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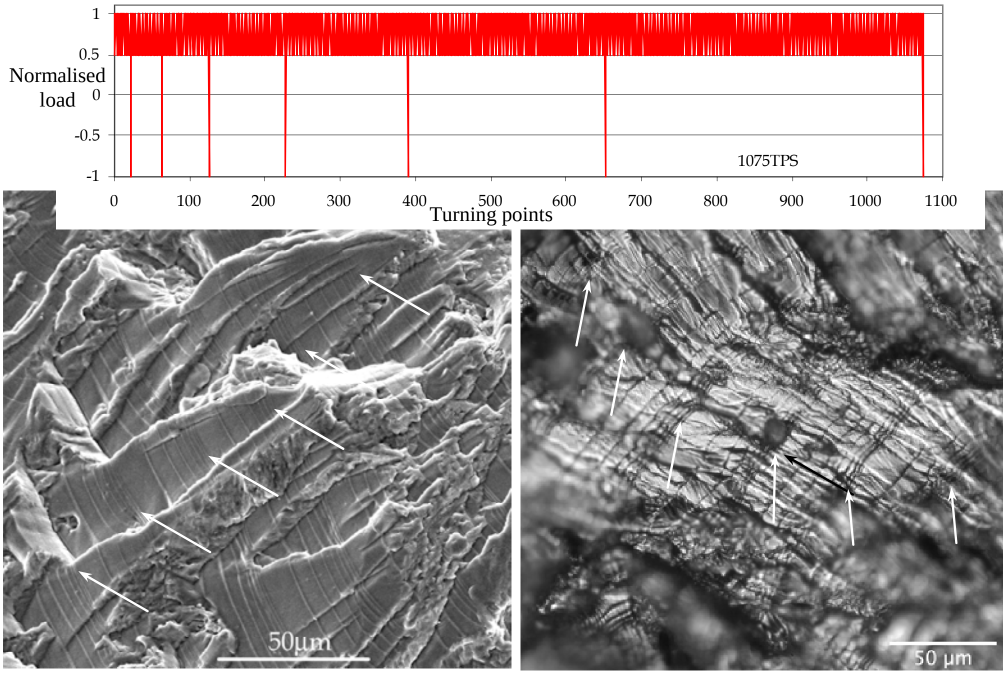
Executive summary

Marker loads for quantitative fractography of fatigue cracks in aerospace alloys



Problem area
The selection of fracture surface marking methods based on exploiting or altering the required fatigue loads is of much interest for many fatigue test programmes. Although there are many references in the literature, there are no guidelines.

Description
This report reviews the various fracture surface marking methods with a view to obtaining guidelines and procedures to optimise their use for quantitative fractography of fatigue crack growth. Numerous examples are provided to substantiate the guidelines.

Applicability
The guidelines and procedures are applicable to aerospace alloys tested as coupons, components and full-scale test articles.

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Marker loads for quantitative fractography of fatigue cracks in aerospace alloys

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Marker loads for quantitative fractography of fatigue cracks in aerospace alloys

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Summary

The selection of fracture surface marking methods based on exploiting or altering the required fatigue loads is of much interest for many fatigue test programmes. This is particularly true when crack growth measurements during testing are not possible or insufficiently accurate. In such cases, post-test Quantitative Fractography (QF) of the fatigue crack growth may then be needed, and this can be made possible and/or greatly facilitated by fracture surface markers. Examples of fatigue loadings that create fracture surface markings are presented and discussed with a view to obtaining guidelines and procedures to optimise their use for QF measurements of fatigue crack growth. The guidelines are presented in this report, which is a contribution to the ICAF 2009 Symposium, to be held in May 2009 in Rotterdam, the Netherlands.

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MARKER LOADS FOR QUANTITATIVE FRACTOGRAPHY OF FATIGUE CRACKS IN AEROSPACE ALLOYS

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Abstract: The selection of fracture surface marking methods based on exploiting or altering the required fatigue loads is of much interest for many fatigue test programmes. This is particularly true when crack growth measurements during testing are not possible or insufficiently accurate. In such cases, post-test Quantitative Fractography (QF) of the fatigue crack growth may then be needed, and this can be made possible and/or greatly facilitated by fracture surface markers.

Here, several examples of fatigue loadings that create fracture surface markings both naturally, as sometimes happens, and intentionally are presented and discussed. While these examples are from fatigue life tests of aircraft alloy specimens and components, particularly high strength aluminium alloys, under normal environmental conditions (air at ambient temperatures), it is probable that some of the fatigue load histories may provide fracture surface markings for other materials and in other environments.

The advantages and disadvantages of the various intentional marking methods are detailed with a view to obtaining guidelines and procedures for optimising quantitative fractography of fatigue crack growth. These guidelines are presented in this paper.

1 INTRODUCTION

The introduction of Damage Tolerance (DT) principals for determining the useful fatigue lives of aircraft structures calls for eliminating the time it takes a fatigue crack to initiate, since it is to be assumed that cracks are already present at the start of the service life. This assumption supposedly simplifies analysis of each critical area, but real structures are usually complex and not easily fully analysed. As a result, in-service fatigue problems that were not predicted during the design DT analyses often occur. This is particularly the case in tactical aircraft, for which unexpected fatigue cracking has resulted in costly structural repairs and unscheduled frequent inspections [1],[2],[3] despite extensive analyses and full-scale fatigue tests to validate them. In retrospect these discrepancies should be expected, since in-service load histories can differ markedly from the design assumptions and full-scale test conditions: the service usage may be more severe, the aircraft's role may change, the overall weight may increase, and the service environment may be different.

The situation appears to be less severe for transport aircraft, but similar problems with service load histories, changed mission types and increasing weights do occur. In addition, though this is not confined to transport aircraft, there may be incentives to fly the aircraft well beyond the original design goals.

Owing to the many (unexpected) fatigue problems that can occur during the life of an aircraft, there has recently been a shift in the focus of fatigue research from the original DT concept, as set out in MIL-STD-1530A [4], to a more holistic total life approach that includes fatigue crack initiation mechanisms and short crack growth analyses [5],[6]. This approach somewhat belatedly recognises that in many cases most of the fatigue life is spent while fatigue cracks are initiating and small, a fact known for at least 40 years [7].

Fatigue cracking – in both critical and apparently non-critical locations − may start from small discontinuities in the material (constituent particles and voids), discontinuities produced in manufacturing such as scratches, burrs, nicks and excessive pitting from surface treatments, design inadequacies (unexpected stress concentrations), or degradation processes such as corrosion and fretting. Use of an holistic approach makes it necessary to determine (1) the nature of the fatigue crack origins, (2) the times it takes for cracks to initiate and (3) the growth rates both when the cracks are small[1] as well as large enough to be detectable by Non-Destructive Inspection (NDI). All three aspects require post-test or post-service study of the fatigue fracture surfaces by Quantitative Fractography (QF). QF endeavours to determine the initial crack sizes and shapes and the subsequent small-to-long crack growth rates.

QF of short-to-long fatigue crack growth, in normal air at ambient temperatures, is the main subject of this paper. Other environments are not explicitly considered, although at least one example considers elevated temperature fatigue crack growth. The range of crack sizes includes not only cracks detectable by conventional NDI, but also extends down to the so-called microns to millimetres range, where much of the fatigue life of natural cracks may be spent.

QF of fatigue cracks requires an ability to match features found on the fracture surfaces with the loading/environmental history of the specimen or component. This is sometimes possible as a natural consequence of test or service load histories that produce well-defined fracture surface markers. However, when natural markers prove insufficient, QF's main usefulness lies in reconstructing the fatigue initiation and crack growth processes during tests with modified load histories that produce fracture surface markers.

Load history modifications may vary from nothing (natural markers) to several different marker load strategies. This paper gives some examples of natural markers before addressing strategies that have been reasonably successful in marking fatigue fracture surfaces. A fuller set of examples may be found in Barter and Wanhill [11]. The marker load strategies fall into five main categories:

1. Reordering the load spectrum
2. Overload additions
3. Underload additions
4. Constant Amplitude (CA) groups or bands of similar load amplitudes
5. Combinations of categories 1 – 4.

The advantages and disadvantages of different strategies are discussed with respect to maintaining the representativeness of the load history. Also, a particular strategy may be successful for one type of material, but not another. The discussions are illustrated by fracture surface images for crack sizes in the microns to millimetres range. These images are intended to give the reader an impression of what to expect when looking for fracture surface markers and attempting QF.

We note here that there have been a number of other studies on selecting load history modifications to obtain fracture surface markers, for example those by Schijve [12], Willard [13], Wanhill and Hattenberg [14] and those found in AGARD-CP-376 [15]. Some of the information from these studies is included here.

2 FRACTURE SURFACE MARKER REQUIREMENTS

For QF the fatigue fracture surface markers should ideally be readily visible, requiring only simple equipment and little technical and interpretative skill. Unfortunately, this is rarely the case. Crack growth measurements usually need high magnifications and experienced personnel, particularly for interpreting the fracture surface images (fractographs).

Since optical measurements are generally cheaper than SEM examination, it is beneficial − provided the appropriate equipment is available − if fracture surface markers are visible at magnifications ≤ 2,500 over the entire range of the crack sizes of interest. However, there are several caveats:

1. High magnification optical microscopes with long working distances are much less commonly available than SEMs.

[1] Fatigue cracks less than about 0.5 mm in size often grow faster or more erratically than would be predicted from long crack data [8],[9],[10]. This is the so-called "small crack anomaly". Be that as it may, in the present context a small fatigue crack is taken to be one that is below the NDI detection limit, which can be well beyond 0.5 mm.

2. If crack growth is to be traced back to small sizes, < 0.1 mm, then SEM fractography will most probably be needed anyway.
3. Even for larger cracks the fracture surface markers may be very finely spaced. This is the case for CA loading where measurements of fatigue striation spacings must be made, and also for very low overall crack growth rates, where again, SEM fractography will be needed [14],[15].

In the light of the foregoing remarks, it is no surprise that SEM examination dominates current QF research. Nevertheless, it is sometimes possible to complete crack growth measurements using optical microscopy. Hence examples of fractographs using this technique are also given. Some of these fractographs are compared with SEM fractographs of the same areas.

QF of fatigue fracture surfaces is limited to regions where the crack growth rates are high enough for progression markings or striations to be seen. In practice the SEM limit for QF is about 2×10^{-8} m using a Field Emission Gun SEM (FEG-SEM) and for the optical microscope about 5×10^{-7} m, so there should be an aim to mark the fracture surface at intervals greater than these and probably at least 5×10^{-7} m so that the marks may be easily distinguished.

It is important to note here that although progression markings and striations may be found down to very small spacings, they do not necessarily correspond to the macroscopic crack growth rates [16],[17],[18]. In other words, the use of very finely-spaced progression markings and striations for determining overall fatigue crack growth rates should be carefully considered and evaluated, since the growth rate indicated by the visible striations may differ markedly from the overall growth rate of the crack at that depth.

2.1 Number of markers

Following from the above, a basic consideration is the number of markers to be included in the fatigue load history. Too few markers will result in rather crude crack growth curves, while an excessive number will cause measurement difficulties. There is no straightforward answer to what is too few or excessive. The number of markers to be selected depends on the crack growth regime, the type of test and its purpose, and also the material. Some broad guidelines are given here, but pilot tests may be required.

Marking small cracks: Even though small fatigue cracks less than about 0.5 mm in size can grow faster than predicted from long crack growth data, the crack growth rates will generally be low. Also, since most of the fatigue life is spent in initiating and growing small cracks, their study often involves collecting detailed information on their growth. In other words, there should be many markers, but not too closely spaced.

If CA loading is being investigated, the markers need to be at intervals producing resolvable spacings as noted above, as will be the case for VA and spectrum loading (although in these cases it will be more difficult to specify the marker intervals *a priori)*. However, there have been VA and spectrum loading studies of small fatigue crack growth that may be helpful [19],[20], in addition to some of the examples in the following sections.

Type of test and purpose: Some examples of differing types of test and purposes are:

1. *Basic tests* with naturally initiating cracks and long periods of crack growth while the crack is small. The chosen marker intervals are likely to be regular, which has obvious analysis advantages. However, resolution of the marker spacings is an issue for small cracks, see the above remarks. This means that the choice of marker interval can depend on the crack growth regime. For small cracks a larger interval between marker applications may be necessary than for cracks in the NDI-inspectable regime.
2. *Threshold crack growth tests*, which begin from a starter crack and typically run under decreasing ΔK conditions. It may be desirable to progressively increase the number of cycles between markers, such that their spacings are still resolvable close to threshold. Although markers are not specified for threshold tests, they can be useful as a check on the macroscopic measurements of crack growth. They also assist studying the behaviour of crack fronts, their interactions with microstructural features, and environmental effects on crack growth [21].
3. *Full-scale tests* produce a few large cracks (those that cause failure or will lead to the first failures) and many smaller cracks [22],[23],[24]. Some of these smaller cracks, and others that subsequently occur in service, may later become the focus of attention as “new” critical locations needing total life assessment. Between 30 and 50 markers would be ideal for total life assessments of the smaller cracks. Unfortunately, in complex tests it is not possible to estimate the ideal marker intervals beforehand. When the cracks are small, some early marker spacings may be unresolvable. On the other hand, if

testing is continued after repair of initial and early failures, as is usually the case, the smaller cracks may grow to failure with many more repeats of the markers. For this reason it is sometimes desirable to include several marker load strategies in the one test.

