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FATIGUE CRACK GROWTH HISTORY IN CONCEPT OF DAMAGE TOLERANCE OF AIRCRAFT STRUCTURES

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Abstract. *The knowledge of the real history of fatigue process is very valuable for design, development and reliable operation of structures exposed to the time-variable loading service conditions. Information of this type is encoded in the fracture surface morphology. It is possible to decode this information by means of quantitative fractography and transform it into the form interesting from engineering point of view. Application of these fractographic methods is conditioned by the existence and detectability of fractographic features the characteristics of which are correlated with fatigue crack growth rate. In the paper presented, three various fractographic features are used for the fractographic reconstitution – striations (in the case of constant amplitude loading), beach marks (for simple program loading), and special inserted fracture marks (for complex program loading). Importance and irreplaceable role of the fractographic analysis is illustrated by some case studies dealing with the full-scale fatigue tests of aircraft structure parts.*

Keywords: metal fatigue, crack growth rate, crack front, quantitative fractographic analysis, striations, beach marks, fracture marking, fractographic reconstitution of fatigue crack growth, full-scale test, aircraft structure parts

1 INTRODUCTION

Prevention of the failures the many of which can be catastrophic is conditioned by the development of effective failure analysis methods. The cost of failure analysis may exceed the value of the fractured part, but the cost of service failures usually far exceeds the cost of failure analysis [1]. As a traditional "ex-post" experimental method, fractography has played an important and often irreplaceable role in analysis of service failures, in full-scale testing etc. Topography of fracture surface created by a growing crack is a result of interaction between material microstructure and service conditions, especially character of loading, temperature, environment etc.[2]. Information on a failure process is encoded in the fracture morphology. Main tasks of fractography is to decode this information, i.e., to find a correlation between identified fracture morphological features and corresponding physical processes, and to transform it into the form interesting from engineering point of view. Each fractographic feature can be characterized by a set of qualitative and/or quantitative parameters. Qualitative parameters give fundamental information dealing with the fracture character (static or fatigue, brittle or ductile, transgranular or intergranular etc.). Quantitative parameters are measurable characteristics of fracture surface, e.g., the area percentage of the particular fractographic feature, its size (e.g., ductile dimple diameter, striation spacing, cleavage facet size, etc.), local crack growth direction and others. A typical feature of current fractography is an effort to increase the volume and quality of quantitative data supplying better and deeper understanding of the fracture processes, and an integration of the experimental results with the theoretical knowledge of fracture mechanics. One of the main contributions of quantitative fractography is the reconstitution of fatigue process history, i.e., setting of dependence of the crack length (or other variable expressing the failure extent) on the number of cycles (or on an other time related variable, e.g., service time, number of flights, etc.). The reconstitution is conditioned by the existence and detectability of a fractographic feature, some quantitative characteristic of which is correlated with the fatigue crack growth rate, e.g., striations, beach marks, marking lines, etc.

According to standards[3], a special consideration for wide spread fatigue damage must be included in the damage-tolerance evaluation. Probable locations and modes of fatigue damage should be demonstrated with sufficient full-scale test evidence. The efficiency of these exacting and expensive experiments can be considerably increased by application of quantitative fractography. Whereas possibilities of visual monitoring methods are limited (especially in the case of hidden and inaccessible cracks), fractography can give precious supplementary data. Information encoded in fracture micro-morphology is objective and often unobtainable in other ways. By the methods of fractographic reconstitution, it is possible to obtain detailed information on the fatigue process in the tested structure parts - e.g., the length of crack initiation period; crack growth rates in various locations of the failed area; time-dependent, two-dimensional description of fatigue crack growth; time sequence of individual failures and their interaction; consequences of applied repairs, etc.[2,4,7]. In addition to the assets mentioned, the quantitative fractography is indispensable for the study of fundamental principles of fatigue mechanisms[5], for the evaluation of prediction models of fatigue crack growth under variable amplitude loading[6], etc.

