The Effects of Loading Waveform and Microstructure on the Fatigue Response of Ti-Al-Mo Alloys

A.A. Shaniavski

State Center for Safety of Civil Aviation Flights, 103340, Moscow, Russia, shana@flysafety.msk.ru.

ABSTRACT. *Fractographic analysis was performed to estimate crack growth period in specimens of Ti-6AL-2Sn-4Zn-2Mo-0.1Si titanium alloy with two types, á/â, and, á, of material structures tested under triangular and trapezoidal shape of cyclic loads. It was shown that facetted pattern relief dominantly forms under trapezoidal vawe form of cyclic loads for both investigated structures. Special methodology was introduced for quantitative fractographic analysis in the case of locally formed fatigue striations between facetted patterns. Crack growth periods, estimated on the bases of the striation spacing measurements, were used to determine lifetime to failure for tested specimens. Results of performed investigations are brafely discussed and they are compared with experimental data.*

INTRODUCTION

In-service fatigue failures of titanium compressor disks of aircraft engines is well known problem [1-5]. Fatigue crack pierces through the interface boundaries and performed the facetted pattern fatigue fracture surface, which reflected this phenomenon. The facetted pattern can be seen on the fracture surface for two-phase Ti-Al-Mo alloys with lamellar or equiaxed structures. This surface dominates for in-service disks failures and include itself local places with blokes of fatigue striations, which have orientations in various directions. The fatigue striations can also be placed between oriented zones with facetted pattern and are propagated in the perpendicular direction to the mainly orientation of the fatigue crack growth.

It was established that various cases of in-service fatigue cracks growth in titanium disks caused by technological inheritance for two scale levels of the material structure: mesoscopic [1,2] and macroscopic [5].

It was performed method for the titanium alloy selection during disks manufacture to prevent their in-service failures after a short lifetime of an operation [2]. Also, performed methodology of the crack growth period estimation for in-service disks on the bases of the quantitative fractographic analysis of failed disks [3]. This methodology used all knowledge about titanium alloys sensitiveness to the cyclic loads shape on the two scale levels [1-5].

Consequently, to prevent earlier titanium compressor disks in-service failures it must be introduced special improvements in technology, which diminished material sensitiveness to cyclic loads shapes on the macro- and meso-scale levels.

One of these technological improvements for Ti-6AL-2Sn-4Zn-2Mo-0.1Si titanium alloy was discussed in paper [6]. Two types of material's micro- and macro-structures with mixed α/β and only β-phase were investigated. It was shown that specimens with hardened surface had in three times more long lifetime to failure (durability) with a new recommended technology.

As a matter of fact, it was interesting to know crack growth period for tested specimens to correlate its value with modified lifetime. The information about number of cycles for crack growth period for tested bar specimens could be only taken from the fracture surface analyses on the basis of quantitative fractography. But this problem turned out very complicated because the facetted pattern relief was dominant for fracture surfaces performed under trapezoidal shape of cyclic loads. That is why a new methodology was used for quantitative fractographic analyses of fracture surfaces with the dominant facetted pattern relief for titanium alloys [1-5].

This paper discussed results of performed fractographic analyses of the specimens from Ti-6AL-2Sn-4Zn-2Mo-0.1Si titanium alloy on the basis of this methodology.

INVESTIGATION PROCEDURE

Fractographic investigations of the Ti-6AL-2Sn-4Zn-2Mo-0.1Si titanium alloy were performed for cylindrically shaped specimens. These specimens have passed low cycle fatigue (LCF) tests by triangular cyclic loads form with frequency of 0.5 Hz or 30 cycles per minute and by trapezoidal shape of cyclic loads with hold (dwell) time under maximum stress of cyclic loads during 1, 2 and 5 minutes [6]. Maximum stress level for both cyclic loads shapes was about 800 MPa with stress ratio R≈0.

There were provided 12 fragments from the specimens with fatigued zones and 8 slices from them for fractorgraphic and metallographic analysis respectively. The information about test conditions for each specimens wasn't provided for fracture surface analyses on the first stage of the performed investigation because the subject of this work was reconstruction of fatigue crack growth kinetics and tests conditions for fatigued specimens for the titanium alloy on the bases of the fractographic analyses using the techniques employed for solving similar tasks in State Center of Flight Safety of Civil Aviation (SCFSCA) and detailed in papers [1-5].