A strategy that works well, provided it is acceptable, is to change or reorder the initial load spectrum block. Figure 1 gives an example of the effect of spectrum changes on full-scale fatigue fracture surfaces. The spectra were quite different, and the fracture surface changes produced were found for cracks varying in size from about 1 mm to more than 100 mm.

Another possibility is to change the type of marker after an appropriate number of spectrum blocks and at reasonable intervals (10 – 30 blocks) and thereafter.

In addition to spectrum alterations, full-scale tests include discrete events, planned or unplanned, that also affect crack growth, such as strain surveys, failures that momentarily increase the loads on other cracks, and subsequent repairs. If needed, particular markers may be applied immediately upon resuming testing, in order to indicate crack sizes when these events occur, although the events themselves may be sufficient.

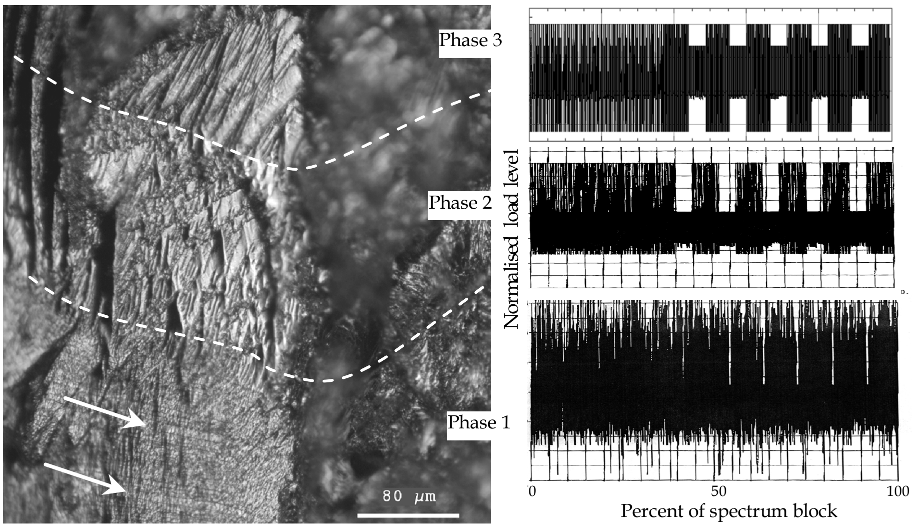

Figure 1 Optical image of an aluminium alloy fatigue fracture surface from a full-scale test. Three different loading spectra (phases 1 – 3) were applied during the test, resulting in different fracture surface topographies. The arrows indicate visible repeats of the first spectrum.

Material: Given that a material will show markers on its fatigue fracture surfaces[2], then the finer the microstructure, notably the grain size, the harder it may be to distinguish the markers. This is because local fracture surface deflections occur when cracks cross the grain and subgrain boundaries. To compensate for the finer microstructure the marker intervals can be decreased such that several markers should be visible on the relatively flat fractures between boundaries. This aspect of using markers will be very much influenced by the nature of the material and the type of fatigue test. Pilot tests may be required to finalise appropriate marker intervals before extensive coupon and full-scale tests commence.

3 ASSESSING LOAD HISTORIES FOR INTRINSIC QF “READABILITY”

So far, we have discussed marker visibility without going into detail about the markers themselves. In this section we discuss the intrinsic QF “readability” of fatigue load histories, i.e. the visibility of natural markers on fatigue fracture surfaces produced by the required loading (and environment) acting on the test material. It is useful to check this readability before deciding on a deliberate marker load strategy, since natural markers allow the most straightforward interpretation of the test results.

[2] Markers are usually visible for high strength aluminium alloys in normal air at ambient temperatures. This is not necessarily so for other classes of materials, e.g. titanium alloys and high strength steels, which may show poorly delineated cyclic crack growth on fatigue fracture surfaces.

For both simple and complex load spectra it is often possible (on at least parts of the fatigue fracture surfaces) to detect markers and markings produced by repeated load spectrum blocks, one or several bands or groups of loads, or one or several of the high loads. Certain intrinsic features of loading spectra can provide easily detected repeating patterns or obvious markers. These intrinsic features are usually similar to those deliberately added to produce marker bands, namely overloads, underloads, bands or groups of loads, or various combinations of any of these. For example, aircraft load spectra may have grouped gust or manoeuvre loads, as in the upper two spectra schematically shown in Figure 1.

Some further examples of natural markers for simple and complex load spectra are discussed in the following Subsections, followed by a summary at the end of this Section. The examples have been selected (1) to illustrate the types of markers/markings that may be observed when different spectra are applied to different materials, and (2) what the markers/markings may look like at different crack growth rates, and when observed with either the SEM or a high powered light microscope. Two of the examples are from full-scale tests, and some comments about the difficulties of selecting marker strategies for these tests are given in the summary.

Example 1: simple CA + underload spectrum; AA7050-T7451

Figure 2 shows a schematic of a simple fatigue load spectrum with images of aluminium alloy (AA)7050-T7451 fracture surfaces produced by this spectrum. The spectrum consists of increasing numbers of high-R cycles between fully reversed (R = -1) cycles that cause intermittent underloads. This is a very simplified analogy of varying numbers of gust and intermittent Ground-Air-Ground (GAG) loads for a transport aircraft lower wing. Both SEM and optical images show repeats of the spectrum blocks. These repeats are readily visible at the locations shown, and it can be concluded that intermittent underloads have the potential to produce well-defined fracture surface markers under some circumstances - in this case where the other cyclic loads have a high mean stress. Furthermore, it is clear from this example that underloads could be used to produce markers during CA tests, specifically when regular striations are not resolvable. This would allow QF of very slow CA fatigue crack growth such as in threshold crack growth tests. The reasons why underloads can produce well-defined fracture surface markers are discussed by White *et al*. [25].

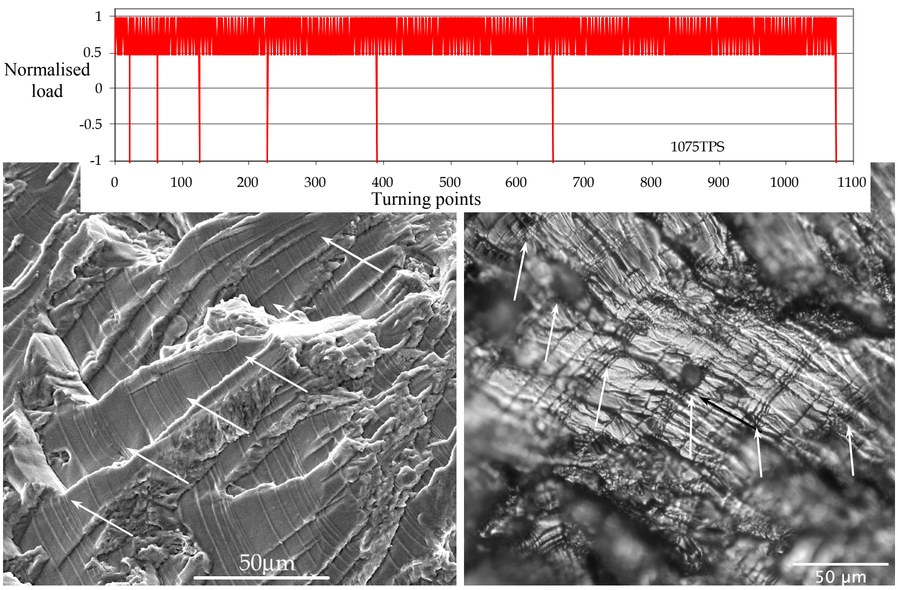

Figure 2 SEM and optical images of an aluminium alloy fatigue fracture surface produced by a simple CA + underload spectrum, shown schematically. The arrows point to repeats of the spectrum blocks.

3.1 Example 2: complex manoeuvre + buffet spectrum; AA7050-T7451

Figure 3 shows the spectrum block of a manoeuvre + buffet load history (omitting the buffet loads from the schematic) and images of an aluminium alloy fracture surface produced by the complete spectrum. This example is from a full-scale fighter empennage test [22], for which the spectrum was applied without considering QF readability. However, there were considerable periods of buffeting (high frequency near-CA loading) that made recognisable markings and bands on the fatigue fracture surfaces: with buffeting the total number of turning points was more than 10^6, compared to 1.5×10^5 for the manoeuvre loads only.

The arrows in the SEM and optical images show repeats of the spectrum blocks. The optical image is from a later stage of crack growth, when some buffet load periods were resolvable as bands. In the SEM image these bands appear as single markings with little or no detail between them.

Comparison of the SEM and optical images in Figure 3 shows that well-defined markings during early crack growth can become broader and more detailed later on, and possibly more difficult to recognise. Then the key to determining repeats of the spectrum blocks can change from recognising entire blocks to recognising markings due to repeated sequences or peak loads within the blocks. Since realistic spectra will include several peak or near-peak loads, and may contain large load excursions that mark like peak loads, see Example 3, there is a potential for confusion. In fact, the peak and near-peak spectrum loads in the present example did produce similar markings until local tensile tearing by microvoid coalescence made the peak load more obvious.

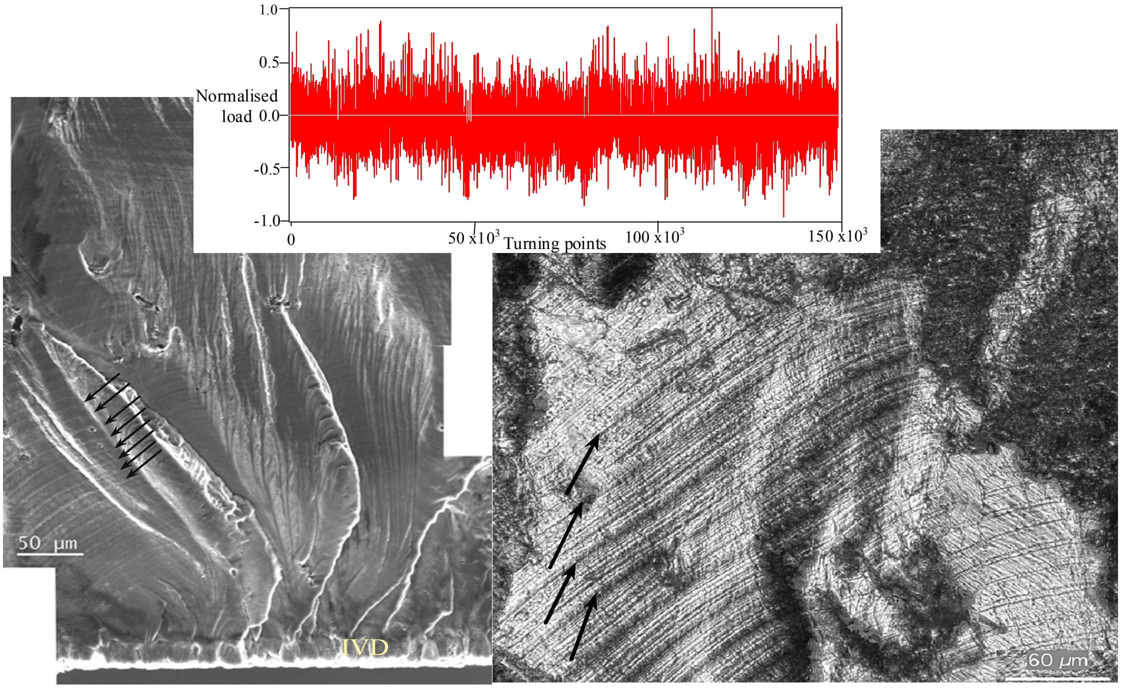

Figure 3 Manoeuvre loads from a manoeuvre load + buffet spectrum, and SEM and optical images of the fatigue fracture surface produced. The arrows point to repeats of the spectrum blocks. Note the different appearances of the repeat markings (see text).

3.2 Example 3: simple flight-by-flight spectrum; AA7075-T651

A comprehensive study of simple flight spectra by Abelkis [26] provides the example shown in Figure 4. One of the load histories studied consisted of repeats of the simulated flight shown in the schematic, and one of these flights is indicated on the accompanying transmission electron microscope (TEM) replica image.

This example demonstrates the potential for confusion when large load excursions mark like peak loads. The peak load excursion C_{min}–C_{max} and the large positive load excursion D_{min}–D_{max} produced similar "giant" striations. The only difference appears to be the strength of the unloading marks (black lines) at D_{min} and E_{min}: since this image is a TEM replica, the black lines probably represent fissures into the original fracture surface.

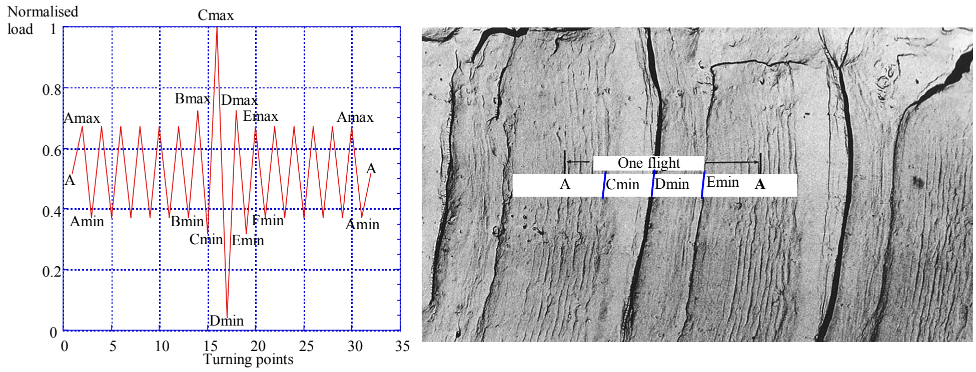

Figure 4 A single-flight spectrum and TEM replica image of an aluminium alloy fatigue fracture surface produced by this spectrum [26].