2 FRACTOGRAPHIC RECONSTITUTION OF FATIGUE CRACK GROWTH

2.1 Method based on striation spacing measurements

Basic problem of this method is a relation between striation spacing and macroscopic crack growth rate. Application of this method, which can result in the most detailed information on fatigue crack growth, is illustrated with help of following case study.

The experimental study of fatigue cracks propagation in the wing spar of LM 200 was realised[9,10]. The web plate of thickness 1.5 mm was riveted to the L-profile flange plates with dimensions 5x40x40 mm. On both flange plates, sheet strips of 2 mm thickness modelling wing skin were furthermore riveted. All the main structural components of the wing spar were made of Al-alloy type 2124. Model of wing spar was loaded with four-point bending with constant sinus cycle at stress ratio $R = 0$ and loading frequency $f = 2$ Hz. In the critical area, the loading force induced a stress with $\sigma_{max} = 100$ MPa. During the test two fatigue failures propagated in the spar. One of them initiated in spar web on vertical sharp notches in the hole of rivets connected the spar web and the lower flange plate (Fig. 1). The second one failed the lower flange plate (Fig. 2).

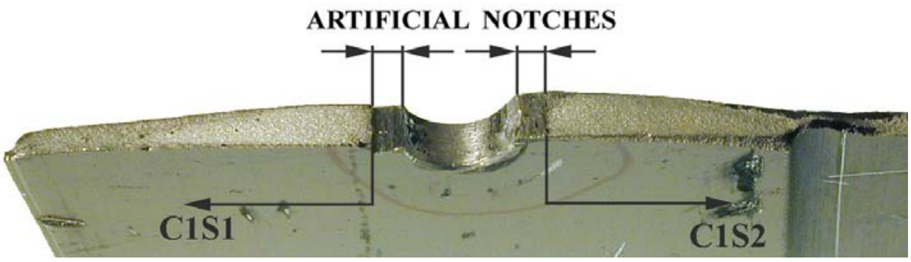


Figure 1: Failure of the spar web - two fatigue cracks C1S1 and C1S2 propagated from notched rivet hole.

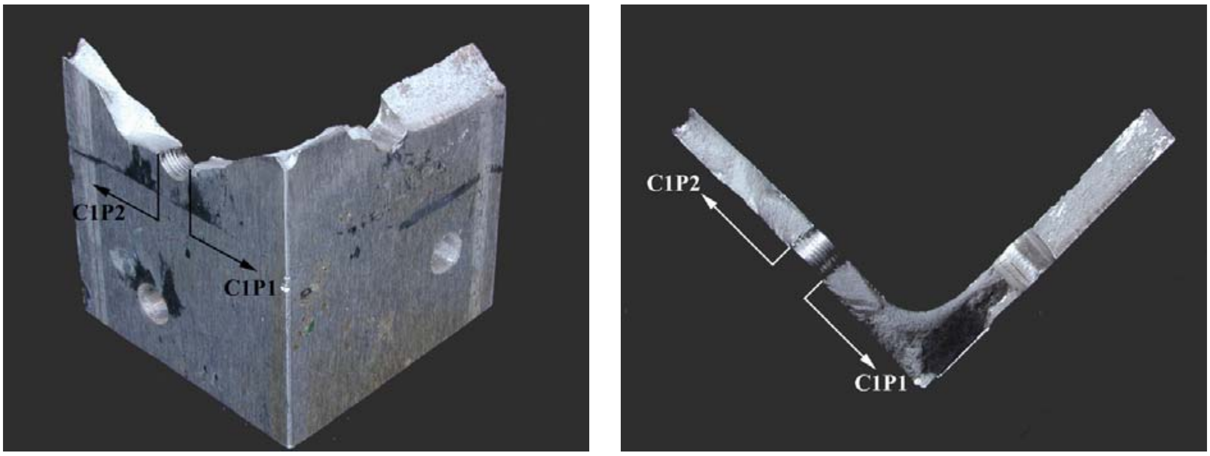


Figure 2: Failure of the lower flange plate - two fatigue cracks C1P1 and C1P2 were propagated from rivet hole.

