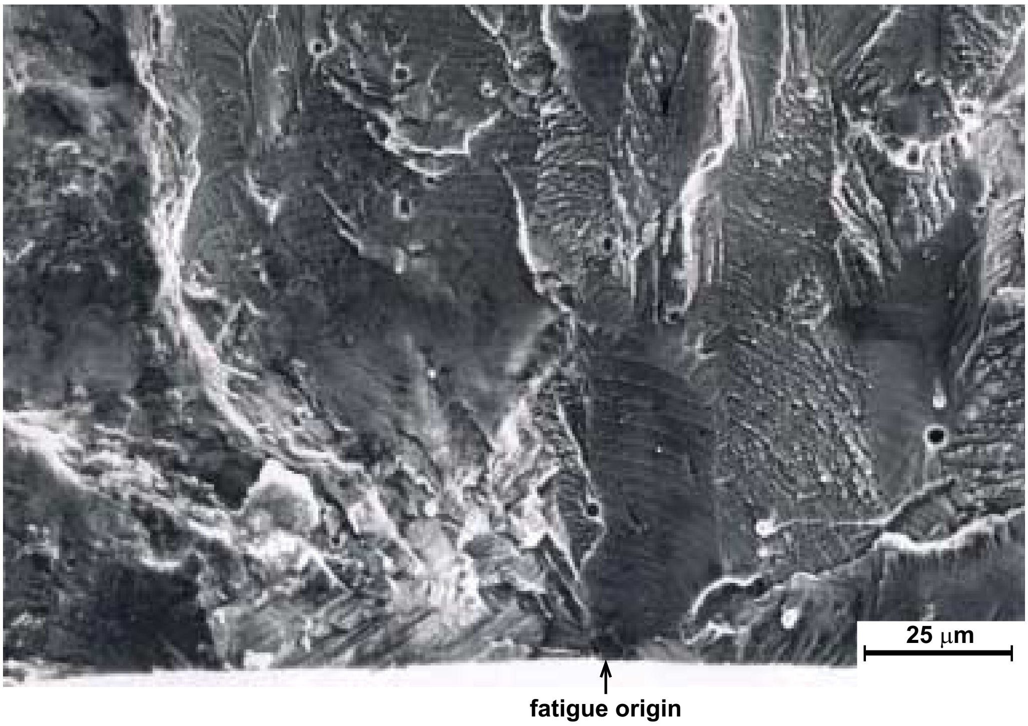

FIGURE 4 Fatigue crack initiation and early crack growth in a SENT specimen tested with the Fokker 100 Reduced Basic (RB) gust spectrum [1]. The spacings of the bands on the fracture surface above the fatigue origin correspond to blocks of 5000 flights

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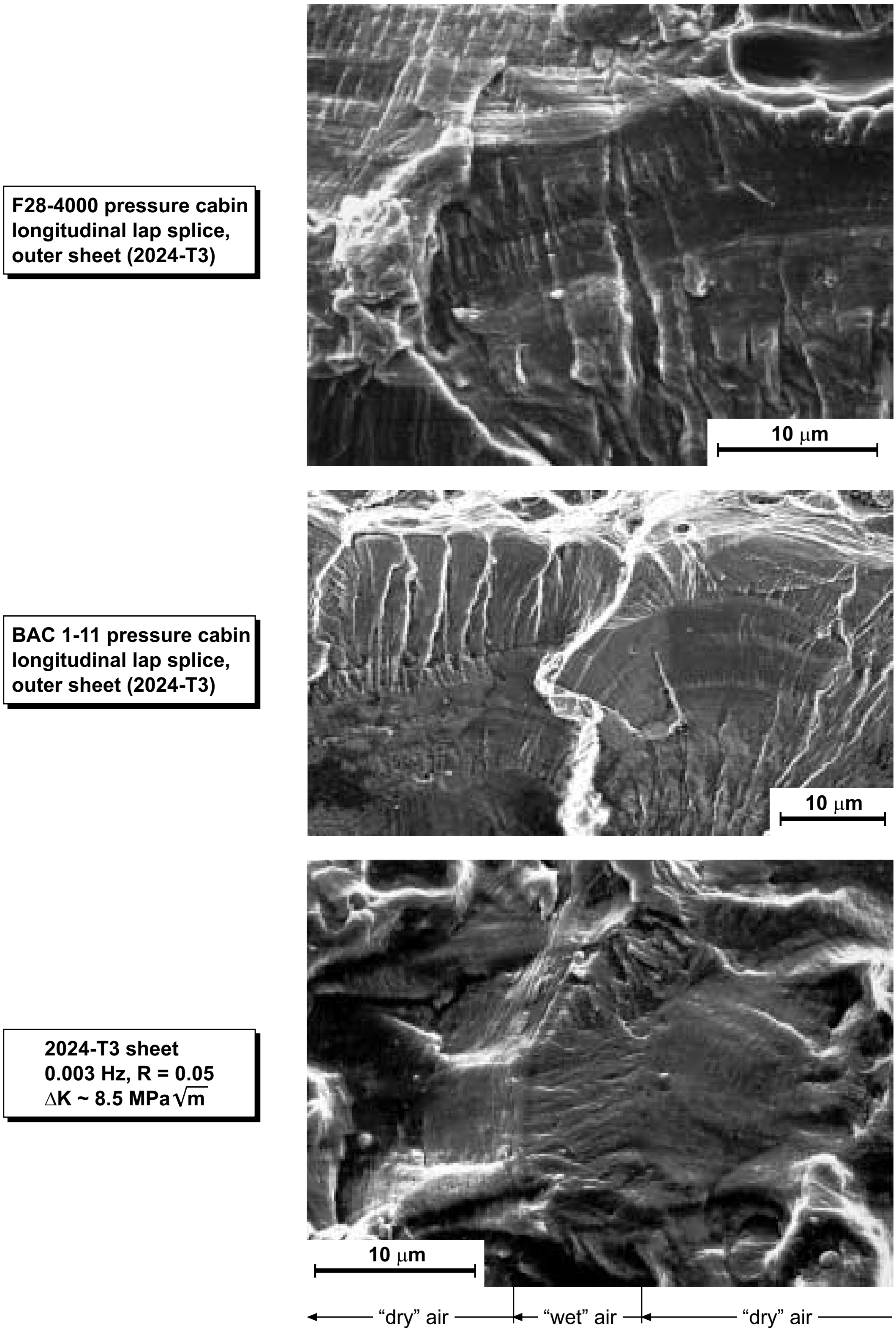

FIGURE 5 Examples of "beach marks" for early MSD fatigue crack growth in service aircraft and similar topographical changes produced by very low cycle frequency tests in "dry" and "wet" air in the same crack growth rate regime [3, 4]