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Surface deformation relief as an indicator of fatigue damage under two-step loading sequences

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Abstract

The study investigates the possibility of predicting the residual fatigue life of clad structural aluminum alloys based on the quantitative evaluation of surface deformation relief formed during cyclic loading. Fatigue damage accumulation in metallic structures is accompanied by microstructural transformations caused by dislocation motion along crystallographic planes. These processes lead to the formation of characteristic surface features such as slip bands, extrusions, and intrusions. Although these structures are three-dimensional, their development can be effectively assessed using two-dimensional optical microscopy images, enabling quantitative analysis of the deformation relief evolution during fatigue loading. The research focuses on clad aluminum alloys widely used in aircraft structures, including D16ATV, V95, 2024-T3, and 7075-T6. A damage parameter D was introduced to characterize the saturation level of the deformation relief. This parameter is defined as the ratio of the surface area occupied by deformation relief features to the total observation area. Experimental observations were carried out using metallographic microscopy at magnifications of 200–400×. The obtained data allowed regression models to be developed that relate the damage parameter to the relative residual fatigue life. The proposed approach was extended from regular cyclic loading to simple irregular loading regimes, specifically two-step loading sequences of the "low–high" and "high–low" types. The results were compared with predictions based on Miner's linear fatigue damage summation rule. Experimental fatigue tests on D16ATV alloy specimens demonstrated that the accuracy of residual life prediction using the deformation relief based damage parameter depends on the stress range. Within a certain range of cyclic stresses, the developed regression model provides prediction accuracy comparable to, and in some cases exceeding, that obtained using Miner's rule. The results confirm that the saturation of surface deformation relief can serve as a structurally sensitive indicator of accumulated fatigue damage. The proposed methodology can be applied both to direct monitoring of clad aluminum structural components and to the fatigue indicators for metal structures of aircraft, bridge, pressure vessels.

Key words: fatigue, alclad alloy, deformation relief, Miner's rule, residual life, fatigue indicators.

Introduction

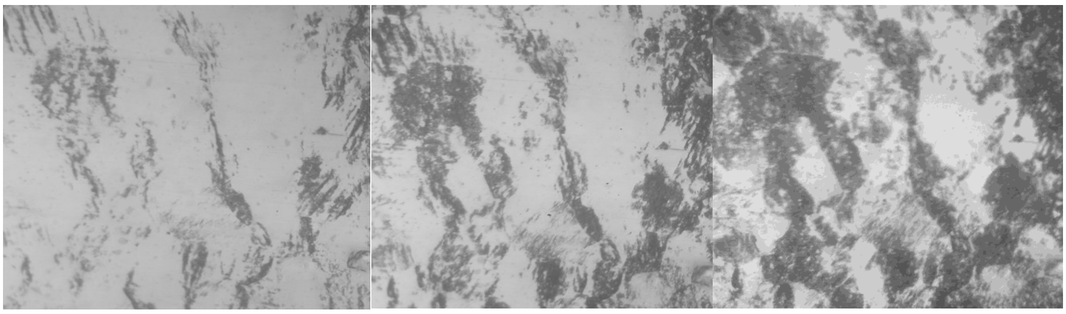
The phenomenon of fatigue damage in metallic structures is studied with the aim of preventing catastrophic failures, optimizing maintenance, and developing methods for technical condition diagnostics. The existence of a large number of diverse approaches to assessing accumulated fatigue damage indicates that current understanding of the fatigue process mechanisms remains insufficiently developed and that further accumulation of experimental data is required for subsequent generalization. The process of fatigue damage accumulation consists of structural transformations in the metal which, for a number of metals, exhibit features that can be observed using relatively simple surface examination methods. As a result of dislocation motion along crystallographic planes, extrusions, intrusions, and slip bands can be observed on the surface of many metals, forming a deformation relief. These surface structures are three-dimensional; however, even a two-dimensional digital optical image obtained using a metallographic microscope makes it possible to quantitatively assess their saturation level and evolution during cyclic loading. The general form of cyclic loading is irregular loading, i.e., loading in which the cycle parameters are not constant during the service life of the structure. This is a typical situation for aircraft structures, which are subjected to loads of different origins and, accordingly, of different amplitudes, load ratio (cycle asymmetry), mean stress, sequence of applied loads, uniaxial and multiaxial loading, as well as in-phase and out-of-phase loading. An analytical assessment of accumulated fatigue damage for such structures under such loading conditions has not yet been fully resolved. The use of simplified models requires large safety factors, while instrumental monitoring methods are still under development and have not yet found widespread practical application. One of the reasons for the imperfection of existing methods is the insufficient attention paid to damage indicators that are not merely accompanying effects of metal fatigue (such as changes in electrical resistance), but that directly reflect the nature of the phenomenon – namely, changes in the metal structure resulting from dislocation motion. Below, key stages of a research cycle devoted to studying the evolution of deformation relief during cyclic loading are presented. The possibility of quantitative evaluation of the deformation relief of the cladding layer surface of widely used structural aluminum alloys is demonstrated for both regular and stepwise cyclic loading.