The main results of qualitative and detailed quantitative fractographic analysis of the both failures were very similar and can be summarised as follow:

- The both fatigue cracks in the web (C1S1 and C1S2 – see Fig. 1) initiated on artificial sharp notches in the rivet hole. Fatigue cracks in flange plate (C1P1 and C1P2 – Fig. 2) initiated on the drilling races in the rivet hole (it was not the same hole as in the case of initiation of cracks in the web).
- All cracks propagated mostly by striation mechanisms.
- Striation spacing s was measured and presented as a function of crack length a, where a = distance of measured micro-area under study from rivet hole axis. Each point in the graphs in Figs. 3 and 4 represents a weighted mean value of about ten striation spacing data at the same crack length (over 700 individual measurements of striation spacing were carried out on the investigated fracture surfaces).
- Results of striation spacing measurements for spar web (Fig. 3) imply that both fatigue cracks C1S1 and C1S2 were propagating at very similar rates.
  The results for cracks C1P1 and C1P2 (Fig. 4) in lower flange plate lead to the analogical conclusion, i.e., the both cracks were propagating at very similar rates.

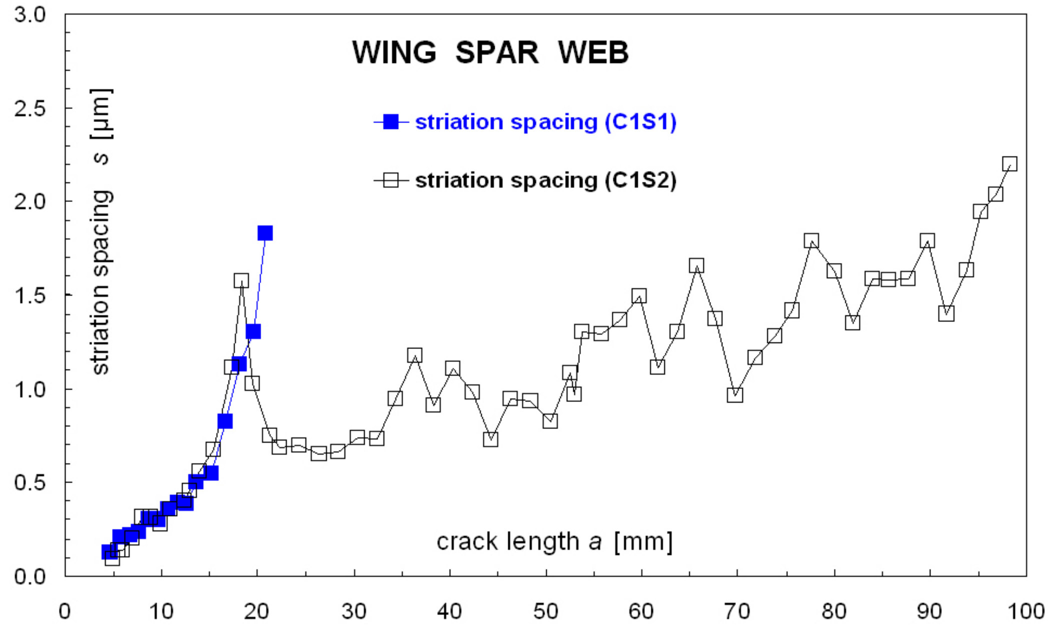


Figure 3: Striation spacing vs. crack length measured for the cracks in the spar web.