The specimen material microstructure was of two types: "alpha/beta" for specimens numbers 1-8 and "beta" for specimens' numbers 9-12, Fig.1. The structure presented in Fig.1 is typical for all specimens of both groups and just it (geometry of its elements and their orientation relative to the specimen axis) defines the location of material fracture planes (facets) at the stages of stable fatigue crack propagation.

For convenience of further presentation of the investigation results the alpha/beta structure specimens will be attributed to the group 1 and the beta structure specimens will be attributed to the group 2.
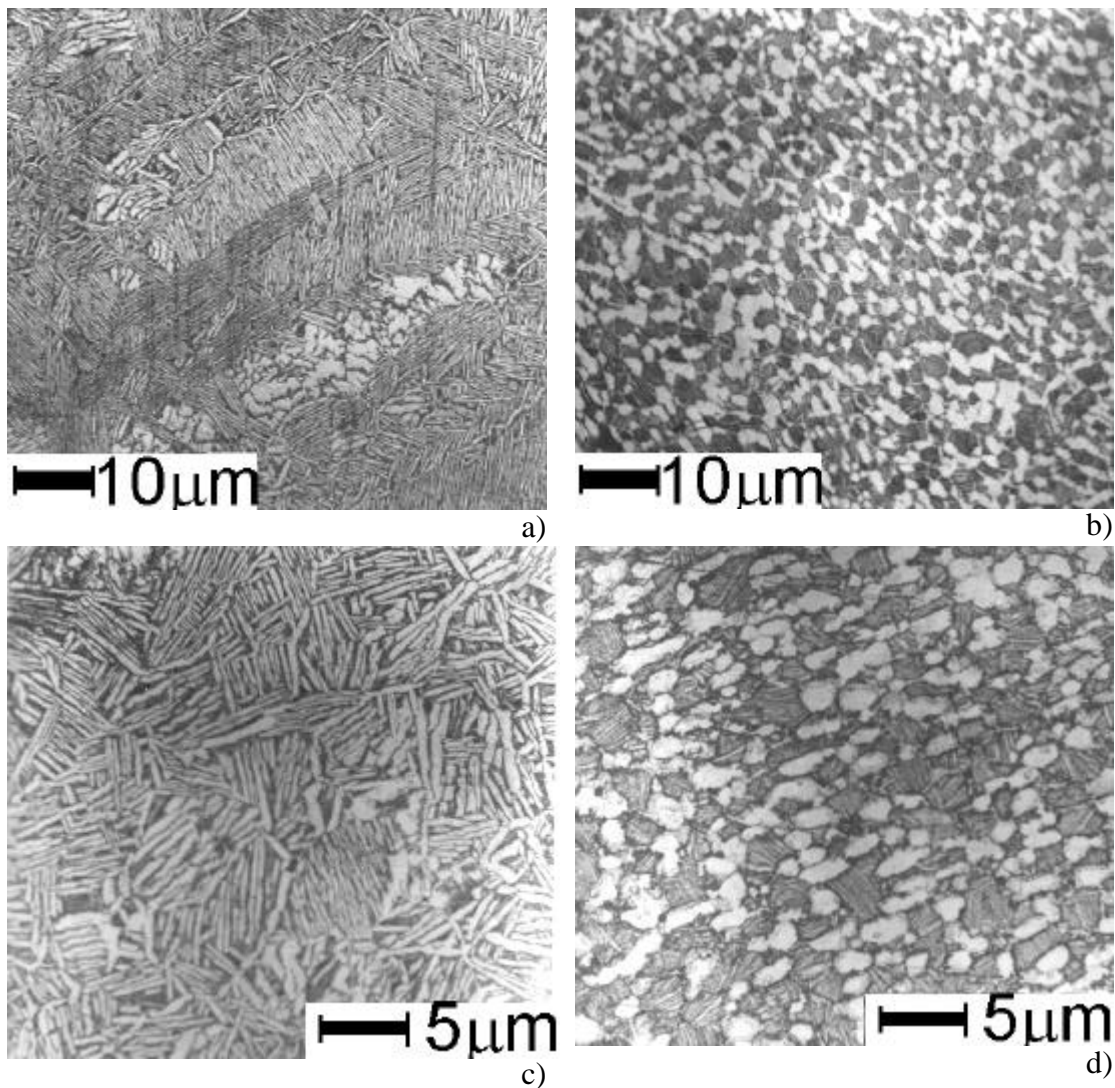
Figure 1. Illustration of the material microstructure (a,c) of group 1 (numbers 1-8) and (b,d) of group 2 (numbers 9-12) specimens.