If these two giant striations had not been produced by successive large positive load excursions, they could have been confused with each other. This would also have been possible when viewing the fracture surface directly, using either optical or SEM imaging, since the contrast between large and small fissures is usually not strong in such instruments.

3.3 Example 4: complex gust spectrum; AA7175-T736

Figure 5 shows the spectrum block of a gust load history applied to the empennage of a transport aircraft during a full-scale test and images of an aluminium alloy fracture surface produced by the spectrum. The spectrum consisted of blocks of 5000 simulated flights separated by GAG cycles. The three severest flight types, A, B and C are also indicated in Figure 5. In the first instance this spectrum was applied without considering QF readability. However, unanticipated cracking of the vertical stabiliser main hinge fitting led to a fractographic investigation and recognition of the spectrum blocks and sub-blocks on the fatigue fracture surfaces [27].

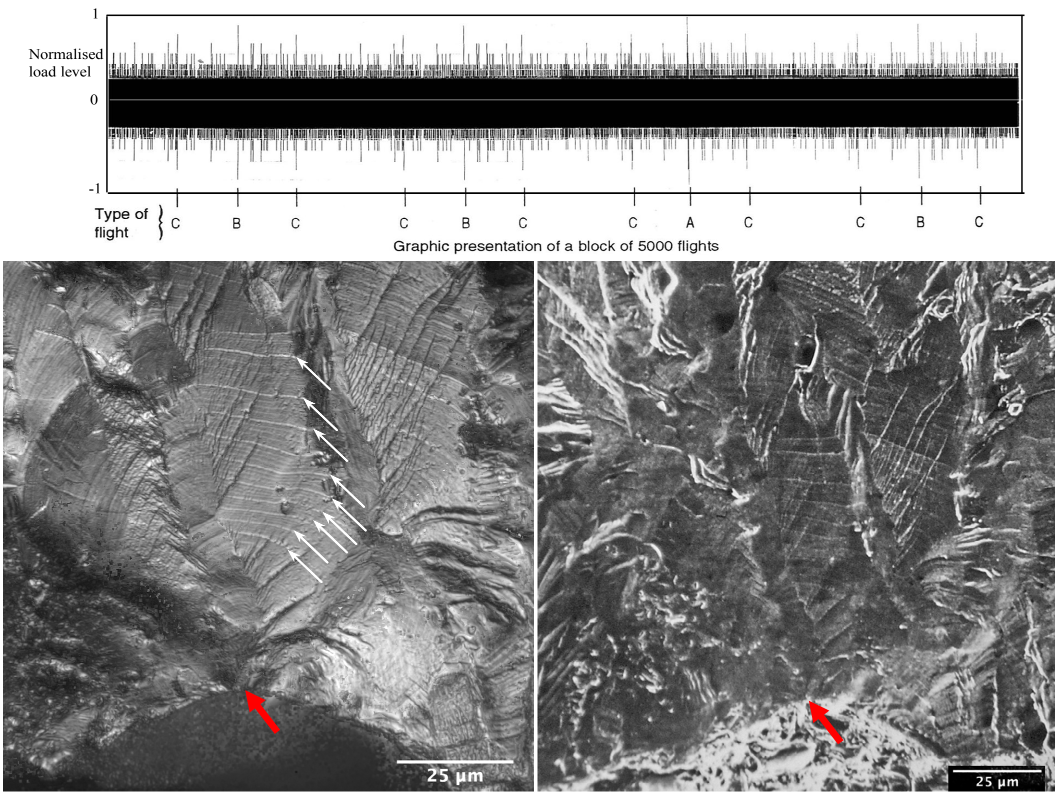

Figure 5 Optical and SEM images of the repeat markings on a fracture surface from an AA7175-T736 forging, as the result of applying the spectrum shown above them. The images are from the same area and include the fatigue crack origin (red arrows).

The fractographs in Figure 5 are of the same area and include the fatigue crack origin (large arrows). The white arrows in the optical image show spectrum block repeats marked by the A-flight peak loads. There are also sub-block markings due to the B-flight peak loads. These are less clear in the SEM image.

Although the spectrum was complex, the high loads were rather evenly spaced. This enabled easy recognition of the spectrum blocks and sub-blocks when the crack was small. At crack depths beyond those in Figure 5 the blocks became more difficult to detect because they spread out over many facets, and steps between facets, angled away from the average crack plane. The facets were due to local differences in crystallographic orientation between grains or subgrains in the material. In addition, as the crack size increased the various high loads started to produce similar-looking striations.

Later on, the A-flight peak load once again became obvious, since it started to cause local tensile tearing by microvoid coalescence. This new natural marker occurred very helpfully over much of the later crack growth.

A note of caution about examining cracks from full-scale fatigue tests is worth mentioning here. The optical image in Figure 5 shows that the repeating pattern changes after the last of the white arrows. The spectrum was apparently changed by moving one or two of the B-flights from before the next A-flight to after it. Such changes are not uncommon in full-scale fatigue tests, since the task managers may change the order of some of the loads, flights or flight blocks to suit test or operational requirements. Also, other loads such as strain surveys may be brought forward or delayed. Thus fractographers need accurate and complete descriptions of the loads applied during a full-scale test.

Load changes are usually confusing, but sometimes they may be useful in establishing the exact depth of a crack at a specific time during the test. This may be a particular advantage when fracture surfaces have been damaged either at the beginning or end of crack growth, as can occur in a full-scale structure. To make sure that a load change is recognisable, it is of course possible to add a deliberate marker.

3.4 Summary of intrinsic QF “readability”

The above examples of natural markers on fatigue fracture surfaces were presented in order to make some points about the intrinsic QF “readability” of fatigue load histories. In each case, schematics of the load spectra or parts of the load spectra were included to demonstrate which spectrum features produced the fracture surface markings. Naturally, the examples were chosen to clearly show markings that matched the spectrum features. However, in many cases this matching is difficult or may be impossible. For instance, the simulated flights in the well-known TWIST and mini-TWIST gust spectra [28],[29] can be very difficult to identify on a fracture surface [30]. Furthermore, even for the examples given, it was usually found that although markings were identified at some crack growth rates, they could be very difficult to identify at others.

The following points can be made from the above examples and discussion:

1. Many test load histories produce well defined natural markings on fatigue fracture surfaces during some phases of crack growth. However, some do not.
4. The markings may change their appearance as the cracks grow, and this may make spectrum repeats hard to distinguish at some crack growth rates.
5. Positive load excursions of similar magnitude, but with significantly different peak values, may produce similar markings. Notable examples are the upward parts of GAG cycles, which can produce markings very similar to those caused by high positive gust loads. This similarity can result in confusion if large positive load excursions are relied upon for crack growth measurements.
6. In some cases individual loads, groups of loads, or simulated flight sequences can be identified, and these may all be important to the full QF analysis. Unfortunately, there is still the risk of confusion, since prominent markings come from several sources: peak loads, large positive load excursions and groups of loads.

From these points it is clear that it is always worth considering deliberate marker load strategies. These will be discussed in the following Sections.

4 REORDERING THE LOAD SPECTRUM

If an unaltered spectrum is difficult to 'read', i.e. there are no well defined natural markers, then a simple option may be to reorder the spectrum loads. This can improve spectrum readability, but may change the severity of the spectrum with respect to fatigue crack initiation and growth. Unfortunately, the effects of reordering on readability and spectrum severity are often hard to predict. Hence it is usually necessary to carry out a number of trials and have a strategy for determining the reordering effects.

There are several methods for determining whether changes to a spectrum have had significant effects on its severity. A full discussion of the ways that spectrum changes can be validated is outside the scope of this paper. However, several analytical and experimental methods are available, with the severity comparison by coupon testing usually being the most reliable. We note here that spectrum severity changes are not necessarily bad provided they are validated and understood.

Three methods of reordering load spectra to improve or enable QF readability have been suggested: (1) single loads can be repositioned, (2) groups of loads can be repositioned, or (3) single loads can be grouped and then re-positioned. These methods are discussed and illustrated in the following Subsections and Examples. A summary is given at the end of this Section.

4.1 Repositioning single loads

Repositioning single loads usually means moving the highest (peak) load close to other high loads to help produce an easily observable marker or group of markers. In general, the higher the peak load with respect to the other loads in the spectrum, the more prominent a marker will be. Since the peak load is usually repeated at least once in a spectrum block[3], placing two peak loads close to each other (clustering) may produce a pair of markers that are recognisable as a band at low crack growth rates (about 10^{-8} m/cycle) or as an easily recognised pair of marks at medium crack growth rates (10^{-8}-10^{-6} m/cycle). At still higher crack growth rates the peak loads may cause local tensile tearing by microvoid coalescence, as mentioned in Example 4. This tearing mode causes markings that can be useful in tracking crack growth, see Figure 8 in Example 8. This works best when there are only a few high loads in the spectrum block. Many high loads would produce similar markings that make it hard to identify a particular load.

The main problem with clustering peak loads is that crack growth retardation caused by the first peak load may alter the effectiveness of the following peak load (or loads). Also, removing a peak load from another part of the spectrum may result in locally increased crack growth. This is likely to be less of a problem to the overall spectrum severity.

Since Example 3 showed that prominent markings are also produced by large positive load excursions, *even when not reaching a peak load*, then moving the lowest turning points to just before the peak turning points to create the largest positive load excursions should result in *very* prominent markers. Strictly speaking, this is modifying rather than repositioning single loads. Of course, this modification will also affect crack growth, possibly resulting in considerable crack growth retardation.

On the whole, however, clustering two or three peak loads or generating large positive load excursions for each peak load are not very effective at producing markers at all crack sizes [30]. In other words, additional modifications to the spectrum may be required.

4.2 Repositioning groups of loads

As illustrated by Example 4, aircraft fatigue load spectra are usually organised into simulated flights. These can be repositioned in the load histories to create well defined marker bands. This procedure is similar to repositioning single loads, except that each flight may consist of several hundred loads. This may mitigate altering the amount of crack growth retardation, but it still can be a problem.

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[3] Repeated peak loads are usually due to spectrum "clipping", whereby the very highest loads in a spectrum are lowered to a specified level. Clipping is done to reduce crack growth retardation after peak loads, thereby ensuring shorter (conservative) crack growth lives.

The following gives an example of flight-repositioning changes to the standard manoeuvre spectrum FALSTAFF (Fighter Aircraft Loading STAndard For Fatigue) [31].

4.3 Example 5: modification of FALSTAFF; AISI 4340

FALSTAFF consists of a block of 200 simulated flights typical for fighter aircraft usage in the 1970s. There are two peak loads, in flights 31 and 172. In this example FALSTAFF was modified by moving flight 31 to the beginning of the block, which brought flights 172 and 31 (now flight 1 in the block) closer together during repeated applications of the block.

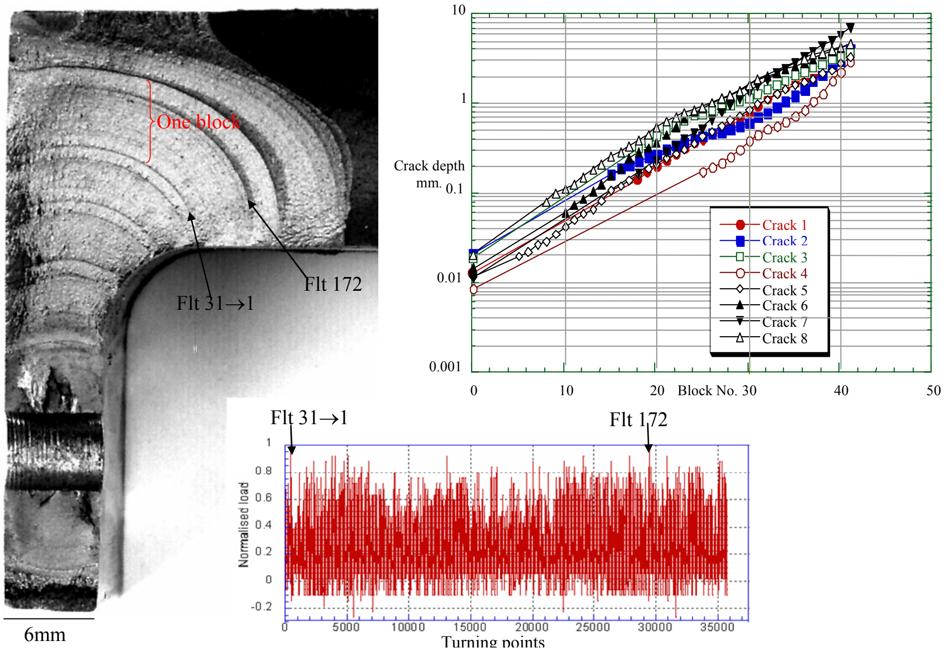

Figure 6 Low magnification optical image of one of the fatigue fracture surfaces from an AISI 4340 steel wing attachment boom tested with the modified FALSTAFF spectrum shown in the schematic. The arrows link the peak loads in each flight block and two of their markers. This figure also shows QF-obtained crack growth curves for some of the other cracks in the boom.