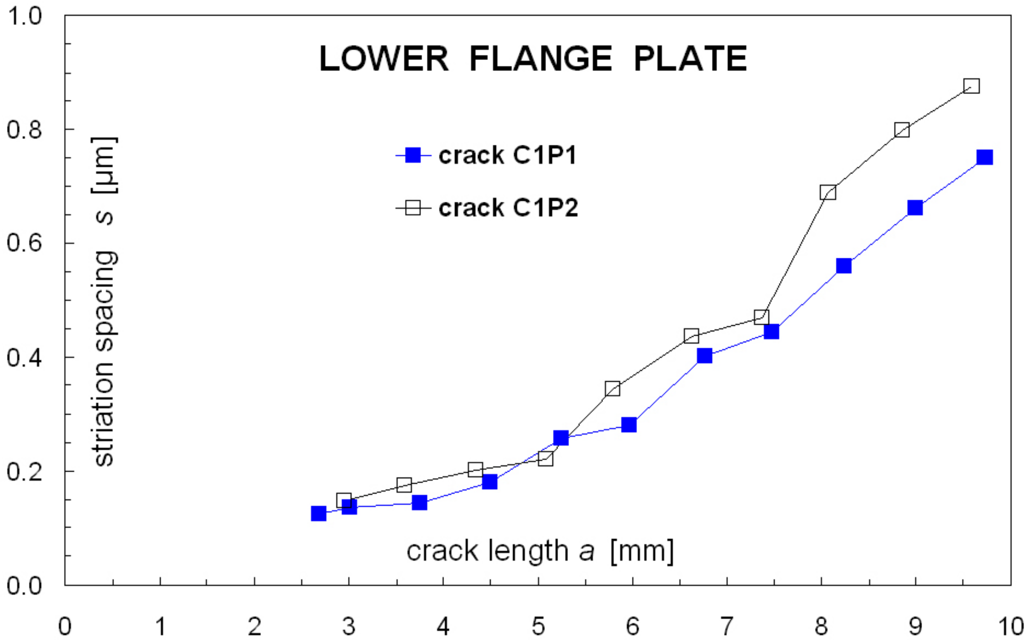


Figure 4: Striation spacing vs. crack length measured for the cracks in the lower flange plate.

Ex-post reconstitution of the fatigue process history was based on the results of quantitative microfractographic analysis, i.e., on the dependence of striation spacing on crack length (s_i, a_i), i = 1,2,...,n. Details of the method used were described previously in papers[7,8].

Processing of the data consists of two steps:
a) recalculation of the striation spacing into the macroscopic crack growth rate,
b) integration of the results obtained into the relation of the crack length as a function of the number of applied cycles.
Generally, striation spacing s and macroscopic crack growth rate v cannot be taken as identical. The ratio of the variables

$$D = \frac{v}{s} \tag{1}$$

can vary within several orders ($10^{-3} < D < 10^{1}$)[e.g., 8, 11]. This fact is a consequence of the three following phenomena[2,7]:

- Discontinuous propagation of fatigue crack front both in time and in space, i.e., existence of the so called "idle cycles".
- Deviation of local direction of fatigue crack growth from the macroscopic one.
- Synergy of striation micro-mechanism with other ones, e.g., ductile dimple fracture, inter crystalline decohesion, quasi-cleavage, etc.

An a priori quantitative information on ratio D is very desirable for applications in practice. For these purposes, the most suitable form is relation $D = D(s)$, which can be determined from laboratory tests on simple bodies made of the same material as the fractured structural part under study. Also close correspondence of testing conditions with the service ones is very advisable.

In addition to the above information, knowledge of some couple of corresponding data (a_i, N_i) contributes noticeably to the quality and exactness of final results of fractographic reconstitution. This pair may be given by the number of cycles and corresponding crack length at the moment of service interruption, termination etc.
If $D = D(s)$ and one couple of corresponding data (a_i, N_i) are available, the following equation can be used to reconstitute the fatigue crack growth history

$$N_x = \int_{a_i}^{a_x} \frac{da}{D(s) \cdot s(a)} + N_i \, , \tag{2}$$

where N_x is the number of cycles corresponding to the given crack length a_x, and (N_i, a_i) is a priori known or determined couple of corresponding data.

