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QF MARKER RESEARCH

Risto Laakso, Keijo Koski, Aleks Vainionpää, and Aslak Siljander

VTT Technical Research Centre of Finland Ltd
P.O. Box 1000, FI-02044 VTT, Finland
firstname.lastname@vtt.fi

Abstract: Experimental crack growth rates using actual load histories increase confidence level of a structural lifetime in two ways: damage rates can be (1) used as a direct estimation method in defining the remaining useful lives, and (2) used in selection of the proper calculation parameters.

Post-test quantitative fractography (QF) together with embedded marking sequences in the fatigue loading enables to determine the crack growth curves experimentally. The periodically applied markers leave a trace along the fracture surface of the progressing crack. The identification of the traced markers depends on the load and condition history, as well as on the skills of the analyst, and can be carried out with e.g. an optical microscope (OM) or a scanning electron microscope (SEM).

The main research questions are a) how to define and add marker blocks to a given real usage spectrum of a fighter aircraft, b) the former in terms of effects on both small aluminium specimen and full-scale fatigue tests, c) the former two without affecting the structural lifetime of the test article, and finally d) the applicability of the QF in analysing small crack growth. The future research question is how to use machine learning to automate the marker identification process.

Functionality of marker loads especially in relatively short and slow fatigue crack growth (FCG) region is of primary interest. If every loading spectrum contains natural or inserted markers, distinguishability might become a problem during the early stages of the FCG. The marker loading can also appear differently on the surface as the crack growth progresses.

The work started with a literature review, followed by a pre-planning of the marker loads. The pre-chosen marker blocks were calculated with crack growth analysis to see the effects of markers on the structural life. Specified fatigue tests were arranged to obtain experimental results. The research is ongoing, thus only preliminary, and intermediate results can be presented. Taken the intermediate objectives into account, the QF results were examined: the hypothesis to use an optical microscope alone, cost-effectively, and appropriately in tracing the crack growth particularly at small crack sizes was tested by comparing obtained findings during SEM usage of this and previous projects.

Keywords: QF, markers, SEM, OM, small crack growth

INTRODUCTION

Since the main objective of the ability to analyse small cracks is to obtain crack growth curves based on physical evidence, the marker bands identified with quantitative fractography from the fracture surface must be combined with the load history.

The marker blocks, i.e. some additional loading cycles, were included in the F/A-18 Hornet basic operational loading spectrum ("BOS2", Figure 1) of the Finnish Air Force (FINAF). The FINAF-typical spectrum causes severe structural fatigue in practice. Laboratory loading levels were adjusted in terms of fatigue lives of several types of small specimens. In addition, some natural parts of the spectrum that presumably leave visible and traceable markers were present (areas A and B, Figure 1).

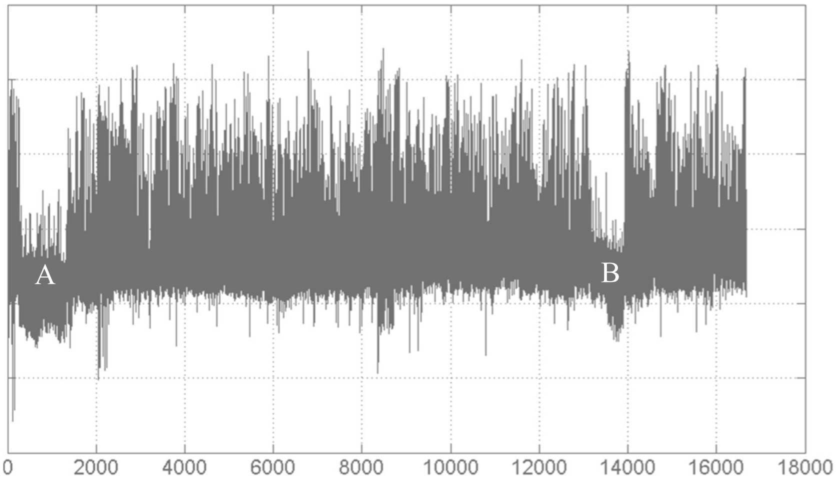


Figure 1: FINAF's BOS2 spectrum. Horizontal axis: number of turning points; vertical axis scale hidden. Two weakly influencing parts, possible causing natural visible markings (e.g. beach marks and striations), are visible at around areas from 300 to 1400 turning points (A) and from 13200 to 14000 turning points (B).

Marker block versions to be tested were selected based on the report "Study of Marker Loads" [9]. The report [9] was compiled particularly according to Reference [3], but also more extensive literature review was included.

In selection of markers to be tested, both fracture mechanics analysis [1] and well-known characteristics of the material (alloy) and the spectrum are valuable. Possible negative effect of marker loads on fatigue lives of specimens was evaluated with fracture mechanics and with fatigue tests. However, calculations or e.g. visual examination of the spectrum itself as a time history do not help in evaluating the visibility of the marker block on a fracture surface. The desirable effect on the functionality of experimental crack growth analysis was determined with QF.

Several fatigue life and fracture surface studies were carried out, the purpose of which, in addition to investigate possible changes in fatigue lives and in test duration, was to ensure that the added marker loads – and natural marker-like parts of the spectrum – leave visible and traceable bands on the surfaces.

At first, only the scanning electron microscope was used to assess the functionality of the marker loads. However, in QF-marker tasks, the use of SEM was found to be too time-consuming [8] [10] [12] and inconsistent in comparison with Reference [3]. Now, in this study, for a moment, and for the sake of comparison, both SEM and optical microscope were in use. In the end part of the study and from then onwards, the primary equipment is meant to be the optical microscope.

Once the marker block type was selected, a test series with approx. 100 specimens was launched. Within fatigue tests, initial QF analyses were carried out to achieve crack growth curves and to have more feedback regarding marker loads. In addition, more accurate estimates of required time for analysing fracture surfaces with an optical microscope were achieved and compared to SEM analyses.