1. Deformation Relief of Metal Surfaces Formed under Cyclic Loading

As a result of cyclic loading, a deformation relief is formed on the surface of many pure metals and alloys. The deformation relief caused by the crystallographic slip includes extrusions, intrusions, and rotational structures of the surface layer of the metals. Detail description of relief components has been done in papers [1, 2]. Extrusions, intrusions and their role in the fatigue cracks forming and propagating in polycrystalline copper considered in the paper [3]. In the paper [4] it was shown that cyclic loading results in well-developed slip markings in the fully pearlitic steel. In the research [5] the evaluation of the extrusion/intrusion structure was conducted by the measuring surface roughness thus predicting location of the fatigue crack initiation. It was found by the authors of [6] in the results of in situ observations and characterization of the formation of Persistent Slip Bands (PSB) in micrometer-sized Ni single crystals, that a relatively large number of cycles (>106) was necessary to nucleate PSBs in microcrystals compared with bulk scale, and correspondingly, extreme fatigue lifetimes were exhibited at the micrometer scale. The PSB surface have an inherent roughness immediately on formation; then the roughness of the PSB remains stable with further cyclic loading. The slip traces formed in the first ~10 cycles are also found to identify the locations where PSBs and cracks form. The grain size effect and initial dislocation density on surface roughness evolution in Face Centered Cubic (FCC) Ni single crystals during the early number of cycles of mechanical cyclic loading has been simulated by the authors of the work [7]. For the number of cycles modeled, larger crystals showed a uniform surface step distribution compared to smaller crystals where the surface roughness was more localized in surface slip bands. In the work [8] the surface roughness of specimens made of Medium-Carbon Steel 42CrMo4 (SAE 4140) was measured using a confocal microscope to confirm the surface roughness evolution. The surfaces of the specimens changed during fatigue testing, moreover, the roughness evolution of the specimens at several applied stress amplitudes might correlate with the lifetime. Extrusions and intrusions under cyclic loading do not form in all materials. They were not observed in exploratory experiments on unclad D16 alloy conducted within the framework of the present study. At the same time, the cladding layer, formed from commercially pure aluminum or some of its ductile alloys, is sensitive to cyclic loading and exhibits the formation of surface deformation relief that reflects the process of deformation localization in the crystal at the micro-, meso-, and macro-levels.