The fractographic reconstitution of fatigue cracks growth in the wing spar was based on the knowledge of the empirical relation $D = D(s)$, based on our previous laboratory experiments of similar Al-alloy[8], see equation in Fig.5. The known couple of data N_f = 117 500 cycles and a_f = 98.5 mm, corresponding to the fatigue test termination, was used as a "initial condition" in the relation (2). Results of fractographic reconstitution of fatigue cracks growth in tested model of wing spar are plotted in Fig. 5. For comparison, results of macroscopic monitoring crack length are presented in this graph.

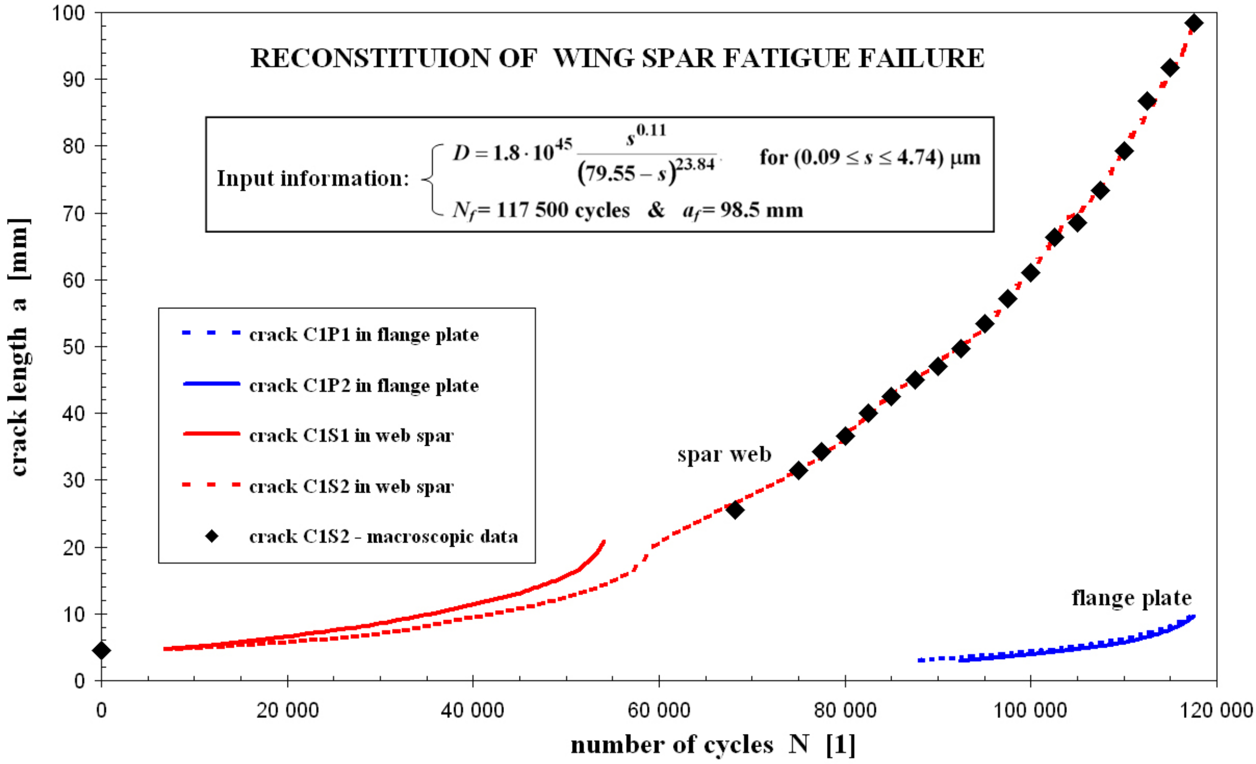


Figure 5: Result of fractographic reconstitution of fatigue crack growth curves. Lengths of crack C1S2 measured optically during fatigue test are plotted for comparison.