DEFINING AND ADDING MARKER LOADS

Starting point

In addition to experimental fatigue test results, also fracture surfaces can be used in determining the structural lifetime. From fractures, an attempt can be made to estimate the crack growth rate by observing the number of test spectra along the crack. If there are no natural marker loads within the spectrum itself that would already leave traces on the fracture surfaces suitable for observing spectrum repetitions, at least one additional marker load area, with minimal effect on structural lifetime, must be inserted to the spectrum.

Without fatigue calculations, fatigue testing, and quantitative fractography, straightforwardly implemented markers may, in addition to affecting the test results unfavorably, also cause untraceable or even non-existent striations on surfaces. In any event, the first thing to do is to obtain fatigue test results without any inserted marker loads for reference. Then, subsequent first test results with implemented markers should be compared with these references and examined with QF to achieve representative results, i.e. to ensure the visibility and traceability of the markers with minimal effect on structural lives.

Most of the structural life is consumed when the crack is less than 1 mm deep (“small cracks”); often even less than 0.1 mm deep. In fracture mechanics, the choice of the initial flaw size often has the greatest impact on the achieved results. Thus, the most important and interesting crack length is equal to the first 100–500 μm, where several “microcracks” are often linking into one larger macro-crack that accelerates in crack growth rate and eventually leads to the final failure.

Although the effect of the FINAF’s BOS2 spectrum on fracture surfaces has been studied with marker loads before [10] [12] (Figure 2) and has been shown to contain features (Figure 1) that could possibly be followed like markers, further testing is still required. From fractures generated with the BOS2 spectrum, tracing striations – even with implemented marker loads – is challenging across the board [10], and particularly challenging in the 100–500 μm region. The difficulty level of BOS2's marker analysis is typical, cf. e.g. [4] and [5].

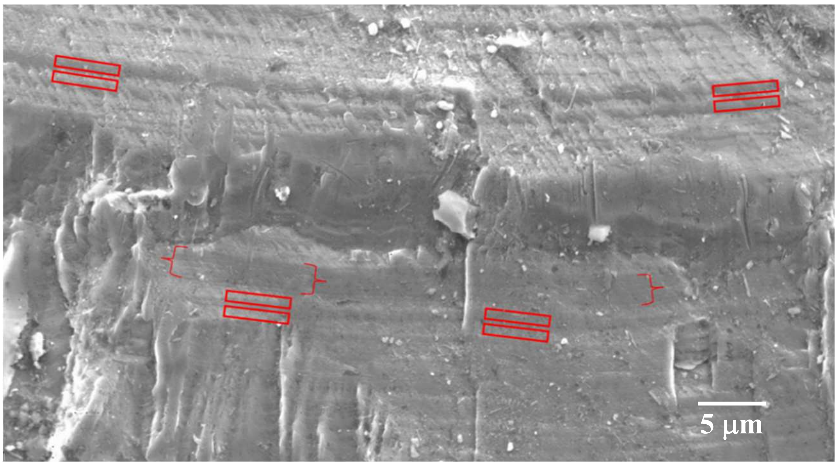


Figure 2: Ongoing QF using SEM with magnification of 1000 x [10]. Aluminium specimen (7075-T76) was fatigue tested with BOS2 spectrum, and some traced striations are pre-marked.

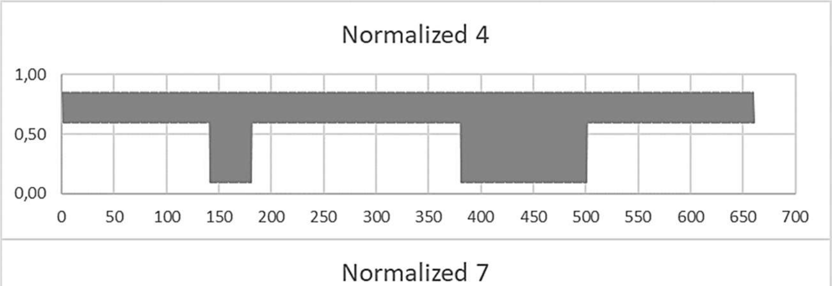
As mentioned, visual inspections of loading spectra or calculated crack growth time histories do not clarify, what kind of a marker tracking will be achieved. Since too many different potential variations of marker loads exist, in practice it is hardly ever possible to test them all. In this study, an additional challenge was the limited number of available pre-test specimens. The marker load versions to be pre-tested were pre-selected based on the report [9] and checked first with fracture mechanics.

Pre-design of marker loads

In aluminium, the most suitable marker load type for slow crack growth and for small cracks appears to be closely repetitive and large R-changes, whose load ratios are significantly different from the average R-value of the spectrum [6]. Generally, according to literature reviews carried out in References [7] and [9], marker loads should be implemented primarily as constant amplitude loading blocks and load ratio changes to avoid problems with over- and underloads. These could be e.g. exceeding the design and operational loads and cause buckling. Although this study is about small specimens, the work aims nationally at obtaining experimental crack growth curves, via marker blocks and QF, from full-scale component spectrum fatigue tests, with realistic boundary conditions in terms of optimized marker load blocks. The pre-design also aims at taking these aspects into account in a correct order.

Depending on the test case, it might be a good idea to try and implement even several marker load blocks (different from each other) into the same spectrum, which are then identifiable via internal markings to keep the tracking as good as possible. It might e.g. be appropriate to implement different kind of marker loads for the area of small cracks than for the growth of the mid-size and final cracks. In terms of controllability of fatigue tests, the spectrum which includes marker loads should anyway be identical from start to end of the test. This means that all implemented marker loads are always included in the marker spectrum and the loads are effective regardless of whether they are visible from the fracture surface at some stage of the crack growth or not. Marker spectrum is not necessarily involved in every spectrum repetition, i.e. not all passed spectra are necessarily marker load spectra.