Figure 6 shows an optical fractograph for a crack in a high strength steel component subjected to this FALSTAFF modification, together with a schematic of the modified loading block and QF-obtained crack growth curves for other cracks in the same component [32]. The arrows point to two of the fracture surface markers produced by flights 31→1 and 172. The repositioning resulted in sets of two markers, flight 172 followed by flight 31→1, making it easy to do QF for larger crack sizes. However, even with this modification it was difficult to find the sets of markers at small crack sizes. This is not unusual for high strength steels, whose fatigue fracture surfaces are harder to mark than those of aluminium alloys.

When this test and others were done it was not expected that the markers could be made more obvious for small cracks. However, QF was often successful, with some difficulty, down to crack depths below 0.2 mm, see the crack growth curves in Figure 6.

On an analytical strain-life basis, with crack growth retardation considerations included, supplementary coupon tests with the original and modified FALSTAFF sequences demonstrated that the spectrum severity was unchanged. This useful result was probably due to the overall length of the FALSTAFF flight block, whereby there were still many loads between the peak loads in flights 172 and 31→1.

4.4 Repositioning single loads

Spectra unamenable to simple re-ordering for improved marking usually contain many high loads that are approximately evenly spaced and of similar magnitude. In such cases either low or high loads may be grouped to form CA bands. Low loads are preferred, since grouping high loads may result in significant changes in spectrum severity. Even so, the grouping of low loads can have an effect on severity.

The following example of repositioning and grouping similar single loads to obtain CA bands was one of the modifications to the service-generated manoeuvre spectrum BASIC carried out by Van der Linden [33].

4.5 Example 6: repositioning similar single loads into bands; AA7075-T651

This type of modification to the BASIC spectrum was based on those made to the Snowbird spectrum [34]. Similar single loads were extracted from BASIC and grouped to form CA bands. These bands were placed just before the peak load in the spectrum. There were three versions, named Snowbird I, II and III after the original Snowbird modifications. These versions had CA bands containing 427, 1177 and 2204 cycles, respectively.

The Snowbird I and II versions of BASIC produced very good markers for crack sizes above about 1 mm. However, the Snowbird III version, with a much larger CA band, marked the fracture surfaces well for all crack sizes. Figure 7 shows some fractographs of the Snowbird III markers.

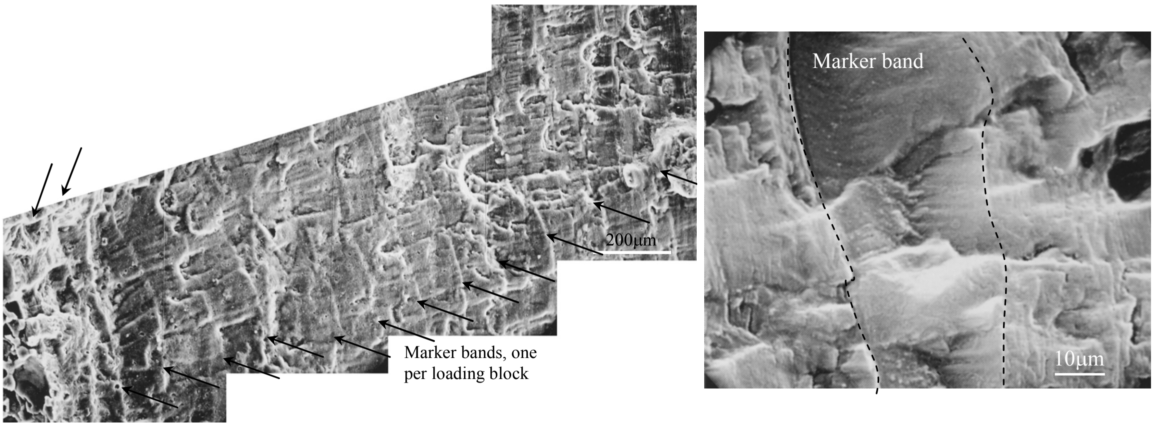

Figure 7 Optical and SEM images of CA marker bands on the fracture surface of a AA7075-T651 plate specimen [33]. The marker bands were obtained by grouping 2204 cycles extracted from the BASIC spectrum and placing the group just before the peak load in the spectrum.

4.6 Summary of reordering the load spectrum

The preceding Subsections and Examples discussed and presented markers obtained by three ways of reordering the load spectrum. Reordering has the advantage of not increasing the severity of the spectrum by adding extra loads. Nevertheless, spectrum severity changes due to reordering may still occur, and these have to be evaluated. The following points about reordering load spectra can be made:

1. Good markers may be obtained by repositioning the peak loads or the flights containing the peak loads.
2. In general, repositioning one or two single loads will not produce markers that are easy to recognise for all crack sizes: additional modifications to the spectrum will usually be required.
3. An alternative to moving single loads or flights is to generate CA marker bands from the lower loads in the spectrum. These bands can produce well defined markers.
4. Removal of many low loads from a spectrum may reduce the QF readability. For example, it can be more difficult to analyse fracture surfaces produced with mini-FALSTAFF instead of FALSTAFF [23]. (Spectrum severity changes may also be expected from this type of spectrum modification.)

5 ADDING OVERLOADS OR UNDERLOADS TO THE LOAD SPECTRUM

This strategy for improving QF readability is probably the most common, particularly the addition of overloads. However, it requires considerable care to avoid significant changes in spectrum severity, or at least to minimise these changes. The following Subsections discuss the addition of overloads and underloads, respectively. A summary is given at the end of this Section.

5.1 Overload additions

During fatigue crack growth a positive load excursion typically more than 20% higher than the other spectrum loads may produce a good mark but can also result in crack growth retardation, as has been found notably in aluminium and titanium alloys. Similarly, if a peak load is followed by a large number of lower loads before the next peak load, the crack growth rates between the peak loads may have an average growth rate lower than those without the peak loads. Crack growth retardation may be intrinsic to representative load histories, e.g. gust and manoeuvre spectra, and/or it can be enhanced by adding overloads to the spectrum.

From a QF readability point of view, the interest in peak loads, overloads and crack growth retardation is the formation of easily recognisable markers and a distinct change in fracture surface topography following them. An overload cycle causes a relatively large crack extension that produces a fracture surface marking sometimes referred to as a "stretch zone"[4]. These stretch zones can be evident at some stages of crack growth. If the overload causes (1) a change in the microscopic or macroscopic fracture mode, or (2) a reduction in any crack closure behind the crack, owing to stretching the crack tip open, or (3) changes the damage state of the material ahead of the crack, then *accelerated* crack growth may initially occur and persist over many post-overload cycles. Following accelerated crack growth the growth rate may progressively fall and then gradually recover, resulting in a period of retardation.

Such events can significantly change the total severity of both CA and VA loading and result in large changes in crack growth lives[5]. Obviously, as mentioned above, these events can be intrinsic to representative load histories, but their importance shows that the addition of overloads to improve QF readability can disturb the intrinsic crack growth acceleration/retardation behaviour and complicate the interpretation of spectrum severity changes.

Intrinsic overloads may occur as a natural part of a test spectrum. The transport aircraft gust spectrum TWIST, even when clipped to level III can cause significant intrinsic retardation [10],[35]. Other results, obtained with both TWIST and mini-TWIST, showed that the amount of retardation was greatly dependent on the clipping level for the high gust loads [10],[35],[36], being more pronounced for thinner sheet gauges.

Since even intrinsic crack growth retardation depends not only on the load history, but also the material thickness and peak load clipping levels, it is advisable not to alter the spectrum characteristics or add overloads without a thorough understanding of their effects. But the following example of an intrinsic overload shows that overloads can in some cases be of considerable use when QF is required.

5.2 Example 7: overload required in spectrum loading; AA2024-T8

This example concerns the proof tests required for continued service operation of the General Dynamics F-111 aircraft. The in-service load history for the wings of these aircraft was punctuated with limit load proof tests every 2000 service flight hours. The proof tests were for the wing root structure, which was made from an ultra-high strength steel. The proof test load was considerably higher than service peak loads, in part due to flight restrictions on the aircraft. These proof tests resulted in significant crack growth retardation in many locations of the AA2024-T8 lower wing structure, i.e. these loads were beneficial to the fatigue life of the wings in service. Figure 8 shows an example fracture surface produced by the service and proof test loads and subsequent full-scale fatigue test and proof test loads. The progression markings due to the proof test loads are very evident because they resulted from local tensile tearing.

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[4] Not to be confused, despite possibly similar appearances, with the stretch zones that occur when fatigue crack growth suddenly changes to final overload failure.

[5] The effects on crack initiation lives are uncertain because these have been little investigated, although 15% overloads at the beginning of the testing of low K_t AA7050-T7451 specimens made no statistical difference to the total lives or early crack growth rates. However, placing the same overload prior to the start of each of the loading blocks in this test series produced small but significant retardation during early crack growth [37]. (Early crack growth is often considered a part of crack initiation).

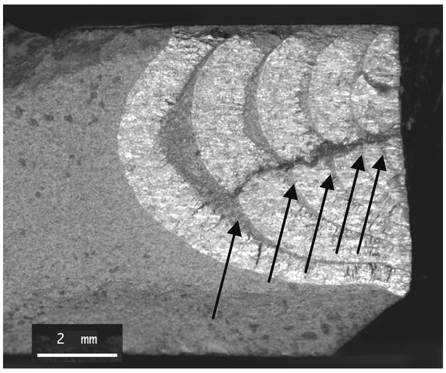


Figure 8 Optical image of a fatigue fracture surface from an AA2024-T8 wing plate: the crack grew from a poorly drilled fastener hole. The fracture surface markings due to the proof test loads are arrowed [38]

5.3 Underload or compression load additions

Fatigue cracks are generally thought to advance only during positive load excursions and then only when the crack faces are no longer in contact, i.e. the crack is fully open [39]. The latter assumption may not be entirely correct, but the general view suggests that compressive stresses arising from crack closure during negative load excursions will not cause significant changes in crack growth rates. However, there is compelling evidence that high compressive loads, for both long and small fatigue cracks, can cause accelerated crack growth, significant markings on the fracture surfaces, and changes in crack growth planes [25],[40]. These markings can be used as fracture surface markers [25],[41] see Example 8 after the following brief review of the literature.

Crooker [42] showed that the compression part of a fully reversed, tension/compression cycle could contribute up to 50% to the fatigue crack growth rates in medium-to-high strength steels and titanium alloys. Topper and Yu [43] measured near-threshold crack growth rates in AA2024-T351 specimens using baseline CA cycling interspersed with compressive underloads at varying intervals. The underloads always increased the overall crack growth rates.

Others have reported similar results, and an analogy can be made between these simple VA sequences and the complex VA load histories characteristic of transport aircraft lower wings. For example, De Jonge and Nederveen [44] found that when GAG cycles were removed from TWIST the fatigue crack initiation and growth lives of AA2024-T3 specimens increased by factors of 3.4 – 3.5.

Crack growth acceleration due to compressive underloads has been explained using crack closure concepts. Topper and Yu [43] suggested that compressive underloads flatten the asperities on fatigue fracture surfaces of aluminium alloys, resulting in less roughness-induced crack closure. This explanation appears very reasonable (although there are other hypotheses based on the plasticity states ahead of and/or behind the crack tip).

5.4 Example 8: underloads in simple CA loading; AA7050-T7451

Fatigue fracture surface markers due to underloads as per Example 1 when applied to AA7050-T7451 plate specimens are shown in Figure 9. A schematic of the CA + variable underloads load sequence is shown in Figure 2, which also shows optical and SEM images of a fracture surface region produced by repeats of this sequence when viewed perpendicular to the fracture plane. The underloads were easily identified. If we now look at this fracture at a high angle (about 60^o to the average fracture plane) as shown in Figure 9, we can see that the markers consist of both ridges and depressions (which may be associated with fissures). These markers were produced by the underloads and their nature depended on the local angle of fracture facets with respect to the overall crack growth direction. The depressions and fissures have formed on facets orientated such that they are upward-inclined when viewing in the crack growth direction; and ridges have formed on facets downward-inclined when viewing in the crack growth direction.

The ridges and depressions/fissures were previously noted by Abelkis [37] and Beachem [45], respectively. It is not commonly recognised that fatigue cracks can grow in this asymmetric fashion [25], but it may explain the variability of a single marker when it is followed around a crack front. A marker may change from ridges to depressions, and vice versa, depending on local fracture facet orientations, and may even disappear in some areas. This can also be the case for groups of loads, as will be shown in the next example.

Since the markings produced by underloads are generally well defined, their addition to CA or spectrum loading with high average mean stresses, or their association with large positive load excursions, would appear to offer promise as a marker strategy. Small groups of underloads should have little effect on spectrum severity provided they are applied *before* any high loads in the spectrum, rather than directly or shortly afterwards.