2.2 Method based on beach mark spacing measurements

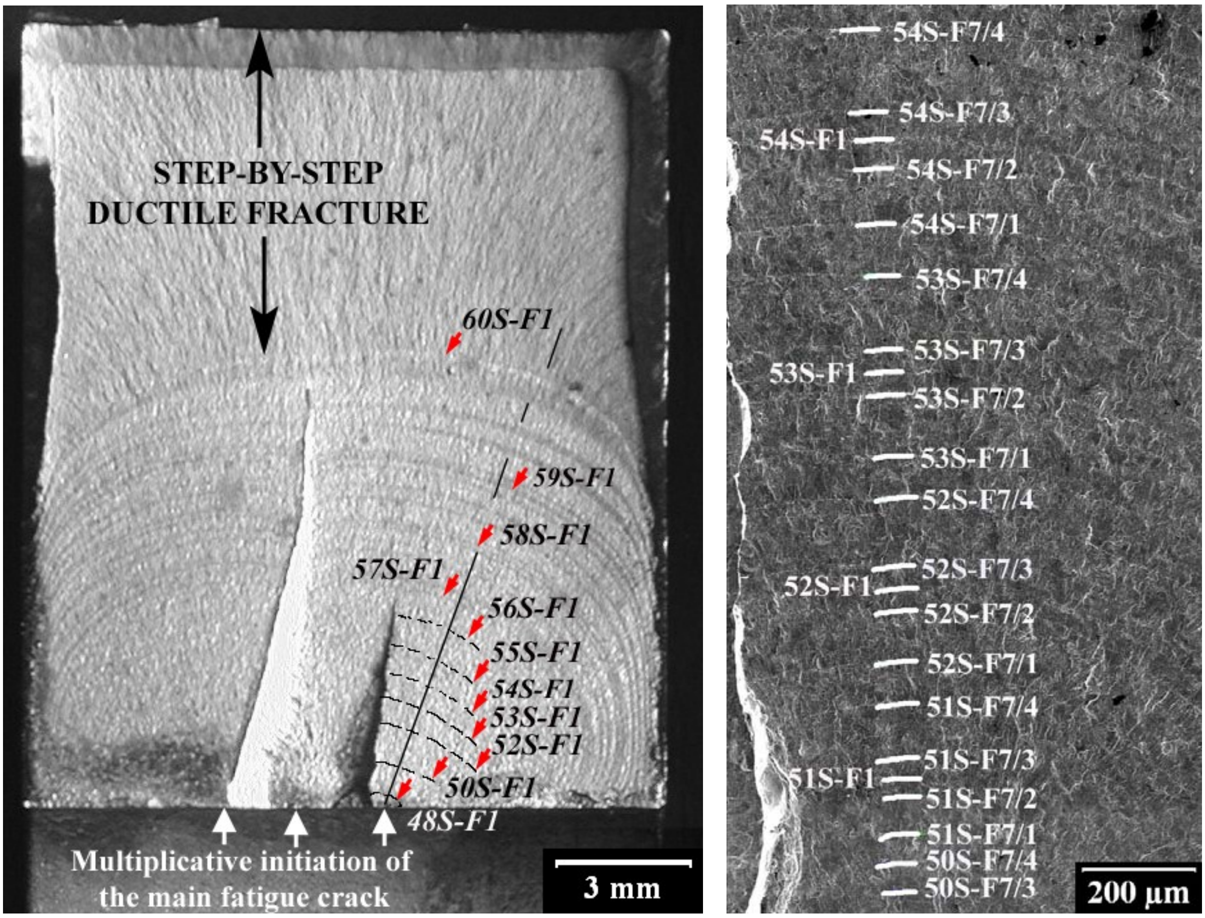
In the case of program loading spectrum, e.g., flight simulation loading, the reconstitution of fatigue crack growth can be based on a fractographic identification of morphological features created by specific inherent part of the spectrum (e.g., gust cycle, the most severe flight etc.). If the beach marks are detectable and their spacing is measurable, neither marking nor special modification of original loading spectrum is needful. In this case, there is no trouble with the relation between microscopic and macroscopic crack growth rate. In addition to the crack growth rate, observation of beach marks is giving information on the crack front shape and its changes in time and space. On this base, two dimensional description of fatigue degradation of body cross section is possible. Application of this method for fractographic reconstitution of fatigue crack growth in aircraft structure parts was presented, e.g., in[4, 12].