2. Formation and Evolution of Surface Deformation Relief in Clad Aluminum Alloys

The surface deformation relief of clad aluminum alloys was investigated in order to develop a method for evaluating accumulated fatigue damage. The deformation relief that forms on the surface of aluminum alloys D16ATV, V95, 2024-T3, and 7075-T6 was studied. A typical appearance of the deformation relief on the polished surface of D16ATV alloy specimens after cyclic loading is shown in Fig. 1. The number of loading cycles and the percentage of the consumed fatigue life are indicated.



a) b) c)

Fig.1. Evolution of the surface deformation relief in the process of the cyclical loading: a) N= 30000 cycles (1.9%); b) N= 100000 cycles (6,3%); c) N= 400000 cycles (25,2%). R=0; σ_{max}=147,0 MPa

For the quantitative evaluation of the saturation of the deformation relief and the corresponding accumulated fatigue damage, a damage parameter was proposed. This parameter is defined as the ratio of the surface area exhibiting features of deformation relief to the observation area. The size of the observation area was 0.3 × 0.3 mm. In the present study, optical images were obtained at magnifications in the range of 200× – 400×.

The deformation relief was investigated during fatigue testing of aluminum alloy specimens under uniaxial tension and cantilever bending with different loading cycle parameters, under biaxial loading with in-phase and out-of-phase conditions, and under simple block-type irregular loading regimes. Typical curves describing the evolution of the deformation relief are shown in Figs. 2 and 3.

Experimental data on the evolution of the damage parameter during cyclic loading made it possible to obtain regression models for predicting the critical state, in which the relative remaining number of cycles $\overline{N_R}$ is considered as a function of the damage parameter.

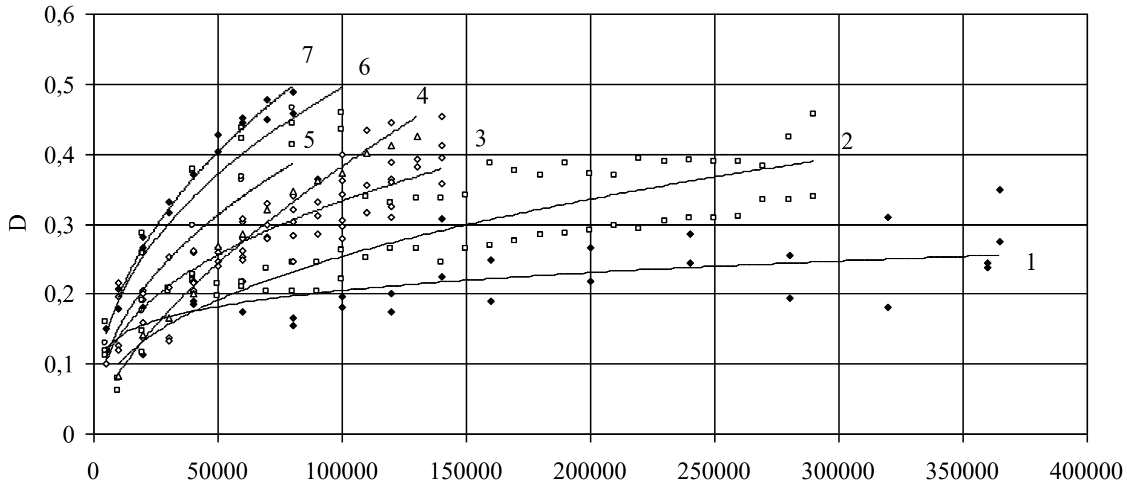


Fig.2. Dependence of the damage parameter *D* on maximum sress of the cycle under the axial cyclical loading: 1 - σ_{max}=76,9 MPa; 2 - σ_{max}=81,7 MPa; 3 - σ_{max}=96,2 MPa; 4 - σ_{max}=105,8 MPa; 5 - σ_{max}=115,4 MPa; 6 - σ_{max}=129,8 MPa, 7 - σ_{max}=134,6 MPa. Stress ratio *R*=0