Preliminary design work of marker loads for the BOS2 spectrum and for small specimens is based on Reference [9]. Changes in load ratios and constant amplitude blocks were chosen as marker load types to be further investigated in this study (Figure 3). Normalization in this context such as in Figure 3 means normalization of the distribution, i.e. standardization.



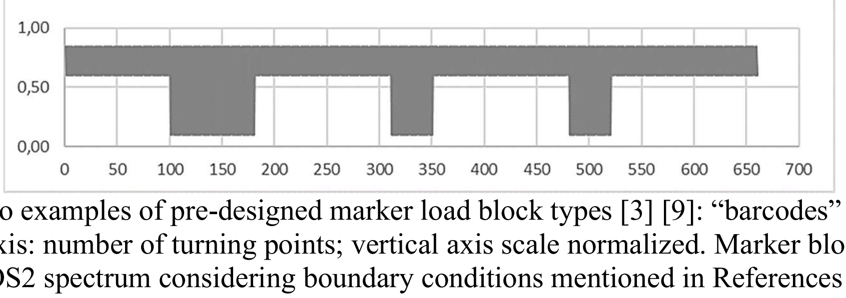


Figure 3: Two examples of pre-designed marker load block types [3] [9]: “barcodes” “4” and “7”. Horizontal axis: number of turning points; vertical axis scale normalized. Marker blocks are to be added to BOS2 spectrum considering boundary conditions mentioned in References [3] and [9].

COMPUTATIONAL FATIGUE LIFE ESTIMATES

Since easy-to-compare relative values were sought (instead of absolute computational lifetimes), the BOS2 turning point spectrum used in fracture mechanics analyses was scaled so that the maximum stress level of the spectrum was just below the yield tensile strength, i.e. 420 MPa. In this study, this calculation spectrum was named as “BOS2K”, which was extended with the marker load block type when applicable, e.g. “BOS2KA4” (Figure 4), if the marker load block type 4 (Figure 3) was inserted in the end of spectrum area marked as A (Figure 1). Not all possible marker blocks were required to be analysed by fracture mechanics due to earlier and intermediate results achieved, and due to outcomes from static and buckling tests of the specimen types [7].

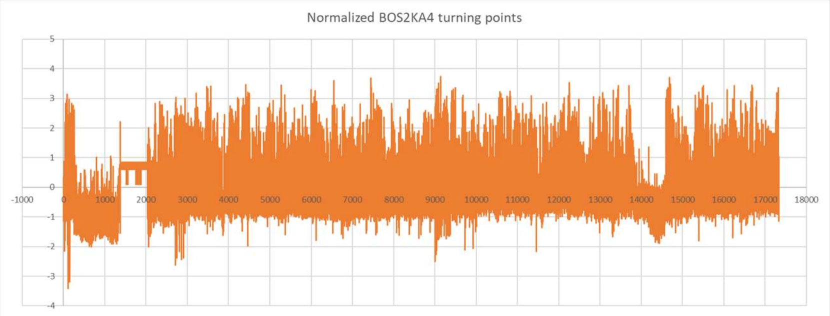


Figure 4: BOS2KA4 spectrum [7] [9]: Normalized BOS2 version for crack growth calculations with pre-designed marker block type 4 in area A. No marker loads have been added to area B. Spectrum’s version used in fatigue test is seen in Figure 9.

DST has set a limit of 5 % for the acceptable change in the expected structural life due to marker loads in its own experiments [2]. This limit was introduced as an evaluation criterion in reviews of this study, too. Another criterion used was that the effect of marker loads on crack growth should not be greater than the effect of a single spectrum without markers [6]. If, for example, only every tenth spectrum contains added marker loading, the total effect should be no more than the effect of 11 spectra without any marker load blocks included.

Computational fatigue life estimates were calculated with AFGROW software [1] and with the initial crack size of 0.1 mm on a surface in 5 mm thick aluminium plate 7075-T7651. All marker load versions were analysed so that every spectrum contained marker loads, after which the results were compared with the reference result without markers.

Calculation results [7] [9] showed that the pre-designed marker block versions do not have an influence on the fatigue life estimates with the computational parameters selected for the analyses. Achieved time histories from calculated crack growths also supported the assumption that there may be natural detectable and traceable markers nearby the areas A and B of the spectrum. Different marker loads had already been tested for the latter area in the past [10] [12], however, the past, SEM-based, QF indicated that they were not visible on the fracture surfaces as expected. In previous tests [10] [12], to some extent and due to high loading levels, these surfaces were ripped making it difficult to detect marker features close to area B with SEM. Because of this, functionality of the BOS2 marker type spectrum was fatigue tested at first at the lowest still appropriate load levels available. Marker characteristics remained unchanged, but less severe spectrum does not tear material so badly, in which case it is to be assumed that the marker striations will be more visible.

Results from crack growth analysis of some marker spectrum loads are presented in Table 1 [7] [9]. Damages from spectra BOS2KA4 and BOS2KA8 can be seen also in Figure 5 and Figure 6.

Table 1: Computational fatigue life estimates; relative values.

Retardation of crack growth	*Spectrum / marker type*	*Number of cycles in spectrum [pcs]*	*Number of cycles [pcs]*	*Number of spectrum repetitions [pcs]*	*c [mm]*	*a [mm]*
	BOS2K	8336	157846	18.9	7.97	5.00
x	BOS2K	8336	201520	24.2	8.15	5.00
	BOS2KA4	8665	164097	18.9	8.34	5.00
x	BOS2KA4	8665	209704	24.2	8.69	5.00
	BOS2KA7	8665	164097	18.9	8.34	5.00
x	BOS2KA7	8665	209704	24.2	8.69	5.00
	BOS2KA8	8665	164097	18.9	8.34	5.00
x	BOS2KA8	8665	209704	24.2	8.69	5.00
	A7 (tests)	8665	164097	18.9	8.32	5.00
x	A7 (tests)	8665	209707	24.2	8.26	5.00

Table 1 shows that – considering also the crack growth retardation (generalized Willenborg model) – the through-crack a = 5.00 mm reference result BOS2K and all the other results (also in References [7] and [9]) with marker loads are the same in terms of the number of spectrum repetitions. Marker load block type in Figure 8, even if scaled, does not have a noticeable influence on computational fatigue life estimates either. BOS2KA7 with the marker type A7 is the spectrum version used in the crack growth analysis. BOS2 test load spectrum with the same marker type, “A7 (tests)” in Table 1, is introduced in the fatigue test series.