As an example, in the full-scale fatigue test, the small civil aircraft wing was loaded by means of flight-by-flight spectrum simulating real service condition. One loading sequence of this spectrum consists of nine randomly arranged flight types (in total 3 156 flights) and corresponds to 2 000 simulated flying hours (SFH). Individual types of flights denoted F1÷F9 have different incidence, maximum loading level and number of individual loading cycles (Tab.1). The wing hinge (made out of steel M300) was fractured after 119 082 SFH, i.e., after application of 59.54 loading sequences[13].

Flight	***F1***	*F2*	*F3*	*F4*	*F5*	*F6*	***F7***	*F8*	*F9*
Incidence	**1**	938	600	50	468	800	**4**	11	20
Rel. max. level	**3.17**	1.58	1.58	2.13	1.58	1.73	**2.99**	2.38	2.38
Number of cycles	**95**	21	13	75	19	23	**133**	119	127

Table 1: Characterisation of nine flight types F1÷F9 in the loading sequence of 3 156 flights. There are the five most severe flights in each sequence (in table marked with bold letters).

Failure of the hinge corresponded to the propagation and coalescence of three fatigue cracks initiated in the hole for bolt (Fig.6a). The cracks propagated mostly by striating mechanism, and fracture micromorphology was characterised by the occurrence of more or less distinct beach marks due to variable amplitude loading. Individual beach marks determined the shape and position of fatigue crack fronts corresponding to the different flights. A detailed study of fracture micromorphology in combination with loading spectrum



a) Macroscopic character of fracture b) Micromorphology of fracture surface

Figure 6: Fracture surface of failed wing hinge – fatigue crack fronts corresponding to the application of the most severe flights F1 and F7 are labelled.

analysis allowed to identify beach marks corresponding to the application of the five most severe flights (i.e., 1 flight F1 and 4 flights F7 in each individual sequence). Based on it, the reconstitution of fatigue failure of the wing hinge was carried out (see Fig.6).

2.3 Method based on fracture marking

If the testing loading unit does not include a suitable cycle with the detectable fractographic repercussion, it is possible to apply some specific marking cycles or blocks inserted intentionally into the testing loading spectrum. Application of the fracture marking is relevant especially in the case of complex random loading. Unlike other marking techniques as a dye penetrant method, heat tinting etc., the methods based on the application of special marking loading cycles or blocks make possible to mark all fractures in the tested structure including hidden or unknown cracks. Application of this marking method is unfortunately complicated by two very antagonistic requirements [14]:

a) *good and unequivocal detectability of marks on the fracture surface*,
b) *minimal influence on fatigue crack initiation and growth, i.e., minimal change of damaging effect of the basic loading spectrum*.

Considerable experimental effort was devoted to different marking methods development especially in aircraft industry. In principle, there are two main types of fracture marking based on special loading cycles:

1) marking by means of special loading cycles inserted into the original loading spectrum[e.g.14, 15],
2) marking by means of rearrangement of original loading spectrum[16].

As an example of fracture marking, full-scale fatigue test of the main beam of fighter body is given[14]: Service conditions were simulated by means of flight-by-flight loading spectrum. This very complicated spectrum consists of many cycles with very different amplitude divided into the three different loading sequences. Fractographic analysis of simple test bodies confirmed that neither the striation spacing measurements nor beach marks identification can be used for the fractographic reconstruction of fatigue crack process. Therefore special coded marking loading blocks had to be developed for the full-scale test of airframe. One marking set consists of 12 different marks symbols of which are given in the Table 2. The symbols used are similar to Morse code: the “dot” consists of 100 constant amplitude cycles, the ”dash” consists of the same 800 cycles.

Mark number	1	2	3	4	5	6	7	8	9	10	11	12
Symbol	....—	..—..	..—	..—.	—....	...—	—...	.—.	—..	...—.	.—..	.—...