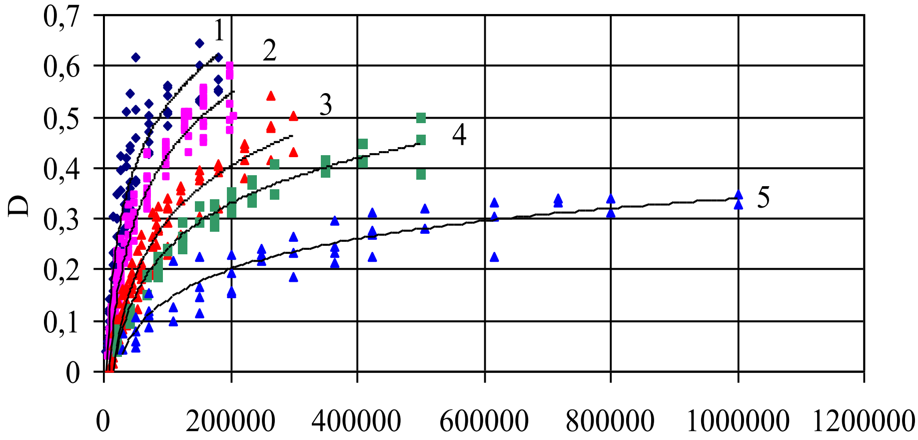


Fig.3. Evolution of the damage parameter *D* at the fatigue test by cantilever bending: 1 – *R* =0; 2 - *R* =0,3; 3 –*R* =0,42; 4 – R = 0,5; 5 – *R*=0,6

The model for predicting the residual fatigue life can be constructed by transforming the model of the evolution of the parameter D during cyclic loading. To estimate the residual life, the following correlation relationship was obtained: $N_R, \% = 119{,}29 - 226{,}3D$. The corresponding experimental values are shown in Fig. 4.

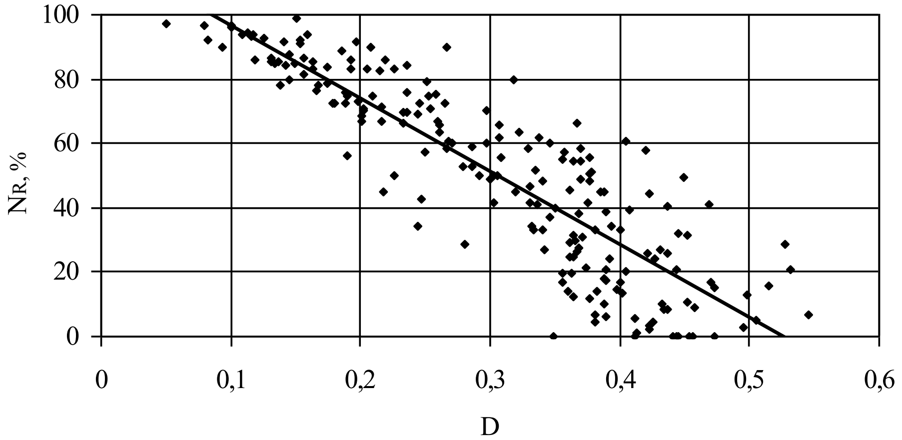


Fig.4. Dependence of the residual life N_R on the damage parameter *D*

3. Evaluation of accumulated damage and residual fatigue life under stepped irregular loading.

The summation of accumulated fatigue damage in simplified engineering calculations is most often performed according to the linear Miner's rule or its modifications. It is well known that one of the shortcomings of Miner's rule is that it does not take into account the sequence of the applied loads. In an experiment conducted on specimens of the D16AT aluminum alloy under a tensile cyclic loading condition, a comparison was made between the results of residual life evaluation obtained using the linear fatigue damage accumulation rule and those obtained using parameters of the deformation relief. The programmed fatigue tests included the implementation of two-step loading sequences: "high–low" and "low–high" (Fig. 5). The selection of stress levels was based on durability data obtained under regular loading regimes.