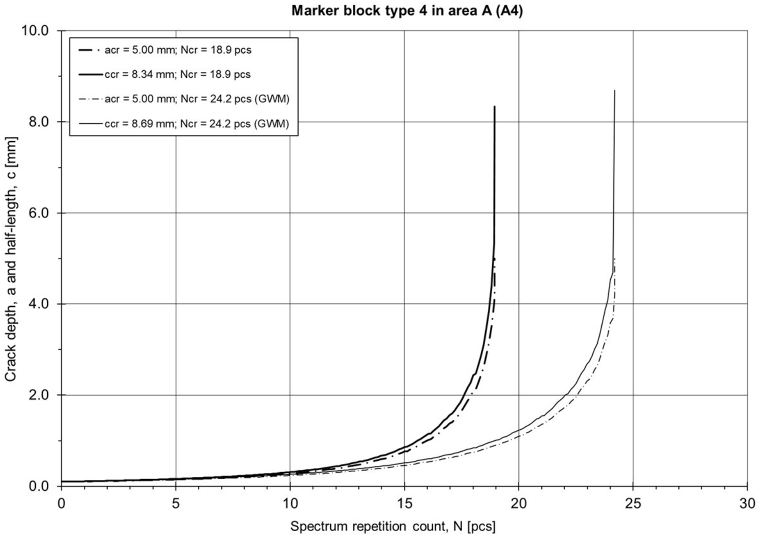


Figure 5: Computational crack growth of spectrum BOS2KA4 as function of spectrum repetitions. Figure is similar for spectrum BOS2KA8. Curves on right are related to retardation of crack growth (generalized Willenborg model GWM).

Deducing from fracture mechanics results and from previous QF experiences related to the BOS2, artificial marker loads were omitted from area B of the spectrum in this context. In case natural marker bands are caused from both A and B, it should somehow be possible to distinguish the region of origin from the traces left by the areas. However, according to previous studies, there was no discernment, so the solution was to add a suitable marker load block to area A only. Marker loads that would stand out in an understandable way, would only be determined by experiments, which is why an educated starting point guess was made based on References [7] and [9] about the most distinctive versions to be tested.

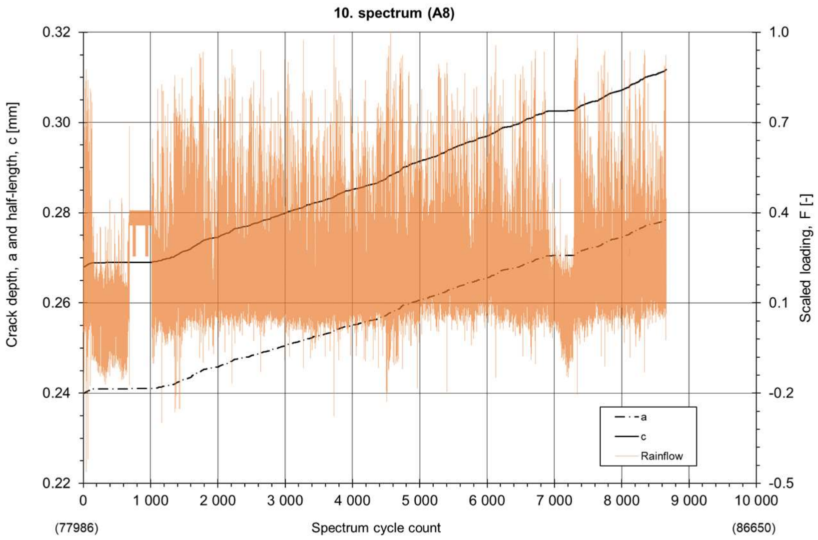


Figure 6: Computational crack growth time histories of spectrum BOS2KA8 with respect to spectrum with added marker loads when calculation is at 10th spectrum.
Figure is similar for spectrum BOS2KA4.

TESTING OF MARKER LOADS

To ensure readability of the markers, and before starting more extensive fatigue test series, a small pilot set was carried out with different marker load blocks and frequencies of the marker load spectrum. Joint specimens, one low load transfer type (LLT) and two medium load transfer types (MLT1 and MLT2) (Figure 7), to be tested were selected from among this bigger test series [11]. At first, one reference lifetime and reference fracture surface were made by fatigue testing without any added marker loads. To avoid any buckling of the specimens, the lowest (compressive) levels of BOS2 were cut away in all the tests. As can be seen in test spectra figures, zero level turning points were added to the beginning and end of spectrum due to testing control needs. All spectra consisted of turning points only.

Figure 7: Three aluminium 7075-T76 ESDU specimen types to be tested [11]. Types counting from top: MLT1, MLT2, and LLT.

Based on References [10] and [12], a simple constant amplitude marker block with a significant change in the load ratio (block R = 0) in view of the BOS2 characteristics was selected as the first test type. Added marker loads were kept constant throughout the spectrum repeats. The marker block was inserted in area A without "barcodes" (Figure 8) [9]. Continuing from the previous tests [10], this experiment investigated further, whether inserted markers and assumed natural features of the spectrum can be monitored by QF. In addition, the effect of the frequency of occurrence of the marker load spectrum was studied. The block version was used for two fatigue tests: first with markers in every fifth spectrum and then with markers in each spectrum. Based on these two tests, marker frequency had no visible effect on fatigue lifetime.