The specimens' fragments with fatigue surfaces were investigated into the scanning electronic microscopes, types CDS-50 with resolution not less than 0.005 ìm and JSM-35 facility with more little resolution.

Below are presented the results of the performed investigations of fatigue fracture surfaces for all twelve specimens in accordance with the above-stated purposes.

RESULTS OF INVESTIGATION

Fatigue crack growth in specimens

The material macrostructure of the group 1 specimens is oriented so that a fibre is directed towards the specimen axis closely perpendicularly (See Fig.1). Therefore all fracture facets considered below, where there are revealed the fatigue fracture surface patterns reflecting the stable crack growth, are positioned primarily perpendicularly to the specimen axis. But the clear fibre boundary was formed on fracture surfaces in the form of steps or ledge not in all cases as a crack passes from fibre to fibre. Therefore, for some specimens the sizes of the fracture surface zone (facet) with evidence of fatigue material features exceed the sizes of separate fibres.

The material microstructure of specimens of the group 2 constitute small-sized equiaxed grains and groups of lamellas and this significantly differs the material of specimens of this group from the material of specimens of group 1. Therefore while analyzing the fracture surfaces of these specimens, special attention was paid to presence of evidence of inheriting texture by material which might be revealed in features of fatigue fracture surface.

The performed fractographic analysis have shown two typical situations for discovered fracture surface patterns, Fig.2. One of them, reproduced in Fig. 2, reflected the dominantly quasi-brittle fracture with dominantly facetted patterns relief. Another situation was discovered for specimen number 5, where the fatigue striations took dominantly place for all area of fatigue crack propagation.

In all specimens crack originating took place under its surface with creation of preliminary one or several facets of quasi-brittle fatigue fracture.

The quasi-brittle material fracture facets with faintly visible fatigue striations are the dominating patterns of fracture surfaces for specimens of both groups (Fig. 2(c)). For instance, the fatigue striations spacing is situated in the range of (0.3 – 0.4) ìm at the distance near to 0.5 mm from the origin for the specimen number 1. The groups consisting of several striations are rather local. Making consideration on crack kinetics in terms of the crack growth rate is possible only by separate fracture zones.

At the boundaries of going from one quasi-brittle fracture facet to another one there was formed the wavy fracture structure, (Fig. 2(d)). Similar shape in the form of the wavy pattern for oriented dimples was discovered at the stage of the specimen fast fracture for specimens numbers 1,7 and number 8. Such features of the fast fracture surface as the wavy pattern may fit the process of gradual crack growing under cyclic loads for low strain rate. But it seems impossible to evaluate the loading rate and respectively the specimen loading conditions by these fracture structure patterns.