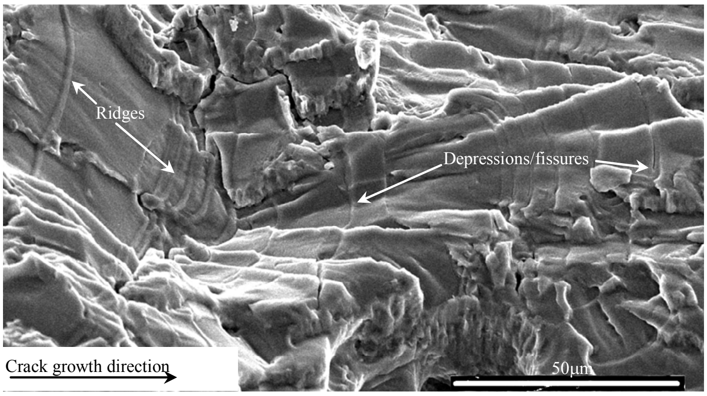


Figure 9 SEM image of repeated underloads on the fatigue fracture surface of an AA7050-T7451 specimen subjected to CA loading with intermittent underloads, see the schematic in Figure 2. The underloads produced well defined markers, depressions and fissures or ridges, depending on the local angles of fracture facets with respect to the overall crack growth direction (see text).

5.5 Example 9: underload groups in a fighter spectrum; AA7050-T7451

Two different underload groups were added to a manoeuvre spectrum, and it was found that five compressive loads associated with five large positive load excursions produced marker bands for most crack sizes when testing AA7050-T7451 specimens. Furthermore, there was only a very slight increase in spectrum severity. Figure 10a gives a schematic detail showing the five compressive loads that resulted in marker bands.

The marker bands were identifiable as apparently single markers when the cracks were very small, up to about 200 μm in depth. The optical image in Figure 10b illustrates this, where the K_{max} values ranged from about 1 – 4 MPa√m. Multiple cracking started from etch pits and coalesced rapidly to form a continuous crack front.

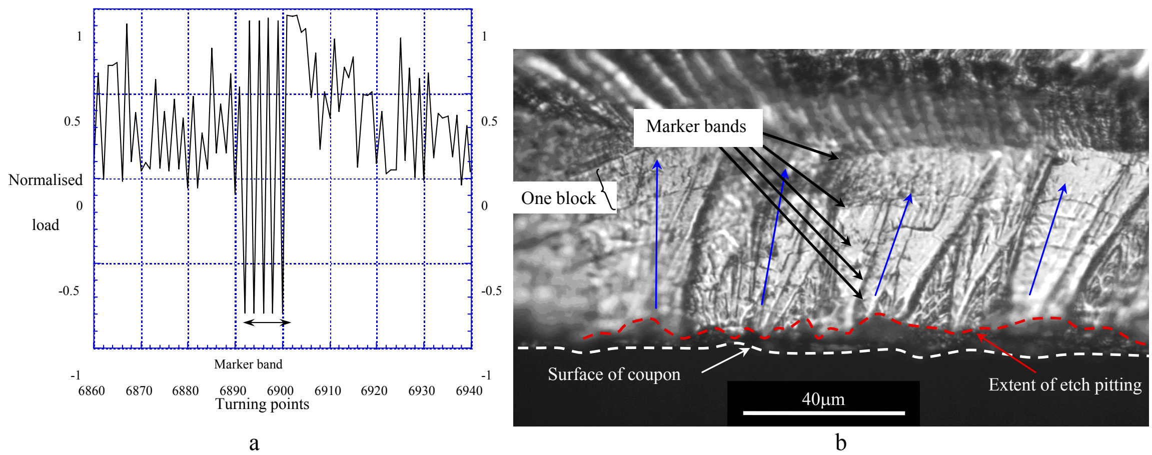
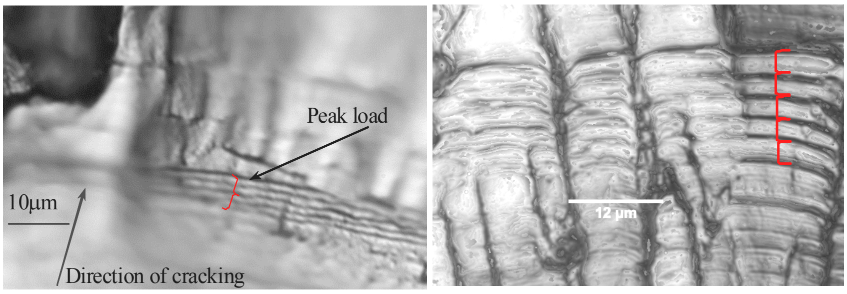


Figure 10 Schematic of the five compressive loads that resulted in marker bands shown in the included optical image near the crack origins: K_{max} ≈ 1 – 4 MPa√m. The bands appear to be single markers. Note that the markers are discontinuous along the crack fronts. The crack started from multiple origins on an etch pitted surface.

Figure 11 a & b show progressive changes in the marker band appearances with higher K_{max} values. At K_{max} ≈ 7 MPa√m the markers became individually recognisable, Figure 11a; and at K_{max} values above ≈ 10 MPa√m the markers appeared quite plastic, Figure 11b. At K_{max} ≈ 20 MPa√m the markers were often associated with local tensile tearing (not shown).



a b

Figure 11 View *a* shows an optical image of the underload marker band at a crack depth of about 0.3mm ($K_{max} \approx 9$ MPa√m). View *b* shows an optical image of the marker band at a crack depth of 1 mm,($K_{max} \approx 17$ MPa√m).

This series of images demonstrates that fractographers have to be aware of the changing appearances of marker bands. In the present example the bands first appeared as single markers, then as a group of five markers (relatively large striations). As crack growth continued the individual marker striations became less easy to distinguish from striations created by other loads in the spectrum. Also, as can be seen from Figure 11b, the marker striations can have a rippled microtopography, probably resulting from slip deformation. The ripples could easily be confused with striations from smaller loads in the spectrum, though they often interweave, which true striations never do. Finally, the optical image in Figure 10b shows that markers are not always visible all along crack fronts. This possibility was mentioned previously and will be shown again in Example 14.

Although the underloads in this example were effective for specimen testing, they were well beyond the negative-g design limit load of the fighter aircraft for which the spectrum had been developed. This made it inadvisable to apply these underloads during a full-scale test, since they could have caused buckling and subsequent static failures in those parts of the structure that were not designed to carry high compressive loads.

5.6 Summary of adding loads to the load spectrum

The following points can be made from the discussions and examples given in this Section:

1. Both overloads and underloads can be used to mark fatigue fracture surfaces.
2. Overloads will generally result in crack growth retardation.
3. Retardation may also occur after the application of severe simulated flights.
4. The extent of retardation can depend to some extent on the material, specimen configuration and spectrum clipping level.
5. Progression markings due to overloads are usually evident. They may also be accompanied by local tensile tearing, which can be very obvious.
6. The use of single or multiple underloads to precede an overload can intensify the overload marker. This allows smaller overloads to be used, thereby reducing any retardation.
7. Underloads generally add to the spectrum severity.
8. The absolute influence of underloads on spectrum severity is usually much less than that of overloads. This would appear to favour adding underloads, but....
9. Underloads will probably be difficult to apply in complex tests, since the underload level needed for producing good markers will usually be well beyond the negative loads in the rest of the spectrum. This means that buckling leading to static failure may occur without appropriate modifications to the test set-up, e.g. the provision of anti-buckling guides.

6 ADDING CA BANDS TO THE LOAD SPECTRUM

Groups or bands of CA loads may be used to obtain markers on fatigue fracture surfaces produced under both spectrum (VA) loading and CA loading. The bands usually contain many CA cycles, whose maximum and minimum loads may differ from those of the VA or CA loading to which they are added. Obviously, the choice of CA marker band load levels will depend on the overall load history. The markers produced by CA bands typically depend on:

1. The relative peak load levels of the bands and the overall load history.
2. The stress ratios, R, of the marker bands compared to the mean R of the loads preceding and following the bands.

3. The number of cycles in the bands.
4. The crack sizes and growth rates when the bands are applied.

6.1 Relative peak load level of a CA band

CA bands with peak load levels significantly different to those of the surrounding VA or CA load histories can produce marker bands that are readily visible owing to changes in fatigue fracture topography. This effect occurs on the fracture surfaces of several important alloy groups: high strength aluminium alloys, high strength steels and some titanium alloys [46],[47],[48].

In particular, for aluminium alloys the overall roughness of a fatigue fracture surface typically increases with increasing crack tip stress intensity factors. This means that applying a CA band with reduced K_{max} compared to the surrounding load history will generally produce a marker band that is flatter than the adjacent fracture surfaces, and therefore be observable. This is not always true, since at low growth rates CA marker bands may show a fine river pattern that makes them slightly rougher in comparison to the surrounding VA crack growth. This may be seen in the following example.

6.2 Example 10: CA bands in a manoeuvre spectrum; AA7050-T7451

Figure 12 shows two SEM images of fracture surface regions produced by repeats of the mini-FALSTAFF spectrum with added CA bands of R = 0 loading where the peak load in the bands was 80% of the peak load in the spectrum. The CA bands consisted of 800 cycles and were added every 15 loading blocks during the FINAL programme [49]. The number of cycles in the CA bands was chosen to obtain about the same amount of crack growth as a single mini-FALSTAFF loading block.

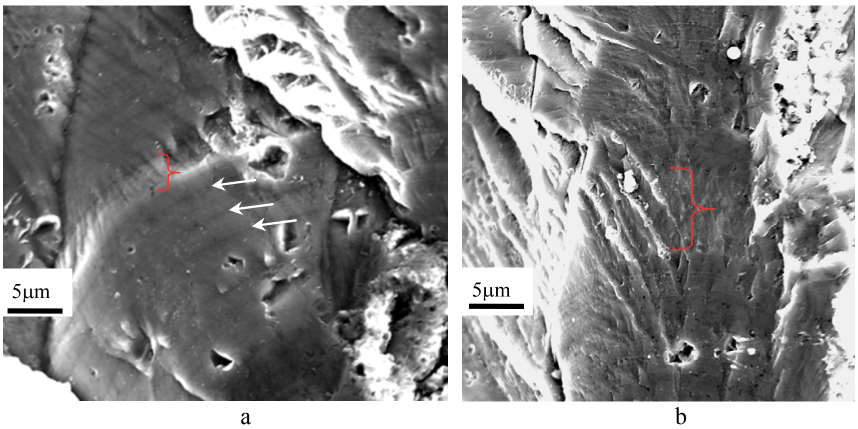


Figure 12 SEM images of CA bands between flight blocks of mini-FALSTAFF V2 loading on the fatigue fracture surface of an AA7050-T7451 specimen. Some of the flight blocks are arrowed in the left-hand image. The CA bands are indicated by brackets.

Figure 12a shows repeats of some of the loading blocks (arrowed) followed by a CA band (bracketed). Note the smoothness of the flight blocks fracture surface in contrast to the fine river pattern on the CA band fracture surface. Figure 12b is from a region of high growth rates, where both the flight blocks and a CA band (bracketed) produced fine river patterns on the fracture surface. Even so, the CA band is distinguishable from the flight blocks.

In this case, further crack growth allowed striations to become visible in the CA bands. The constant spacing of these striations, unlike the variable striation spacings in the flight blocks, made the CA bands fairly easy to detect at faster crack growth rates. This situation persisted until the spectrum peak loads caused local tensile tearing, which increased the overall fracture surface roughness. In turn, this resulted in local variations in the CA band striation spacings.

6.3 Stress ratio effects: CA band R compared to load spectrum R

Besides fine river patterns, CA bands may produce other fracture surface features that allow their detection against a backdrop of other CA or VA crack growth. For high strength aluminium alloys large changes in the R values of CA loading can cause sudden and quite steep changes in the fracture plane at many places around the crack front. The steepness of this change appears to depend on the R ratio, the crack tip K_{max} value, and the crystallographic orientation of the grain that the crack is currently growing in [25]. An example is given in Example 11.

Another possibility, adding another dimension to marker band detection, is CA band R-induced changes in oxidation colours on the fatigue fracture surfaces of gas turbine alloys tested at elevated temperatures. An example is given in Example 12.

For aluminium alloys, changes in the fracture plane can also occur owing to transitions from CA to VA loading and vice versa, notably when the CA band R is 0.5 or higher, and significantly different to the average R of the VA load spectrum. This can be seen in Figure 12a.

6.4 Example 11: R value changes for CA bands; 7050-T7451

Figure 13 shows a load history schematic consisting of four CA bands with differing R but the same peak load, together with an SEM image of the resulting fatigue fracture topography for an AA7050-T7451 coupon. The changes in the crack growth planes and their appearances are striking. In particular, the changes in crack growth planes often provide excellent markers.