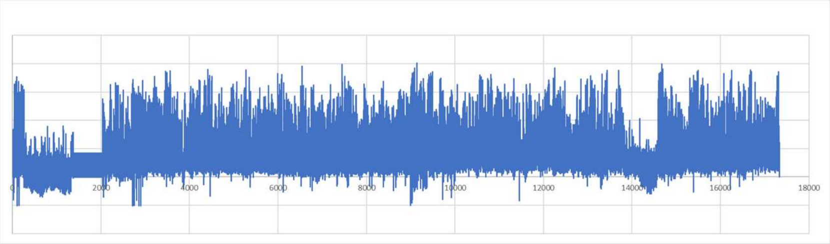


Figure 8: BOS2 test load spectrum with inserted "R = 0" marker load block based on experiences from References [10] and [12].

Next test was carried out with “BOS2KA4” marker load block [9]: one specimen was tested with markers in every fifth spectrum. In practice, the test was a sensitivity analysis, in which marker band visibly different from the previous fracture surfaces was sought (Figure 9). During this test, it was becoming evident that the fatigue tests lasted remarkably longer than anticipated. The longer structural lives compared to the calculated values meant not only insensitiveness to the marker blocks, but also more laborious research for marker bands than was estimated.

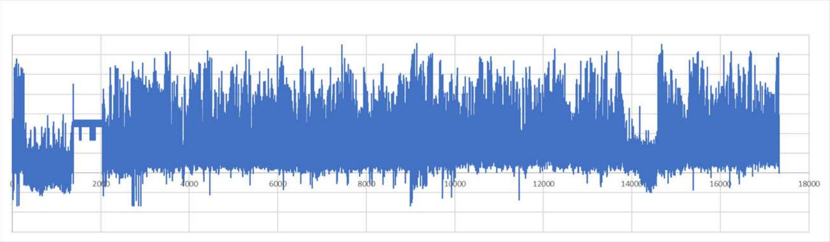


Figure 9: BOS2 test load spectrum with inserted “A4” marker load block [9]. Comparing to normalized calculation version in Figure 4, buckling cut-off level and first and last zero level turning points are involved.

After this, the aim was to find out more about the marker bands that may be caused by the loading areas A and B by inserting one additional, insignificantly fatiguing block into the spectrum. The block location was after area A next to high compressive loads (Figure 10). The experiment became somewhat problematic, as one long-lasting specimen, specimen geometry, and fastener type was chosen as the sample due to the limited number of test pieces reserved for spare and pre-tests. Since all the markers were effective in every spectrum, fracture surface was filled with features to be searched.

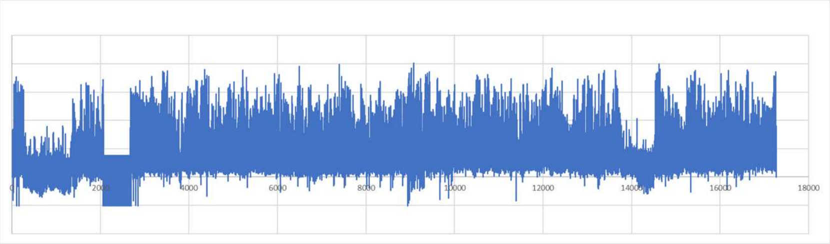


Figure 10: BOS2 test load spectrum with inserted "3rd dead-band" marker load block based on study of traceability of areas A and B.

The "barcoded" marker load block version “BOS2KA7” (Figure 11) [9] was tested and decided to be used as the added marker load type for the actual fatigue test series. The final version was selected based on five QF analysis of this study and a total of 14 fatigue test results. Due to the limited number of pre-tests, the true functionality of added and natural markers of BOS2 was checked again after several different types of small specimen from this large series were tested.

Marker blocks were intended to be used in every fifth spectrum but were initially used in every spectrum for six first test series specimen. Based on the results of these six tests, the chosen marker block is not affecting the structural fatigue test lives of the specimens. In testing, it was decided to not use some number of spectra such as ten first spectrum without marker loads before the "every fifth spectrum contains marker loads" frequency is activated. Marker bands that arise naturally are, of course, active all the time. The added marker load block is located only at the end of the area A and is constant throughout the crack growth.

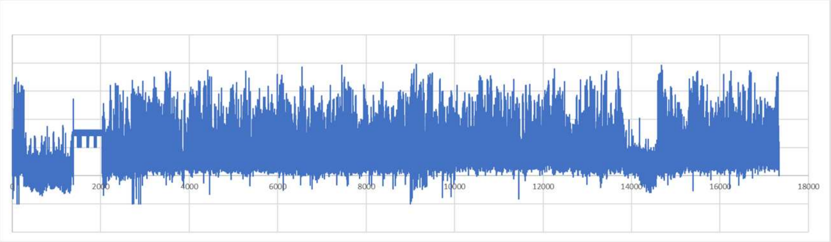


Figure 11: BOS2 test load spectrum which was introduced in actual fatigue test series. Spectrum includes marker block “A7” [9].

PRELIMINARY FINDINGS

QF results were examined while taking into account the intermediate objectives: the hypothesis to use an optical microscope alone, cost-effectively, and appropriately in tracing the crack growth particularly at small crack sizes, was tested by comparing obtained findings during SEM usage of this and previous projects (Figure 12). The preliminary findings aim to demonstrate the applicability of optical microscopy in QF, and its advantages as well as limitations compared to scanning electron microscopy. Historically, the advantage of SEM over OM has been the significantly higher resolution and depth of field, both of which are valuable to successful fractography analysis. For instance, high resolution allows individual fatigue striations to be distinguished, whereas sufficient depth of field is necessary due to high variation in fracture surface topography.