Considering that hold-time for tested titanium alloys under cyclic loads is favorable to manifestation of their capability for brittle fracturing, the described features of specimen fatigue fracture surface permitted to suppose that specimen number 5 and possibly specimen number 2 have been tested with triangular shape of cyclic loads and other specimens – with trapezoidal one.
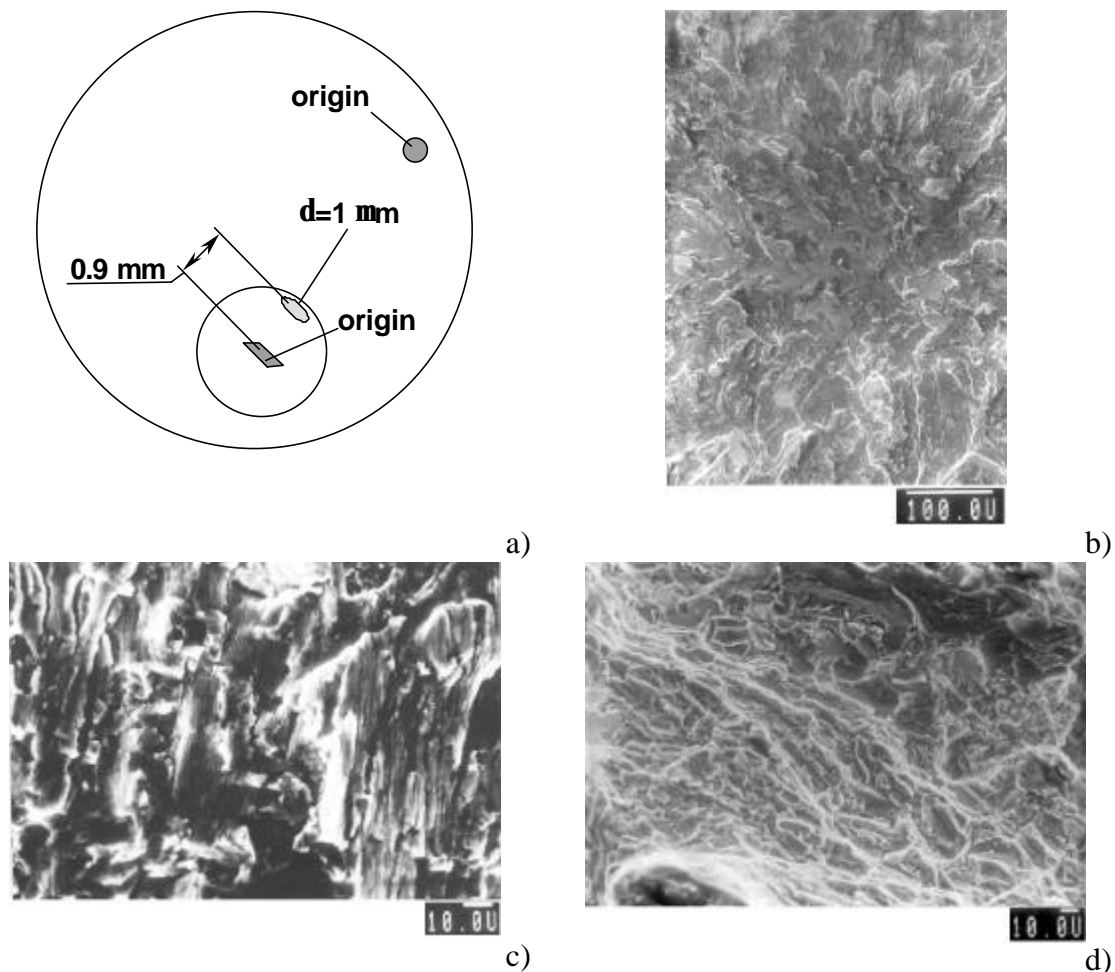
Figure 2. Schema (a) of fracture surface of specimen number 1, (b) fracture surface relief in the form of quasi-brittle faceted pattern in the fracture origin, (c) fatigue striations, and (d) wavy fracture surface.

The material fracture by quasi-brittle (faceted pattern relief) mechanism might have been related to either material structure or material sensitiveness to the cyclic loads shape – hold-time (dwell) for cyclic loads.

Generalizing the results of investigations of specimens of both groups, the following general intermediate conclusions may be done:

- all specimens have the fracture origins located under surface and this is the result of their surface hardening;

- a multi-origin type of fatigue fracture and presence of the dimpled relief with a wavy relief inside may testify that the material was regularly tensed under constant load during any time in the process of specimen cyclic tests;

- hold-time for cyclic loads is favorable to showing the material possible brittleness and in spite of type of material structure (lamellar or equiaxed) results in formation of fracture surface relief of quasi-brittle facet type;

- the cracks of group 1 specimens developed on clearly expressed oriented texture, the cracks of group 2 specimens developed on planes inherited from primary performed material texture which is seen from the shape of the origin quasi-brittle facets;

- when the specimen experiences under the cyclic loads with hold-time (dwell), its fracture origin is a quasi-brittle facet and the formation of fatigue striations in the fracture surface began in the best case at the boundary of origin zone that was discovered for specimens numbers 1,3,4, 7-11;

- decrease in dwell-time of cyclic loads and, especially transition to a triangular shape of cyclic loads possibly caused more active formation of fatigue striations in fracture surfaces of the investigated specimens as it is observed for specimen numder 5; crack growth period may be estimated by the fatigue striations spacing, taking in consideration that the striations spacing value is behind the crack growth rate in the case of quasi-brittle fracture of titanium alloys detected for the majority of the investigated specimens and therefore the crack growth period estimated on the bases of the fatigue striations spacing measurements must be corrected.

Estimations loading conditions and lifetime to failure for specimens
As a result of the performed fractographic investigations it was carried out the systematization of the measured fatigue striations spacings for different specimens and the crack length (depth). Assessment of the crack growth period was made by the average value of the fatigue striations spacing for specimens for which the appropriate change in striation spacing in the direction of crack growth wasn't detected.