Table 2: The list of fractographic marks in Morse code[14].

Individual “dots” and “dashes” were separated by a special cycle with higher stress amplitude. In one marking set, there is no problem with identifying individual marks - each mark differs from each other and thus it is unequivocal. Even in the case of difficulty with direct identification of some mark, there is a possibility to use a second level of information, i.e., define it more precisely by means of identification of the neighbouring (the last before and the next after) marks because the sequence of the individual marks is constant and known. The same marking set is repeatedly applied during the full-scale fatigue test.

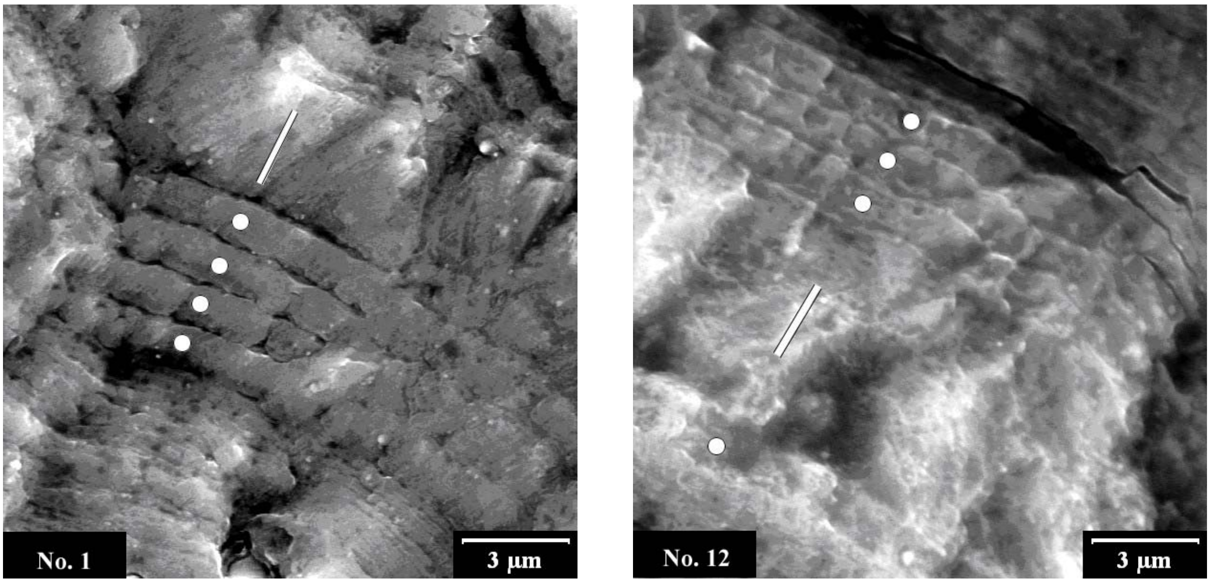


Figure 7: Micromorphological characteristics of the marks No.1 and No.12 (see Tab. 2).

Identification of individual marks on the fracture surface enables complete fractographic reconstitution of fatigue crack growth in the main aircraft beam fracture. Results were summarized as a two-dimensional description of fatigue process in dependence on a number of simulated flying hours (similarly as in the case of wing hinge, see Fig.6).

3. CONCLUSION

The application of fractography to failure analysis of fatigued aircraft structures is very contributing because it permits to precise the identification of causes and failure processes. In order to satisfy current damage tolerant design criteria that require the experimental determination of crack growth rates for various aircraft components, considerable effort has been devoted to the development of quantitative techniques specifically directed to the evaluation of fatigue crack growth. Quantitative fractography is indispensable not only for the study of fundamental principles of fatigue mechanisms but it can also offer detailed information on the fatigue process in the tested structures – e.g., the duration of crack initiation period, crack growth rates, two-dimensional time-dependent description of fatigue crack growth, time sequence of individual failures and their interaction, consequences of applied repairs, etc.

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