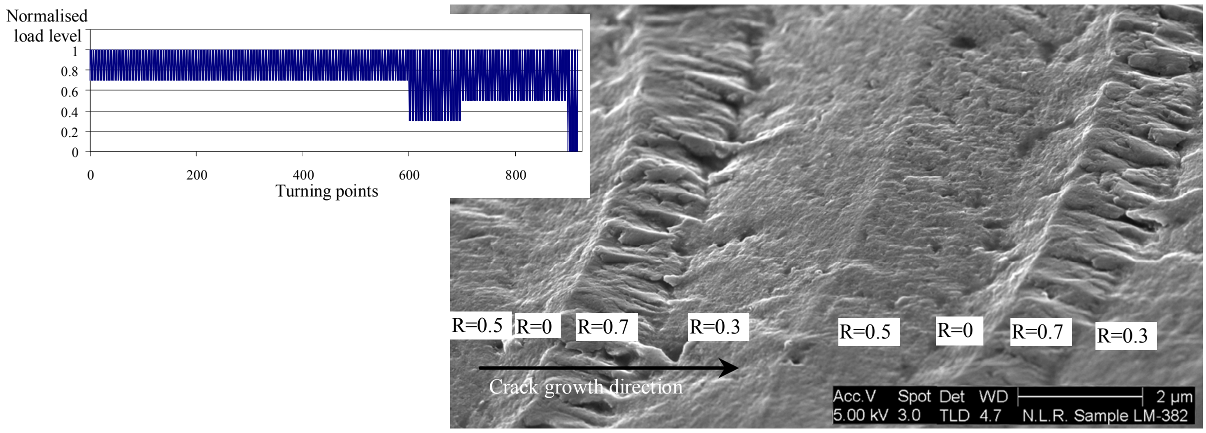


Figure 13 SEM image of R-induced changes in crack growth planes on the fatigue fracture surface of an AA7050-T7451 specimen tested with four CA bands. These bands had R values of 0.7, 0.3, 0.5 and 0 respectively. The large change from R = 0 to R = 0.7, which occurs twice in the image, was particularly effective at producing a marker.

6.5 Example 12: R value change for CA bands; Inconel 718

Fatigue fracture surface markers due to large changes in R were investigated for the nickel-base superalloy, Inconel 718, tested at 600 ºC in air [47]. The load history consisted of repeats of 1000 cycles at R = 0.1 and 1000 cycles at R = 0.8 with the same peak load, whereby the R = 0.1 load levels represented Low-Cycle Fatigue (LCF). The specimen configuration simulated the blade root notch at the rim of a turbine disc.

Figure 14 shows SEM and optical images of one of the fatigue fracture surfaces. The R = 0.8 CA bands resulted in some evident markers owing to changes in the oxidation colours as well as the topography.

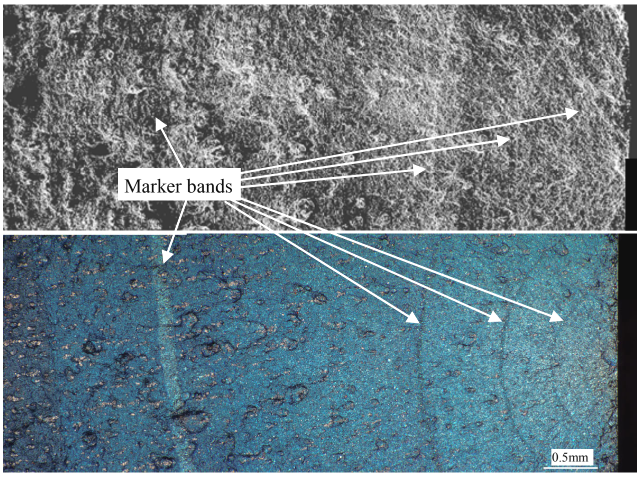


Figure 14 SEM and optical images of CA marker bands on the fatigue fracture surface of an Inconel 718 notched LCF specimen tested at 600 ºC in air.

6.6 Number of cycles in the CA bands and their periodicity

The widths of the CA bands can be important for their recognition. On the one hand, if the bands contain only a few cycles, they may be very difficult to detect near the crack origin and at low growth rates. On the other hand, if the bands contain many cycles they may become a major part of the overall crack growth process and lessen the test validity. This effect can be alleviated by altering the CA band periodicity, i.e. the ratio of CA bands to flight blocks; but it also introduces the complication of variable CA band contributions to the overall crack growth process.

Choosing an appropriate number of CA cycles will depend partly on the test requirements. If it is considered necessary to insert or add CA cycles for every flight block, a few (tens to hundreds) of CA cycles can be used to good effect in combination with a few underloads.

However, it may not be necessary to add a CA band for every loading block. Adding CA bands after a number of flight blocks will lessen their effect on the overall crack growth, thereby allowing more cycles within the bands and making them easier to detect. Demonstrations of this can be found in Examples 14 and16.

6.7 Variable CA band contributions to crack growth

The variability of CA band contributions to the overall crack growth process is a complication that may require detailed analysis. The cause of varying CA band contributions to crack growth may result from the change in crack growth plane associated with (1) the introduction of the CA band, (2) changes in crack tip stress intensity factors, and (3) changing crack closure conditions.

Be that as it may, there is an incentive to choose a CA band width and R value to minimise the variable contributions of the band to crack growth. It would seem best to choose a CA band R value close to the average R of the surrounding loading blocks. On the other hand, from Example 11 we have seen that large differences in R may produce the best markers.

One way out of this dilemma is to insert narrow CA bands with differing Rs into broader CA bands whose R is close to the average R of the surrounding VA loading. This should improve the marker band visibility.

6.8 Crack sizes and growth rates when the CA bands are applied

The crack sizes and hence crack growth rates at which CA marker bands are applied can have a strong influence on their relative contributions to the overall crack growth process. This is not the only effect, since the visibility of the CA bands on the fatigue fracture surfaces also varies. For small crack sizes and low growth rates the bands' fracture topography may blend in with the surrounding VA loading, while for long cracks and high growth rates the generally rough topography of the fatigue fracture surface can obscure the more subtle changes due to changing from VA to CA loading and vice versa.

For most DT analyses and assessments the foregoing problems are likely to be minor, since it is the mid-range of crack sizes and growth rates that are of most interest. On the other hand, a total life approach – which is becoming more favoured, as noted in the introduction to this paper − must account for at least the early part of crack growth.

6.9 Summary of adding CA bands to the load spectrum

As stated at the beginning of this Section, groups or bands of CA loads may be used to obtain markers on fatigue fracture surfaces produced under both spectrum (VA) loading and CA loading. From the subsequent discussions and examples the following general points can be made:

1. CA bands with peak load levels significantly different from those of the surrounding VA or CA load histories can produce readily visible markers owing to changes in fatigue fracture topography.
2. CA bands may produce other topographical features allowing them to be easily detected against a backdrop of other CA or VA crack growth. Notable examples are steep changes in the fracture plane.
3. Fracture plane changes may also occur when the CA loading is changed from one R value to another, particularly if the change is large.
4. Large differences between the CA band R values and the average R of the surrounding VA loading are favourable to producing good markers.
5. Conversely, similar R values for the CA bands and VA loading are unfavourable for good markers, although similar values are desirable to minimise varying contributions of the CA bands to crack growth. This dilemma can be alleviated by inserting narrow CA bands with differing R within broader CA bands whose R is close to that of the average R of the surrounding VA loading.
6. The crack sizes and growth rates at which CA marker bands are applied can have a strong influence on their relative contributions to the overall crack growth process.

7 COMBINATIONS OF MARKER STRATEGIES

The previous Examples have shown that there are many ways in which fairly straightforward changes and/or additions to a load history can result in good markers on fatigue fracture surfaces. In this section we shall consider some progressively more complicated combinations of strategies. As before, these strategies pursue the goals of (1) obtaining good markers while minimising their effects on the basic load histories, and (2) being able to account for the effects of the markers on the overall crack growth.

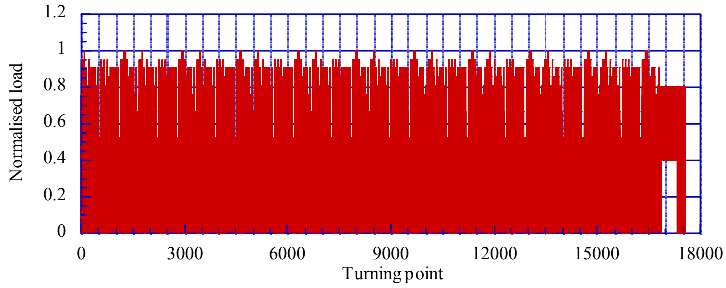
Minimising the effects of markers on the basic load histories is particularly important for fighter aircraft components, which are generally highly loaded. The fatigue lives are relatively short, compared to transport aircraft, and small critical crack sizes may be expected.

Combinations of CA bands can be used to produce markers that are easier to find than those produced by a single CA band. Some more examples are given in Examples 13, 14 and 15.

7.1 Example 13: R value changes for CA bands in VA loading; AA7075-T73

This example, Figure 15, concerns the addition of two CA bands with different Rs to a VA load spectrum used in testing an aircraft rudder hinge fitting made from AA7075-T73. There were several constraints on the use of marker loads:

1. The load history had to be all-tensile to be representative. This prevented adding negative underloads.
2. The critical location was shot peened. This prevented adding peak loads (overloads) higher than those in the spectrum, since the overloads might affect the peening residual stresses, making the test results meaningless.
3. The spectrum flight block was relatively short. Adding a marker band every block carried the risk of an excessive number of markers if cracks initially grew very slowly owing to the shot peening. Not only would a large number of closely-spaced markers be difficult to distinguish, but they would also contribute too much to the overall crack growth.
4. Optical QF would be preferable to SEM QF, in order to reduce time and costs.



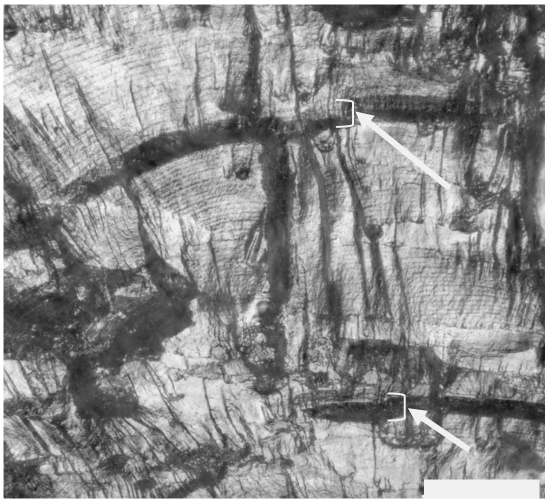


Figure 15 Schematic of the modified spectrum for the rudder hinge fitting, showing the ‘superblock’ consisting of ten flight blocks followed by two CA bands, and an optical image showing the marker bands at the end of two superblocks.

These constraints led to choosing a very specific marker combination:

- The markers were two CA bands with widely different R values. This combination was expected to result in slight changes in fracture plane that would show up well during optical fractography.
- The CA bands consisted of 500 R = 0.5 cycles followed by 200 R = 0.1 cycles, whereby the maximum load was 0.8 of the peak load in the spectrum flight block.
- The total number of cycles in the CA bands was chosen to obtain similar amounts of crack growth from the two bands in comparison to one test loading block: the flight block contribution was estimated using an analytical crack growth model.
- The marker bands were applied every ten flight blocks. This was to ensure that the markers would not be too close together and that errors in the crack growth equivalency of the two CA bands and one flight block would be small in terms of the overall crack growth. In other words, the entire load history was repeats of a “superblock” closely equivalent to 11 test loading blocks. This simplified the QF analysis.

Figure 15 shows a schematic of the “superblock”, with the two CA bands at the end, and an optical image of the repeat marker bands on the fatigue fracture surface of a rudder hinge fitting. Note that the marker bands are evident, as intended, but that the band can disappear at some locations owing to changes in grain orientation with respect to the crack growth direction.

7.2 Combinations of CA bands with counters

The idea of including “counters” in CA marker bands has been proposed and used by several investigators [50],[51],[52]. Example 14 began as a development of such a strategy. However, after several pilot tests the variations were abandoned in favour of the combination that gave the best markers at most crack sizes, for the reasons given in this example.

7.3 Example 14: CA bands with counter cycles; AA7050-T7451

In this example CA bands consisting of 400 R = -1 cycles (CA peak load = 0.5 of the VA peak load) were added to a VA manoeuvre loading spectrum, and counter cycles were added within the CA bands. The counters were varying low numbers of cycles with higher peak loads and lower underloads than those of the CA bands. This strategy worked reasonably well for identifying particular marker bands, albeit over restricted ranges of crack sizes (0.1 – 1 mm) and medium to fast growth rates ($2x10^{-8}$ – $2x10^{-6}$ m/striation for the counter cycles).

Figure 16 shows an SEM image of a marker band on the fatigue fracture surface of an AA7050-T7451 specimen tested primarily under VA loading. The marker band topography was generally smoother than that produced by the VA loading, as intended, but there were some interesting effects owing to the inclusion of 7 counter cycles:

1. The 200 CA band cycles after the counters resulted in significantly more crack growth than those before the counters. This suggests that the counters markedly changed one or more parameters (i.e. crack

closure level, residual stresses, cyclic plastic zone size, or amount of slip at the crack tip) controlling the local crack growth rates. The consequent increase in the contributions of the CA bands to the overall crack growth is undesirable

2. The generally smoother fracture topography of the CA band was less evident after the counters, making it sometimes less easy to make QF measurements.

