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SENSITIVITY OF SINGLE-CRYSTAL FOIL FATIGUE INDICATORS

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It was shown that practical application of single-crystal foil fatigue indicators requires the possibility to control their sensitivity to mechanical loads. It was proved that the single- crystal and separate grain fatigue characteristics significantly depend on their crystallographic orientation.

Показано, що для практичного застосування монокристалічних фольгових індикаторів утоми необхідно мати можливість керувати їх чутливістю до зовнішніх навантажень. Установлено, що характеристики втоми монокристалів і окремих кристалітів суттєво залежать від їх кристалографічної орієнтації.

Introduction

The complexity of metal fatigue process determines the importance of methods both analytical and instrumental for metal fatigue estimation.

The approach for accumulated fatigue damage estimation by single-crystal indicators and ways for indicators sensitivity control are shown below.

The cyclic loads acting on the different aircraft elements substantially differ on magnitude, frequency and shape of load cycle. In the table the basic data of aircraft loads are given [1].

Typical aircraft operational loads

Type of load	Stress cycle, kg/mm^2	Number of load cycles after 30 000 hours
Lift of the wing	–1,4 +9,8	10^4
Wing loads due to gust 3 m/s at flight altitude 2800 m	+2,46	$6*10^5$
Fin loads due to gust 3 m/s at flight altitude 6100 m	+3,22	$2*10^5$
Shearing stresses on the rear spar due to deflection of flap	0–7	10^4
Stresses due to the excessive pressure in pressurized cabin	9,1	10^4
Stresses on the landing gear during landing	0–14	10^4

Taking into account the wide spectrum of loading condition, it is obvious that a problem of indicator's sensitivity optimization in accordance with the actual loading of the elements, damage of which is controlled, appears.

General approach to the single-crystal fatigue indicator sensitivity control

It was shown in work [2] that the accumulated fatigue damage can be estimated quantitatively with the help of foil indicators made of aluminum single crystals or some of its alloys.

Such sensors are the single crystal plates of 15 mm in diameter and 0,2 mm in thickness which are attached to the tested design construction with the help of glue on the base of Cyanoacrylate.

The sensitivity of the single-crystal indicators can be changed in the following way:

– by changing the single-crystal orientation with respect to the axis of loading;

– by changing the composition of alloy for manufacturing single-crystal indicator;

– by application of deformation amplifiers.

The influence of crystallographic orientation on the single-crystal's mechanical properties was investigated by great number of scientists.

The aluminium used for manufacturing of above discussed indicators is referred to the metals with face centered cubic unit cell also possesses a significant anisotropy of properties both at static and cyclic loading.

On the base of notion about influence of crystal orientation on the kinetics of fatigue damage of Al crystals it is possible to presume the indicator sensitivity control by application of the single-crystals with different crystallographic orientation.

The application of material of different composition and cleanliness is the second way to change the fatigue damage indicator sensitivity.

The single crystals of pure metals the most plastic are (for example, in the carried out experiments the aluminum of cleanliness of 99,999% was applied). The decreasing of plasticity can be provided by addition of small amount of Cu and Mg.

However, the described method doesn't allow to increase the single-crystal sensitivity over the certain level.

The application of deformation amplifiers is the radical and some times the only possible way of increasing the sensitivity of fatigue damage indicators. The basic requirements for the deformation amplifier, which is developed to be used with single crystal indicator, are:

– the possibility of wide range changing the amplification coefficient;

– the compactness;

– the reliability of fastening to the tested element of design;

– the minimal strain redistribution in the design elements connected with the amplifier fastening;

– the provision of corrosion resistance of the amplifier and joint.

So, taking into account the complexities of the alloy composition control and deformation amplifires application, one of the most perspective ways of sensitivity control is the variation of indicators crystallographic orientation.

Experimental investigation of the crystallographic orientation influence on fatigue damage process

The influence of crystallographic orientation on the fatigue accumulation process was estimated on the base of experiment results, in which the next objects were tested:

a) the samples of AD-1 alloy with specially obtained multicrystal structure which allows to determine the crystallographic orientation by the back-reflection Laue Method;

b) single is crystal foil indicators;

c) poly crystal foil indicators.

The results of multicrystal specimens test

The specimens of AD-1 alloy with a grain size 20–30 mm were tested. This allowed to apply the back-reflection Laue method for determining the investigated grains crystallographic orientation.