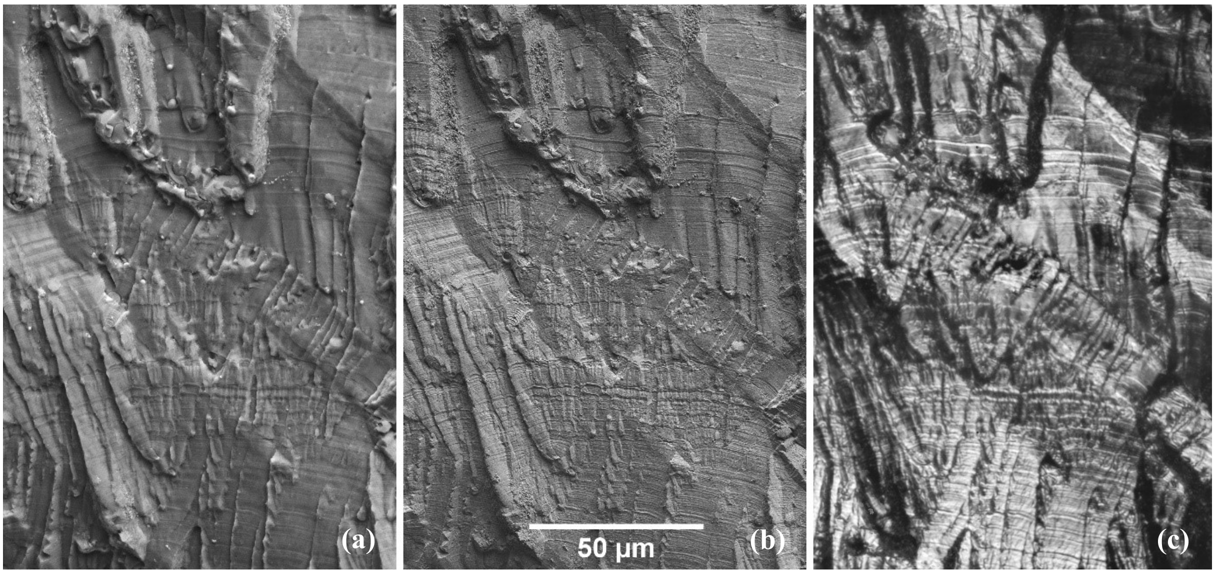


Figure 12: Ongoing QF analysis of the same fracture surface area using SEM with (a) high and (b) low accelerating voltage, and (c) optical microscope [7]. SEM has better resolution, and local crack progression is visible in different way. Difference in usability and operating speed cannot be evaluated from images themselves.

To overcome the depth of field issue in OM, several images of the fracture surface at different focal planes can be acquired and combined into a single high-depth-of-field image. What comes to resolution limitations of OM, they are ultimately determined by the wavelengths of visible light. However, instead of single fatigue striations, the features of interest are the marker load bands, which typically are wide enough to be distinguished with relatively low magnifications (100–1000 x), only exception being at very low crack depths. Therefore, in theory, OM should be adequate for QF. In fact, this method presents several advantages over SEM, such as significantly faster analysis time, and the possibility to utilize varying tilting angles to reflect the light back at the objective lens in different ways. The latter can help to visualize the fracture surface better or can be used to ”highlight” marker bands if they have highly reflective surfaces.

Comparing the use of optical microscope in fractographic studies, and as seen e.g. in Figure 12 and Figure 13, SEM has much better resolution. The crack progression is visible in a different way depending on the accelerating voltage and microscopy method (Figure 12). However, in some areas the fatigue striations can be distinguished better with optical microscope (Figure 14 and Figure 15), and thus the methods are not mutually exclusive. Nonetheless, the question is whether the trackability of marker bands at small crack sizes remain appropriate or not for either or both methods. If not, is it still possible to extrapolate crack growth curves towards the small crack sizes and achieve better calculation parameters for fracture mechanics to some extent. If this is true, in this context, the choice between the microscope types should be made in terms of usability and operating speed. These matters might be of no importance in science, where in fact probably both types together should be chosen to complement each other. Instead, when it comes to business and customer assignments, i.e. to have reliable results fast and cost-effectively, the keywords are the available time and money. The key phrase could even be “good enough” considering the characteristics of the fatigue phenomenon.

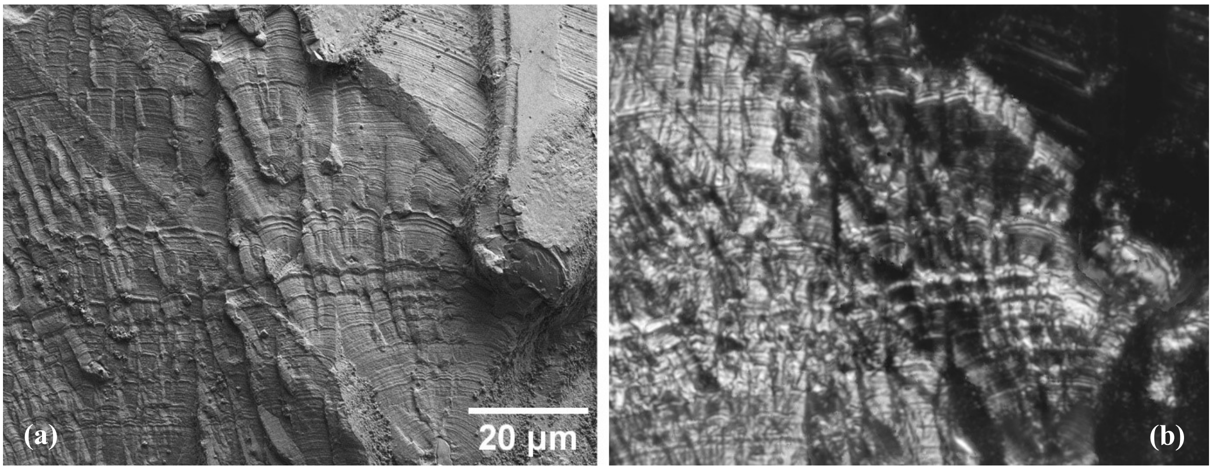


Figure 13: Another example of differences in (a) SEM and (b) OM resolutions [7].