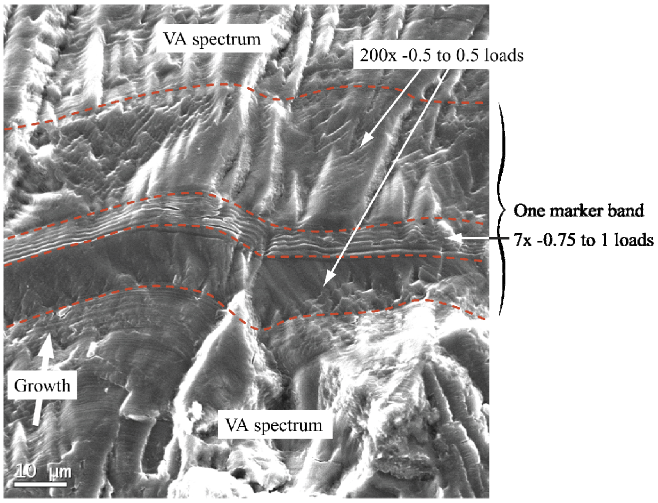


Figure 16 SEM image of a CA band containing counter cycles on the fatigue fracture surface of an AA7050-T7451 specimen.

The first effect means that counters increased the CA band contributions to overall crack growth. This is undesirable, as is the second effect, but both are considered tolerable in view of the following main advantage of counters:

- Readable counters allow crack growth increments to be located precisely during the total life of a crack, whereas the positions of straightforward marker bands can be uncertain if only a few are detectable.

Owing to this advantage, the CA band + counter strategy should certainly be considered, even if used only two or three times during the growth of a crack. In the light of the comments at the beginning of this Subsection, this possibility would seem particularly relevant to QF for DT investigations of slow growing cracks. We conclude that more work needs to be done on selecting the optimum R values for CA bands and counters.

7.4 Example 15: spectrum modification + CA bands; AA7050-T7451

In testing of used Centre Barrel (CB) bulkheads from F/A-18 A/B aircraft [49], spectrum modifications were evaluated using low K_t “dogbone” specimens, resulting in selection of a modified mini-FALSTAFF spectrum where the flights with the high loads were moved closer together as was done in Example 5.

Although the spectrum modification was considered successful for most crack sizes and growth rates in simple specimens, it was envisaged that the full-scale tests would provide some problems with respect to QF readability:

1. The modified mini-FALSTAFF flight block markings would be very closely spaced on the fracture surfaces near the origins of any slow-growing cracks.
2. From full-scale test experiences [34],[45],[53],[49] parts of the fatigue fracture surfaces of some, if not many, of the cracks should be anticipated to be in poor condition in comparison to specimen tests. This is because full-scale tests are longer running and much more complicated than specimen tests, with greater opportunities for fracture surface deterioration owing to local corrosion and contamination by e.g. fretting products, sealant, paint, oil and grease.
3. The tests were to be continued after local failures and subsequent repairs, making it difficult to externally observe any additional cracking and hence essential to be able to do QF measurements.

To improve overall QF readability it was decided to add CA marker bands to the spectrum. The CA bands consisted of 800 R = 0 cycles, whereby the maximum load was 0.8 of the peak load in the spectrum loading block. The first CA band was applied after 30 loading blocks and subsequently after every 15 loading blocks.

This combined load history was intended to enable QF measurements of slow growing cracks via the CA band positions, and faster growing cracks via the flight blocks.

The choice of R = 0 for the CA bands was dictated not only by their ability to provide markers, but also by a more subtle consideration. Many of the cracks occurring in the full-scale tests would likely be generated by secondary bending loads, mainly at integral flanges and stiffeners in the CB bulkheads. To cause cracking, the secondary bending loads in the bulkheads would have to be predominantly tensile, even though the primary loading condition might be dominated by the compressive loads applied to the bulkheads. This reversal of the primary loads would render the CA (R = 0) band cycles ineffective, since they would then be entirely compressive. On the other hand, if the secondary bending loads derived directly and predominantly from the primary tensile loads, then the CA band cycles should cause crack growth. In other words, the presence or absence of CA marker bands on the fatigue fracture surfaces would be diagnostic for the secondary bending loads.

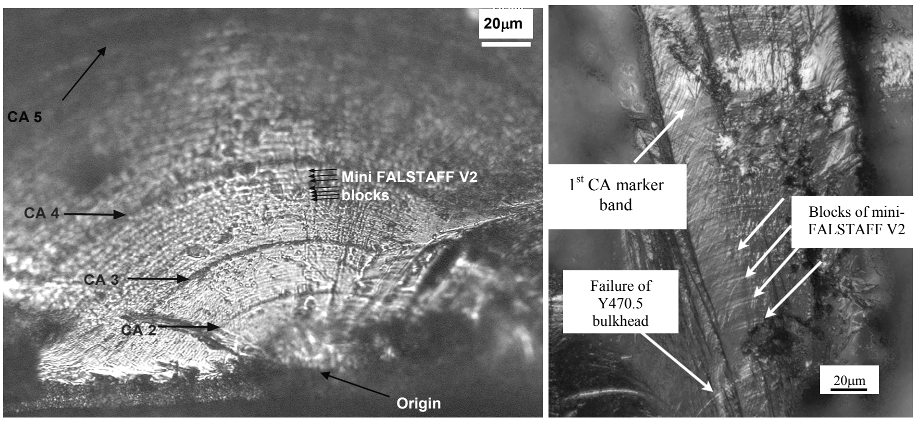


Figure 17 The first optical image shows repeating flight blocks and several CA marker bands (arrowed). In detail the image shows the 2nd, 3rd, 4th and 5th CA marker bands with 15 repeats of the modified mini-FALSTAFF loading block between each. The crack originated from surface pitting under an Ion Vapour Deposition (IVD) coating. The second optical image shows the 1st CA marker band, repeats of loading blocks, some of which are arrowed, and an incidental marker owing to a transient load caused by failure of an adjacent bulkhead.

Figure 17 gives an example of a fracture surface from the full-scale tests. The first image in this Figure illustrates the usefulness of the CA marker bands, since the block markings were very fine.

The second view in Figure 17 shows a fracture surface for a bulkhead crack with an unanticipated marker owing to a transient load caused by failure of an adjacent bulkhead. Such incidental markers can help establish the sizes of any cracks influenced by transient loads at the times of major failures of integral components, or partial failures during tests on multiple load path components. These markers can also aid in determining whether subsequent crack growth was affected by the failures or not.

7.5 Summary of combinations of marker strategies

Combinations of CA bands:

1. A combination of two CA bands with widely different R values can provide very good markers over a wide range of crack sizes, and down to a few tens of microns from the fatigue origin. This combination works very well for high strength aluminium alloys and reasonably well for high strength steels.
2. The fracture plane changes between bands result in good optical contrast that makes QF easy using a high powered optical microscope.
3. The contrast between bands is less visible during SEM examination, but the bands are still readily found.
4. The fracture plane changes along any single marker band are intermittent. This indicates that the changes depend on the local crystallographic orientations of the grains through which the crack grows.

Combinations of CA bands with counter cycles:

1. The use of counter cycles within CA bands may provide reasonably good markers over restricted ranges of crack sizes (0.1 – 1 mm) and crack growth rates (between about $2x10^{-5}$ – $2x10^{-3}$ mm/striation) for the counter cycles. These ranges could probably be extended by using counter cycle bands.
2. Counter cycles combined with CA bands tend to contribute too much crack growth unless the combinations are applied infrequently, e.g. after certain numbers of VA flight blocks.

Spectrum modification + CA bands:

1. CA marker bands added periodically to VA flight blocks can be very useful for QF of fatigue cracks in components undergoing full-scale tests. The CA bands are especially useful for small crack sizes and slow crack growth rates; and also for fracture surfaces partially obscured by local corrosion and contamination (sometimes unavoidable in these long running and complicated tests).
2. Judicious choice of the CA band R value can aid in determining the source of the local secondary bending loads that may be responsible for some of the cracking.

8 CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS

The examples and discussions presented have reviewed a number of methods of providing fatigue fracture surface markers to aid QF of fatigue crack growth. These methods are based on load changes, including reordering the basic load histories and/or adding loads to them.

The main reason why we have prepared this paper is to provide some guidelines for obtaining recognisable markers for a variety of load histories and crack growth regimes in the locations of interest for full-scale tests. As has been indicated, this may be no easy task. There is much to consider, and not all candidate marker load strategies will result in immediate success. Hence it will often be necessary to carry out pilot tests using simple coupon specimens.

The actual approach and choice of marker load strategy that is finally adopted will depend on several factors, including the main purpose of the test, the component or structural configuration, the expected load history, the crack growth regimes of interest, the materials involved, and the test duration.

8.1 Test plan for providing post-test QF-readable fatigue fracture surfaces

The test plan for providing post-test QF-readable fracture surfaces could proceed in the following stages:

1. Examine the spectrum to be applied, noting its form. Spectra with notably different load groups may provide well defined natural markers on fracture surfaces. These spectra may contain large numbers of grouped low loads with periods of higher loading, e.g. the lower wing loads of military transport aircraft in operations where occasional tactical manoeuvring is required, or in many civil transport operations where severe gust loading is included in occasional flights.
2. Consider re-arranging the spectrum to place high loads or high load excursions closer together, or group large numbers of low similar loads. These can be easy modifications if the high loads in the spectrum can be arranged to provide evident markers without changing the validity or severity of the spectrum, or if such changes can be accounted for.
3. If rearrangement is insufficient or unfeasible, then consider what would be the best type of addition to the spectrum: overloads, underloads, CA loading groups, or combinations of these. All have been successful in producing observable markers on fatigue fracture surfaces. Generally it can be said that:
   - Overloads may lead to crack growth retardation, which is difficult to account for and may make the test unconservative.
   - Underloads may cancel crack growth retardation and lead to conservative results, but they are some times impractical to apply.
   - CA bands, if well chosen, will produce good markers, although to do this they may need to contain many cycles and thus consume a notable percentage of the crack growth life. Additionally they may not have a consistent effect over the full extent of crack growth. A two-phase CA band, when well chosen, will generally give very good marker bands on fracture surfaces from the crack origin to the failure depth: a few tens of microns to tens of millimetres!
4. Determine the number of markers required to achieve the test aims.

5. Determine whether a secondary marking scheme will be required, either to account for long-lived cracks or as an aid to defining the position of the markers that can be observed.
6. When spectrum modifications and the addition of marker loads are contemplated it is always advisable to carry out some simple testing at a representative load level, in order to confirm or determine the effects on the spectrum severity. Here QF is again invaluable.
7. Aim to produce markers that have good optical contrast at relatively low magnifications (compared to the capabilities of an SEM). This will allow relatively easy QF with either a low- or high-powered optical microscope.
8. Remember that even with a very effective marker strategy there will be some areas around any particular marker band where the band is not observable.

8.2 Marker load strategies

Marker loads for CA load histories: The following additions to CA load histories will produce markers on most aircraft alloy fatigue fracture surfaces:

1. Single underloads. These may be considered as single changes in R. Underloads are particularly effective for cracks growing under high-R CA loading. They are not expected to provide good markers for cracks grown at lower R values.
2. Overloads. These will be particularly effective for all CA loadings. Unfortunately they can be expected to change the effectiveness of the CA loading, though there may be situations where this is acceptable.
3. Groups of CA loads with different R. If the R value is significantly different to the basic CA R value, then such a change may be effective. The number of cycles required in a group (CA band) can be estimated by simple fatigue prediction methods, although pilot tests will usually be necessary to validate the effectiveness. The effect of the CA band R on the basic crack growth rates may also be questioned. For this reason it may be useful to evaluate the effect of varying the number of basic cycles between the CA bands.

Marker loads for VA load histories: The following additions to VA load histories will produce markers on most aircraft alloy fatigue fracture surfaces:

1. Flight repositioning. Placing flights with high loads close together and/or flights with long runs of similar loads together has been found to be effective. Gust spectra usually have many low loads that if grouped will produce good markings. Thus both options are feasible. The extent of the rearrangement will depend on the aims of the testing and the ability to interpret the loading changes.
2. Underloads. Groups of underloads may be useful, while single underloads will probably be unsuccessful.
3. Overloads. These will be particularly effective if above about 120% of the peak load in the spectrum. Unfortunately, they can be expected to change the effectiveness of many subsequent loads, although there may be situations where this is unimportant.
4. Groups of CA loads. If the CA load mean R value is significantly different to that of the spectrum, then the addition of groups of CA loads can mark by causing crack path changes. For CA loads with a similar mean *R* the crack path change still can be sufficient to provide visible markers. The number of CA cycles required will usually be significant, and this needs to be assessed in view of the aims of the testing – typically, the smaller the group of CA loads, then the harder it is to find the markers. The effect of the CA group on the crack growth rate of the spectrum loading may also be a concern.
5. Combinations of the above. In some cases, combinations of marker strategies may be useful, but these need to be carefully considered in the light of the test objectives.

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10 REFERENCES

[1] Jones, K., McCowin, R., Harris, B. (2006): Current Health of the F-16 Fleet, In: *Proceedings of the USAF Aircraft Structural Integrity Program (ASIP) Conference*, San Antonio, Texas, November 28 − 30, 2006.

[2] Moore, C. D. (2007): Aircraft Structural Integrity and the F-22, In: *Proceedings of the USAF Aircraft Structural Integrity Program (ASIP) Conference*, Palm Springs, California, December 4 − 6, 2007.

[3] GlobalSecurity (2007): http://www.globalsecurity.org/military/systems/aircraft/f-16-life.htm

[4] MIL-STD-1530A (11) (1975): Airplane Structural Integrity Program, Airplane Requirements, Military Standard, USAF.