To obtain such a specific structure it was applied the method of critical deformation and annealing. The method realization presupposes:

a) the pre annealing;

b) deformation;

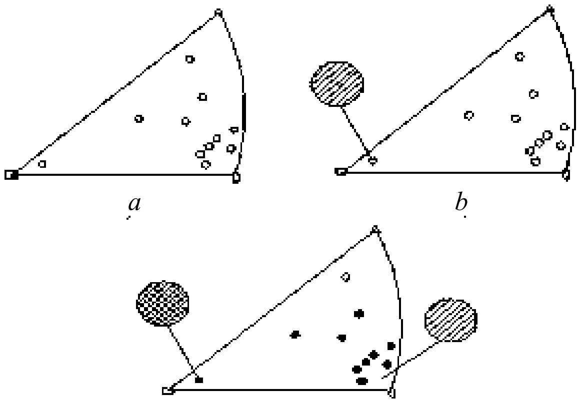
c) recrystallization annealing at which the grain growth takes place.

The deformation level which provides the maximum grain growth has been determined experimentally by previous effort [3].

The specimen with dimensions 200x1,8x60 mm was tested at the loading frequency of 11 Hz.

The maximum stress was 30,0 MPa.

The obtained investigation results have shown that in different grains the velocity of deformation processes, that correspond to fatigue initial stage, is different. Fig.1 demonstrates influence of crystal orientation on the number of cycles, corresponding to initiation of persistent slip bands.



a *b*

c

Fig. 1. The sequence of slip activation in differently oriented crystallites:
a is investigated grains orientations;
b is grain with PSB after N=5 000 load cycles;
c is grains with PSB after N=500 000 load cycles

So, after the 3 000 cycles of loading persistent slip bands were not present on the surface of all grains, then after the 5000 cycles PSB were present on the grain with orientation close to <100> direction and after the 20 000 cycles all grains except those close to <111> direction had marking of slip.

After 500 000 cycles the lines of secondary direction have appeared in the grain with orientation close to <100>.

Under equal external conditions such difference in fatigue initial stage is connected with different crystallographic orientation of separate polycrystal grains, which can be characterized by various sets of orientation parameters. Their selection depends on the fatigue destruction process peculiarities.

The results of single-crystal foil indicators tests

The aluminium single-crystal cylinders of orientations <100> and <110> (fig. 2), were used for indicators manufacturing.

Disks of 20 mm in diameter have been cut out by the electro-spark method to avoid additional deformation.

The indicator of 0,2 mm thickness of has been obtained by electrolytic polishing.

Fastening of the indicator to a sample for tests is made by the glue on the base of Cyanoacrylate.

The control of a surface state of a single-crystal indicator is carried out with the help of optical metallographic microscope with 200–400 times enlargement.

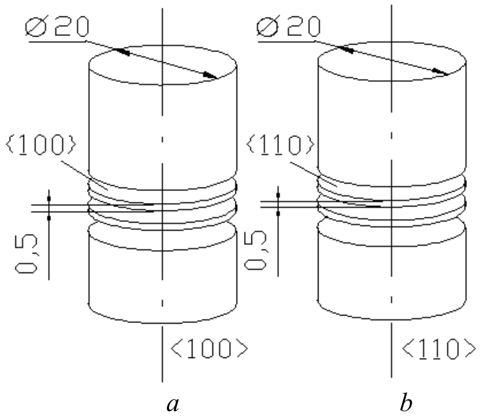


Fig. 2. Scheme of the single-crystal disk preparation for indicators manufacturing:
a is internal surface close to {100};
b is internal surface close to {110};

In the presented research deformation relief has been investigated on the crystals of two different orientations:

– series A is the crystals with the internal surface close to crystallographic plane {100};

– series B is the crystals with the internal surface close to crystallographic plane {110}.

The single crystal foil indicators were fixed on the standard fatigue test specimen.

The test of single-crystal sensors has shown, that the first features of surface deformation relief may be observed after first 2–3 thousand of cycles.

The test has revealed some specific features of relief pattern. On single-crystals of surface plane orientation {100} curvilinear relief formations are formed independently of loading direction. On a surface of single-crystals {110} with axis direction <221> rectilinear relief lines which density grows with increase in number of the cycles loading are formed.

Taking into account the chosen approach for quantitative estimation of accumulated damage it is possible to make conclusion as to preferable crystallographic orientations.

The results of poly crystal foil indicators testing

During the test of the polycrystalline specimens 1,5 mm width made of aluminum alloy AD-1 the number of cycles that corresponds to the appearance of deformational relief lines was determined. Unfortunately the quantity of lines was not calculated because of their high density and low resolution of the optical microscope.

The situation is changed during investigation of the aluminum foil pasted on the specimen for fatigue tests.

The relief lines in grains of size about 0,15 mm are spaced from each other on 0,005–0,05 mm and can be calculated.

The foil aluminium element dimensions of which are 10x20x0,1 mm have been glued on the standard specimen for fatigue test in the same way as in case of the single-crystal fatigue indicator. The fatigue tests were conducted under conditions of pulsating load cycle with maximum cyclic stresses $\sigma_{max} = 140$ MPa.