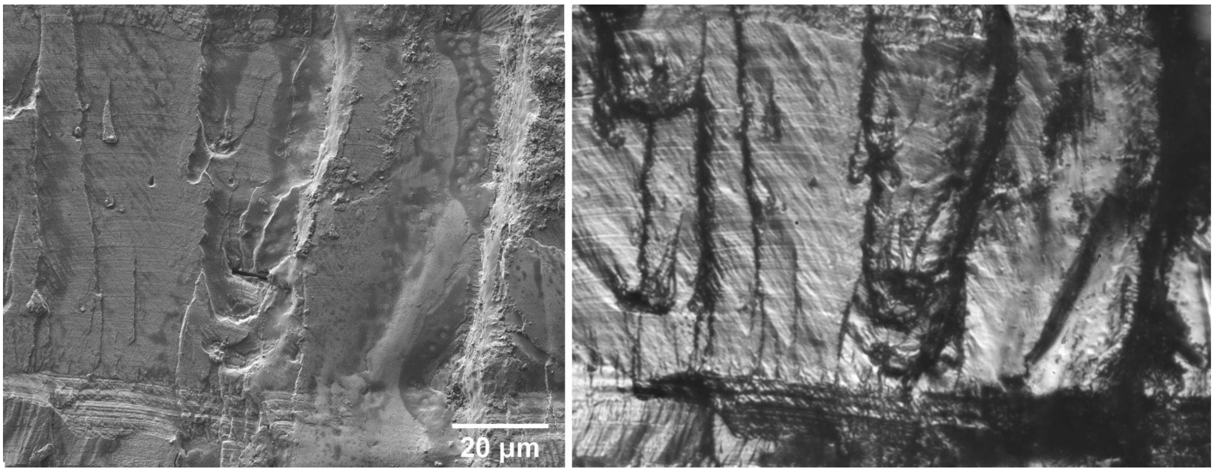


Figure 14: In some areas striations can be distinguished better with OM [7]. Figure 14 and Figure 15 are from the same specimen.

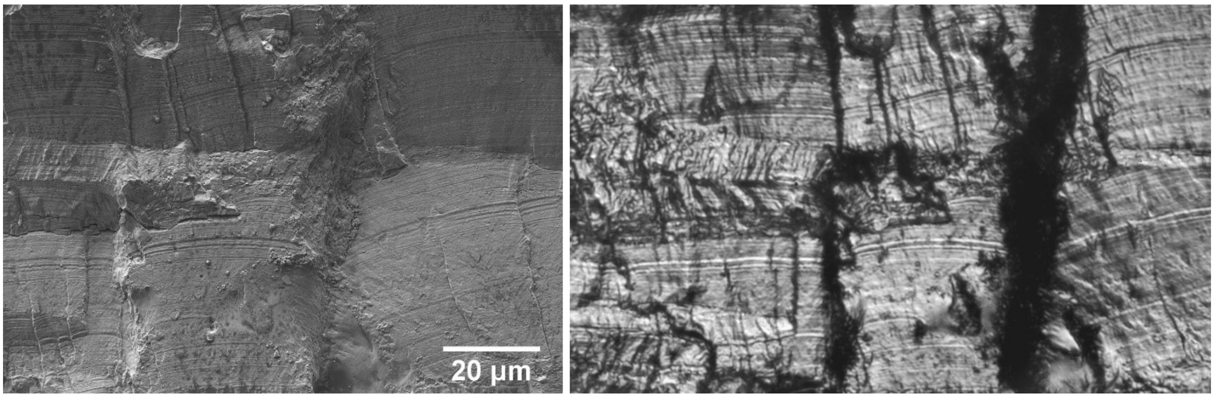


Figure 15: Another example of how striations can be distinguished better with OM [7]. Figure 14 and Figure 15 are from the same specimen.

The functionality of the markers was re-checked after several specimens were fatigue tested. This feedback study included five specimens: one LLT, three MLT1, and one MLT2 (Figure 7). All these included marker loads in every fifth spectrum. For tracing crack growth rates particularly at small crack sizes, the use of an optical microscope alone without SEM analyses was found to be adequate but highly dependent on the fracture surface itself (Figure 16). An example of clearly distinguishable crack progression marks at low crack depth is presented in Figure 17. From this figure, the crack progression can be tracked with ease down to a few hundred microns from the initiation site. Based on the fracture surfaces that were analyzed also with SEM, there was no significant added benefit with SEM while tracing the crack progression. However, higher resolution was helpful for the initial identification of marker bands.