[5] Glaessgen, E. H., Saether, E., Yamakov, V. (2008): Multiscale Modeling of Damage Processes in FCC Aluminum: from Atoms to Grains, In: *Proceedings of the Eleventh Joint FAA/ DoD/ NASA Conference on Aging Aircraft*, Phoenix, Arizona, April 21 – 24, 2008 (to be published).

[6] Liao, M., Benak, T., Renaud, G., Yanishevsky, M., Bellinger, K., Mills, T., Prost-Domasky, S., Honeycutt, K. (2008): Development of Short/Small Crack Model for Airframe Material: 7050 Aluminum Alloys, In: *Proceedings of the Eleventh Joint FAA/ DoD/ NASA Conference on Aging Aircraft*, Phoenix, Arizona, April 21 – 24, 2008 (to be published).

[7] Schijve, J. (1967): Significance of Fatigue Cracks in Micro-range and Macro-range, *Fatigue Crack Propagation, ASTM STP 415*, Editors J.C. McMillan and R.M.N. Pelloux, American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 415-459.

[8] Suresh, S., Ritchie, R.O. (1984): The Propagation of Short Fatigue Cracks, *International Metallurgical Reviews*, Vol. 29, pp. 445-476.

[9] Wanhill, R.J.H. (1986): Short Cracks in Aerospace Structures, *The Behaviour of Short Fatigue Cracks, EGF Pub 1*, Editors K.J. Miller and E.R. de los Rios, Mechanical Engineering Publications, London, pp. 27-36.

[10] Wanhill, R. J. H. (1994a): Damage Tolerance Engineering Property Evaluations of Aerospace Aluminium Alloys with Emphasis on Fatigue Crack Growth, NLR Technical Publication TP 94177 U, National Aerospace Laboratory NLR, Amsterdam.

[11] Barter, S. A., Wanhill, R. J. H., Marker Loads for Quantitative Fractography (QF) of Fatigue in Aerospace Alloys, NLR Client report NLR-TR-2008-644. National Aerospace Laboratory, NLR., Amsterdam The Netherlands. Nov. 2008.

[12] Schijve, J. (1973): Effect of Load Sequences on Crack Propagation under Random and Program Loading, *Engineering Fracture Mechanics*, Vol. 5, pp. 269-280.

[13] Willard, S. A. (1997): Use of Marker Bands for Determination of Fatigue Crack Growth Rates and Crack Front Shapes in Pre-corroded Coupons, NASA/CR-97-206291, NASA Langley Research Center, Hampton, Virginia.

[14] Wanhill, R. J. H., Hattenberg, T. (2006): Fractography-based Estimation of Fatigue Crack "Initiation" and Growth Lives in Aircraft Components, NLR Technical Publication TP-2006-184, National Aerospace Laboratory NLR, Amsterdam.

[15] AGARD-CP-376 (1984): *Fatigue Crack Topography*, Advisory Group for Aerospace Research and Development, Neuilly-sur-Seine.

[16] Broek, D., Van der Vet, W.J. (1968): Systematic Electron Fractography of Fatigue in Aluminium Alloys, NLR Technical Report TR 68002 U, National Aerospace Laboratory NLR, Amsterdam.

[17] Nix, K. J. (1980): The Metallography of Fatigue in High Strength Aluminium Alloys, PhD. Thesis, Department of Metallurgy and Materials Science, Imperial College London , London.

[18] Nedbal, I., Siegl, J., Kunz, J. (1989): Relation Between Striation Spacing and Fatigue Crack Growth Rate in Al-alloy Sheets, *Advances in Fracture Research*, *Proceedings of the 7th International Conference on Fracture (ICF7)*, Editors K. Salema, K. Ravi-Chandar, D. M. R. Taplin and P. Rama Rao, Vol. 5, Pergamon Press, Oxford, pp. 3483-3491.

[19] AGARD-R-767 (1990): *Short-Crack Growth Behaviour in Various Aircraft Materials*, Advisory Group for Aerospace Research and Development, Neuilly-sur-Seine.

[20] Barter, S. A., Sharp, K. P., Holden, G and Clark, G. (2002): Initiation and Early Growth of Fatigue Cracks in an Aerospace Aluminium Alloy, *Fatigue and Fracture of Engineering Materials and Structures*, Vol 25, pp. 111-125.

[21] Wanhill, R.J.H., Barter, S.A., Hattenberg, T. (2009): Fractography-assisted Observations on Fatigue Thresholds in an Aerospace Aluminium Alloy, NLR Technical Publication *in preparation*, National Aerospace Laboratory NLR, Amsterdam.

[22] Simpson, D. L., Landry, N., Roussel, J., Molent, L., Graham, A. D., Schmidt, N. (2002): The Canadian and Australian F/A-18 International Follow-On Structural Test Project, In: *Twenty Third Congress of the International Council of the Aeronautical sciences, Proceedings of the ICAS 2002 Congress*, Toronto, September 8 – 13, 2002.

[23] Molent, L., Dixon, B., Barter S. (2005): The FINAL Program of Enhanced Teardown for Agile Aircraft Structure, In: *Proceedings of the Eighth Joint FAA/ DoD/ NASA Conference on Aging Aircraft*, Palm Springs, California, January 31 – February 3.

[24] Cutshall, J., Blinn, M., Burnside, H., Whitman, Z. and Howell, R. (2007): T-38 Fuselage Structural Life Assessment, In: *Proceedings of the USAF Aircraft Structural Integrity Program (ASIP) Conference*, Palm Springs, California, December 4 − 6.

[25] White, P., Barter, S. A., Molent, L. (2008): Observations of Crack Path Changes Caused by Periodic Underloads in AA7050-T7451, *International Journal of Fatigue*, Vol. 30, pp. 1267-1278.

[26] Abelkis, P. R. (1974): A Study of Fatigue Life and Crack Propagation under Flight-by-flight Loading Spectra, IRAD Technical Report MDC-J5672, Douglas Aircraft Company, Long beach, California.

[27] Hattenberg, T. (1994): Fractographic Investigation of Cracks Found in Vertical Stabilizer Main Hinge Fitting During the 2nd Phase of Fokker 100 TA-22B Testing, NLR Contract Report CR 94123 C, National Aerospace Laboratory NLR, Amsterdam.

[28] Jonge, J. B. de, Schütz, D., Lowak, H., Schijve, J. (1973): A Standardised Load Sequence for Flight Simulation Tests on Transport Aircraft Wing Structures, NLR Technical Report TR 73029 U, National Aerospace Laboratory NLR, Amsterdam.

[29] Lowak, H., de Jonge, J. B., Franz, J., Schütz, D. (1979): MINITWIST - A Shortened Version of TWIST, NLR Miscellaneous Publication MP 79018 U, National Aerospace Laboratory NLR, Amsterdam.

[30] Siegl, J., Schijve, J. (1990): Fractographic Observations on Fatigue Crack Growth under MiniTWIST Flight-simulation Loading, Report LR-631, Delft University of technology, Delft.

[31] Dijk, G. M. van, de Jonge, J. B. (1975): Introduction to a Fighter Aircraft Loading Standard for Fatigue Evaluation “FALSTAFF”, *Problems with Fatigue in Aircraft, Proceedings of the Eighth ICAF Symposium*, Swiss Federal Aircraft Establishment (F+W), Emmen, pp. 3.61/1 − 3.61/39.

[32] Barter, S. A., Clark, G., Goldsmith, N. T. (1993): Influence of Initial Defect Conditions on Structural Fatigue in RAAF Aircraft, *Durability and Structural Integrity of Airframes, Proceedings of the 17th ICAF Symposium*, Stockholm, Editor A.F. Blom, Engineering Materials Advisory Services, Warley, West Midlands, pp. 281-304.

[33] Linden, H. H. van der (1984): Modifications of Flight-by-flight Load Sequences to Provide for Good Fracture Surface Readability, *Fatigue Crack Topography*, AGARD Conference Proceedings No.376, Advisory Group for Aerospace Research and Development, Neuilly-sur-Seine, pp. 11-1 − 11-17.

[34] Dainty, R. V. (1984): Use of ‘Marker Blocks’ as an Aid in Quantitative Fractography in Full-Scale Aircraft Fatigue Testing: A Case Study, *Fractography of Ceramics and Metal Failures, ASTM STP 827*, Editors J.J. Mecholsky and S.R. Powell, Jr., American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 285-308.

[35] Wanhill, R. J. H. (1994b): Flight Simulation Fatigue Crack Growth Testing of Aluminium Alloys, *International Journal of Fatigue*, Vol. 16, pp. 99-110.

[36] Schijve, J., Vlutters A.M., Ichsan, S.P., ProvoKluit, J. C. (1985): Crack growth in Aluminium Alloy Sheet Material under Flight-Simulation Loading, *International Journal of Fatigue*, Vol. 7, pp. 127-136.

[37] Pell, R. A., Molent, L., Green, A. (2004): The Fractographical Comparison of F/A-18 Aluminium Alloy 7050-T7451 Bulkhead Representative Coupons Tested Under Two Fatigue Load Spectra at Several Stress Levels, DSTO Technical Report DSTO-TR-1547, Defence Science and Technology Organisation, Melbourne.

[38] Molent, L., Boykett, R., Walker, K. (2008): Maintaining Reliability and Availability in a Sole Operator Environment, Research and Technology Organisation Meeting Proceedings RTO-MP-AVT-157, Montreal, Canada 13th – 16th October.

[39] Elber, W. (1971): The Significance of Fatigue Crack Closure, *Damage Tolerance in Aircraft Structures, ASTM STP 486*, American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 230-242.

[40] Dawicke, D. S. (1997): Overload and Underload Effects on Fatigue Crack Growth Behavior of Aluminum Alloy 2024-T3, NASA Contract Report NASA/CR 201668, NASA Langley Research Center, Hampton, Virginia.

[41] Barter, S. A., Price, J. (2000): Effect of Surface Preparation treatments on Fatigue Life of 7050-Aluminium Alloy, In: *Proceedings of Symposium 2000 on Structural Integrity and Fracture*, Edited by G. Heness., University of Technology, Sydney, Published by the Institute of Metals and Materials Australasia, Melbourne, June 29 30, pp. 140-153.

[42] Crooker, T. W. (1971): Effects of Tension-Compression Cycling on Fatigue Crack Growth in High Strength Alloys, *Journal of Engineering for Industry*, Vol. 93, pp. 893-896.

[43] Topper, T. H., Yu, M. T. (1985): The Effect of Overloads on Threshold and Crack Growth, *International Journal of Fatigue*, Vol. 7, pp. 159-164.

[44] Jonge, J. B. de, Nederveen, A. (1980): Effect of Gust Load Alleviation on Fatigue and Crack Growth in ALCLAD 2024-T3, *Effect of Load Spectrum Variables on fatigue crack Initiation and Propagation, ASTM STP 714*, American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 170-184.

[45] Beachem, C. D. (1967): Microscopic Fatigue Fracture Surface Features in 2024-T3 Aluminum and the Influence of Crack Propagation Angle upon their Formation, *ASM Transactions Quarterly*, Vol. 60, pp. 630-643.

[46] Rusk, D, T., Arocho, A., Pierce, J., Abfalter, G. (2008): Results of Fatigue Tests of Bare AF1410 Steel Unnotched Flat Plates with Surface Corrosion Damage, Engineering Data Report ADA481230, Naval Air Systems Command, Structures Division, Patuxent River, Maryland.

[47] Wanhill, R. J. H., Hattenberg, T., Ten Hoeve, H.J. (1996): Fractographic Examination of Three EGT Rim Specimens, NLR Contract Report CR 96451 C, National Aerospace Laboratory NLR, Amsterdam.

[48] Huynh, J., Molent, L., Barter, S. A. (2003): Fatigue Life Analysis of the F/A-18 Wing Fold, DSTO-TR-1484, Defence Science and Technology Organisation, Melbourne.

[49] Molent, L., Barter, S. A., White P., Dixon B. (2005): Summary of Recent Australian Full-Scale F/A-18 Fatigue Tests, In: *Proceedings of the Eleventh Australian International Aero Space Congress*, Melbourne, Victoria March 13 – 17.

[50] Conley, F. M. and Sayer, R. B. (1977): Correlation of Predicted and Actual Crack Growth in a Transport Wing, In: *Proceedings of the AAIA/ASME 18th Structures, Structural Dynamics & Material Conference, Volume A*, San Diego, California, March 21 − 23, pp. 119-130.

[51] Sunder, R. (1983): Binary Coded Event Registration on Fatigue Fracture Surfaces, *Proceedings of the International Conference on Digital Techniques in Fatigue (SEECO '83)*, Editor B.J. Dabell, Society of Environmental Engineers, London, pp. 197-218.

[52] Prakash, R. V., Sunder, R. (2007): Crack Closure Stress Estimation by Decodable Marker Banding Techniques and Comparison of Results with Electron Fractographic Technique, *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, Vol. 221, pp. 53-62.

[53] Barter, S. A., Molent, L., Landry, N., Klose, P., White, P. (2003): Overview of the F/A-18 Aft Fuselage Combined Manoeuvre and Dynamic Buffet Fatigue and Residual Strength Testing. In: *Proceedings of the Tenth Australian International Aero Space Congress,* Brisbane. Queensland July 29– August 1.