The state of grains surfaces was controlled after different number of cycles, the quantity of lines was calculated on the base of 0,1 mm.

On the base of measurement results the graphs of dependence of quantity of slip lines *n* on the number of cycles for different grains of polycrystalline aluminum are plotted (fig. 3).

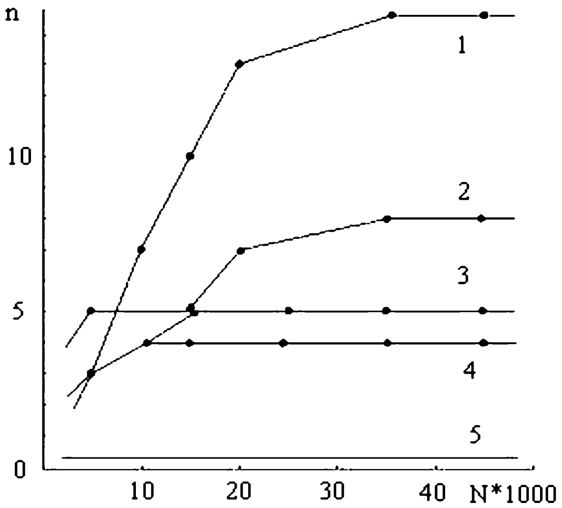


Fig. 3. Slip lines density growth under fatigue:
1 is grain N1;
2 is grain N2;
3 is grain N3;
4 is grain N4;
5 is grain N5

According to graphs the slip lines in polycrystalline aluminum appear both after first thousands load cycles and after considerable number of cycles.

In the rest grains the slip lines were absent during all observation period. In the course of research the relief constitutions were observed, they have not the rectilinear, easily distinguished lines.

The development of such constitutions after defined number of cycles hampers reliable registration of lines quantity in the polycrystalline grains.

It is significant that during cyclic loading of aluminum foil with fine-grained structure as well as model specimens of AD-1 alloy with coarse grain the grain rotation is observed, which is increasing in course of test.

So using the parameter which characterizes the slip lines density allows to control the damage intensity of different polycrystal grains with different orientation. In the conducted research the difference in initial stage of fatigue in different grains is proved.

The crystallographic orientation parameters

The generally accepted crystal orientation characteristic is the position of its axis in the stereographical triangular. In case when mentioned above axis coincide with the external load application axis it is possible to calculate the resolved shear stress acting parallel to the slip direction on the slip plane, if we know the position of crystal axis in triangular.

The shear stress in the slip plane, reduced to the slip direction is:

$$\tau = \sigma \sin\chi \cos\chi = \sigma \cos\phi \cos\phi .$$

The expression $\cos\varphi \cos\lambda$ is called as Schmid factor.

The slip usually takes place in most close-packed crystal face. Directions of slip are also the directions with most close atom packing in the given slipping plane.

According to Schmid’s law, slip in the crystal is started when the resolved shear stresses acting in slip planes reach the critical value. The slip system in which Schmid’s factor is maximum at given crystal orientation is called primary as the slip must be initiated in it.

But the experiments of last years showed that Schmid’s law is not always justified. The slip initiation was observed at Schmid’s factor much less then in primary system.

The slipping in crystals can develop both in one slip system and in two or more. It can take place when different slip systems are equiloaded at the initial crystal orientation, and also when deformation in primary system changes loading of others so that slipping becomes possible in them. In the face-centered cubic crystals due to high symmetry at special orientations the multiple slip occurs, that defines their deformational strengthening intensity.

On the stereographical triangular after denoting the face-centered cubic crystal orientation it is possible to mark out so called “hard” and “soft” orientations. “Hard” orientations characterized by rapid multiple slip initiation are placed at the sides of triangular.

“Soft” orientations characterized by possibility of single slipping – in the centre of triangular.

As the quantitative parameter representing crystal inclination to multiple slip, that is to more intensive deformational strengthening, can be taken factor *Q*. It is defined as a ratio of second by value Schmid’s factor and Schmid’s factor of the primary system.

But even value of factor *Q* does not coincide with the real crystal inclination to multiple slipping and deformational strengthening.

So the application of maximum Schmid’s factor and factor *Q* as the orientation parameter of fatigue damage is not always justified.

Deviation from the Schmid’s law can be connected with a grate role of the free surface in development of fatigue damage.

Conclusions

The control of the foil single-crystal fatigue indicator sensitivity may be performed by the control of single-crystal`s orientation.

The influence of crystallographic orientation on the aluminum single crystals and grains fatigue can be estimated taking into account the number of orientation parameters: magnitude of shearing stress in primary slip system, correlation between shear stresses magnitudes in primary and secondary slip systems, the location of activated slip systems relatively to crystal surface.

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