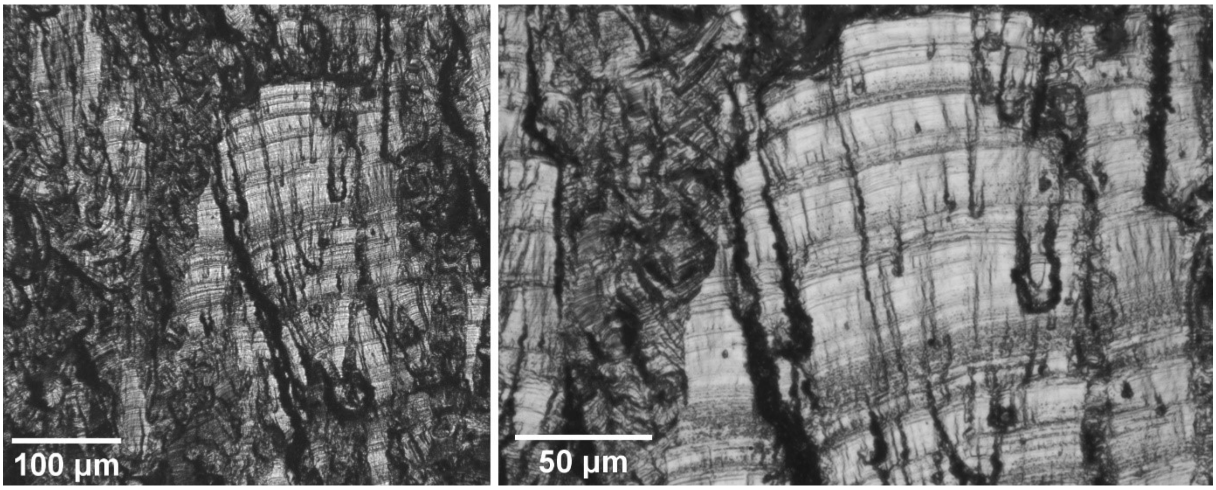


Figure 16: Use of OM is found to be adequate but highly dependent on fracture surface itself.

Overall, the preliminary results indicated that in terms of BOS2 marker bands optical microscope is appropriate, and SEM could be ignored for the upcoming QF analyses. As for analysis times, imaging the key parts of the fracture surface with several different magnification and post-processing takes relatively little time, and thus the total analysis time is mostly dependent on the visibility of marker bands on a particular fracture surface. Initial expectations are roughly 25–50 % reduction in working times compared to SEM analysis, but even 80 % reduction can be achieved if the person performing the analysis is familiar with the marker band. Direction of change is thus correct, and as QF continues, the more fracture surfaces are analysed, the faster analysis will be. It is still too early to evaluate more precisely the final amount of improvement in cost-effectivity.

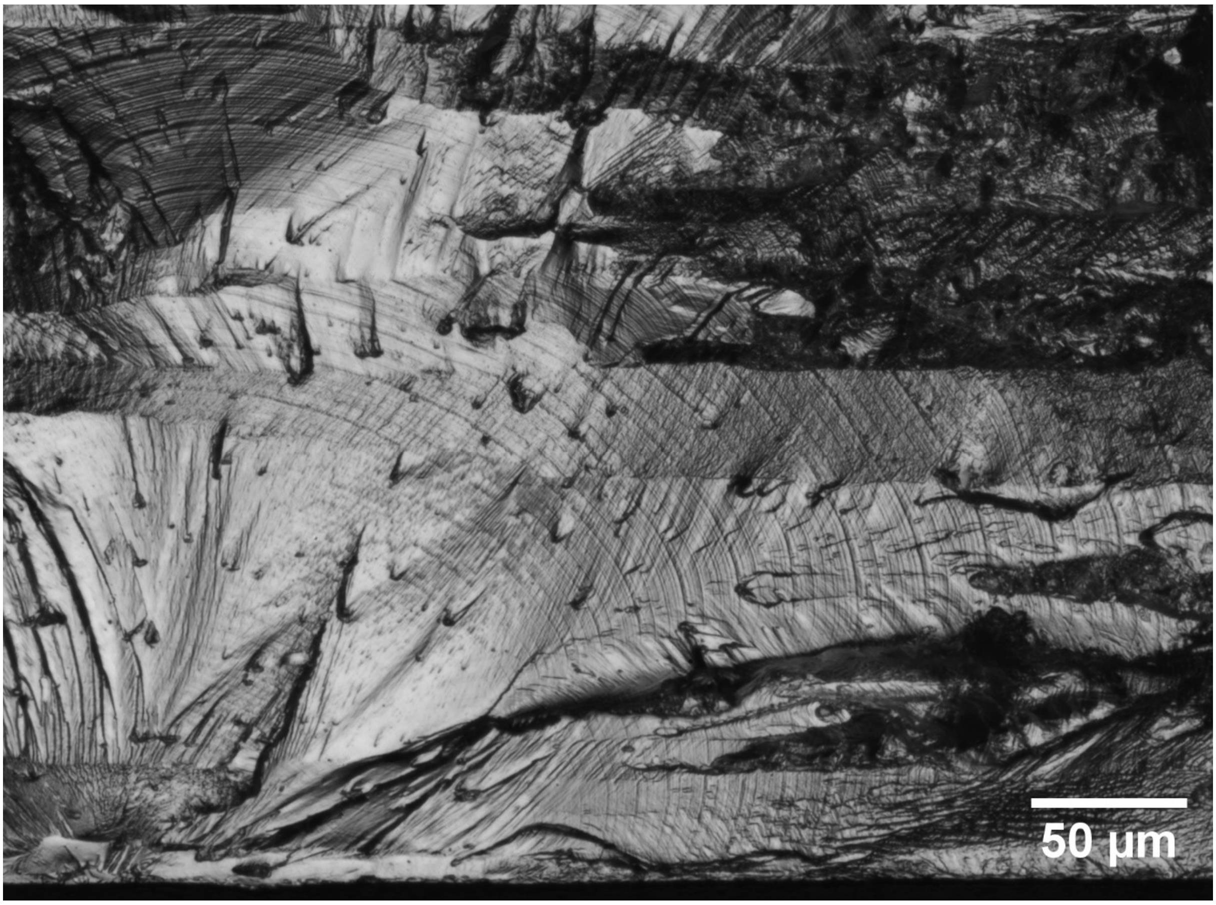


Figure 17: Clearly distinguishable crack progression marks at low crack depth.

FURTHER STEPS

In view of resource availability (testing and fractography) for the approx. 100 specimens, the main part of experimental work remains to be done during 2023. The experimental determination of crack growth curves and better small crack growth calculation parameters are thus yet to come. With all the fractographies available, further aim is to use machine learning to automate the markers' identification process. This is an iterative, time-consuming process, because even more fracture surfaces are needed for verification and validation purposes as well as for teaching the machine learning system to be built.

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