The revealed specific features enable to conclude that the specimen number 12 showed itself best of all, the crack propagation in this specimen was performed during approximately 3200 cycles. It is worth to emphasize once again that this and other subsequent assessments don't take into account the possible discrepancy between the fatigue striation spacing and the crack rate in the case of mainly brittle material fracturing by mechanism of quasi-brittle faceted pattern relief formation. The results of the VT3-1 titanium alloy investigation [2], wherein a close consistency between the crack growth rate and the striation spacing value with the dominating faceted pattern fatigue fracture surface (same as the quasi-brittle facet) was obtained, point to the admissibility of such approach for estimating the fatigue crack growth period in specimens.

The number 5 specimen fracture relief with dominating fatigue striations pattern was taking place during fatigue crack growth about 2000 cycles. The number 2 specimen fracture having the intermediate fracture surface relief continued during fatigue crack growth approximately 1100 cycles.

So, assessment of fatigue crack growth period of other specimens was made by approximately the same deduction that was introduced above. It was shown that specimens numbers 1,3,4 and numbers 7-11 were subjected to cyclic loads with hold-time and have passed through 430-1000 cycles during fatigue crack growth. All results of crack growth period calculation were used for estimation lifetime of tested specimens.

The SCFSCA investigations performed show that the discrepancies in estimations of the compared characteristics of crack growth period and durability at different levels of uniaxial loading (by tension, torsion bending, etc.) are unprincipled and their influence on the considered relationship can be neglected [1,5,7]. The crack growth period is defined not only by level of acting stress or stress ratio, R, but also by concentration of stresses in the zone of fatigue crack initiation. Especially this regards the situation when the specimen surface is hardened and the crack originating takes place under surface, during which the distance from the surface is determined not only by residual stresses and depth of hardened zone, but also by the structural elements of material, i.e. their sizes and distribution in volume.

Estimation of effect of surface state of specimens after their hardening made on the ratio Np/Nf was made in respect of Ti-Al-Mo titanium alloys which are widely used in civil aviation for gas-turbine engines [5]. There have been considered the situations of changing the conditions of chrome plating and hardening of surface by balls of different sizes before chrome plating. Tests for fatigue are carried out under tension and bending with rotation of cylindrical specimens of diameter 8 mm in the operating zone in the range of stress levels 330…850 MPa. It is important to note that the maximum stress level wherein the specimen were tested didn't exceed 870 MPa [6]. Duration of crack growth was determined fractographically when the crack depth was about 0.5 mm.

Based on results of these previously performed investigations obtained for VT3-1 alloy the lifetime of specimens from Ti-6Al-2Sn-4Zr-2Mo-0.1Si material was estimated with the use of the crack growth period data which were obtained as a result of the performed fractographic investigation, Table 1.

Table1 Data on durability, crack growth period and loading conditions of investigated specimens.

Item number	Structure type	Crack growth period, Np, cycles	Durability, Nf, cycles	Loading conditions
1	á/â	1000	2860	t = 1 min
2	á/â	1120	3370	t = 0
3	á/â	460	920	t ≥ 2 min
4	á/â	500	1040	t ≥ 2 min
5	á/â	1940	7500	t = 0
6	á/â	1400	4660	t = 0
7	á/â	750	1880	t ≥ 2 min
8	á/â	820	2140	t ≥ 2 min
9	â	1310	4230	t = 1 min
10	â	430	840	t ≥ 2 min
11	â	460	920	t ≥ 2 min
12	â	3240	15820	t = 0

It was shown that specimens numbers 1,3,4,7-11 of both groups had lifetime to failure in the range of 840-4200 cycles under hold-time for cyclic loads. The lifetime estimation was compared with the information about realized lifetime for tested specimens. It was established that the difference between compared values was not more than 30%.

CONCLUSION

Based of the performed investigation it may be concluded as follows:

- hold-time (dwell) of cyclic loads for the specimens of two structure types leads to a radical decrease in crack growth period relative to the period of specimens fracture in the case of their loading by a triangular shape of cyclic loads;

- significant increase in specimen durability (life-time to failure) with change of material manufacturing process and creation of more disperse and non-textural structure doesn't save material sensitivity in respect of conditions of its loading.

It is also important to emphasize that with all evident benefits of surface hardening of specimens making a positive effect on their durability, material keeps sensitivity to the inherited texture in the process of a crack growth.

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