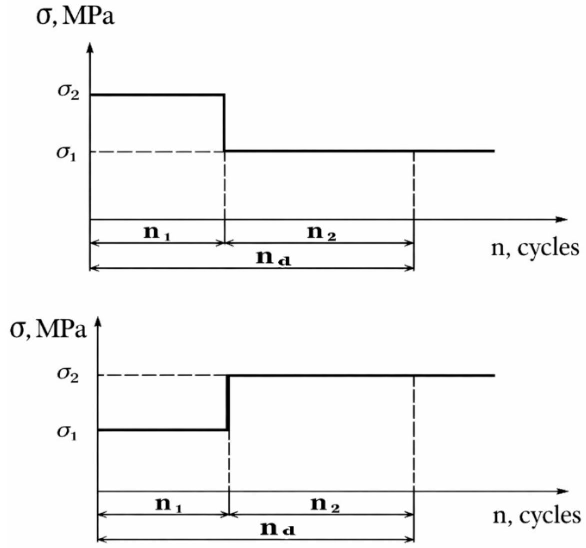


Fig.5. Scheme of two step block loading: n_1 – number of cycles at first step; n_2 – number of cycles at second step; n_d – number of cycles at which the damage was assessed

After the implementation of two loading steps, the tests were continued while recording the number of cycles up to the initiation of a fatigue crack and up to complete failure. The following quantities were determined: the damage parameter *D* and the corresponding residual life at a given cyclic loading level according to the regression model presented above; the relative damage according to the Miner rule and the corresponding residual life; the relationship between these quantitative indicators and the sequence of loading application; and the assessment of the adequacy of the Miner rule and of the method for determining accumulated damage based on the deformation relief state. The relative damage and the sum of relative damages were determined with respect to the moment of formation of a crack with a length of 1.0 mm. The basis for calculating the relative damages according to Miner's theory was the previously obtained fatigue curves. Two series of tests were carried out: with a transition from a lower stress level to a higher one, and from a higher stress level to a lower one. In the first series, the "low" stress level was 79.0 MPa and the "high" stress level was 108.0 MPa. In the second series, the "low" stress level was 79.0 MPa and the "high" stress level was 133.0 MPa. The selection of stress levels was based on data on fatigue life under regular loading conditions and on the results of monitoring the deformation relief. Conditions were taken into account under which the exhaustion of the fatigue life is determined by the damage parameter *D*, regardless of the level of cyclic stress, as well as conditions under which the determination of this parameter is not sufficient for reliable prediction of the remaining number of loading cycles. The loading regimes of both steps in the first series of programmed tests corresponded to the stress range in which the exhaustion of fatigue life can be determined by the damage parameter *D* regardless of the level of cyclic stress, whereas the loading regimes of the second series of tests were partly outside this range. In tests performed according to the "low–high" scheme (79.0 MPa – 108.0 MPa), the average value of the sum of relative damages was $\sum n/N = 1.089$. In tests according to the "high–low" scheme (108.0 MPa – 79.0 MPa), the average value of the sum of relative damages was $\sum n/N = 1.138$. As can be seen, loading with a transition from a lower stress level to a higher one produces a greater damaging effect than loading with a transition from a higher stress level to a lower one, which, according to data reported by other authors, may exhibit a strengthening effect. The features of the damage accumulation process were also considered for loading regimes outside the range from 70.0 MPa to 120.0 MPa, within which the damage parameter is determined by the relative cyclic life and does not depend on the stress level. In tests performed according to the "low–high" scheme (79.0 MPa – 133.0 MPa), the average value of the sum of relative damages was $\sum n/N = 0.796$. In tests performed according to the "high–low" scheme (133.0 MPa – 79.0 MPa), the average value of the sum of relative damages was $\sum n/N = 1.605$.

Table 1 presents the results of calculating the residual fatigue life both according to Miner's rule and using the damage parameter.

Table 1

Results of residual fatigue life evaluation under a two-step loading program

Loading scheme	Residual life according to Miner's rule n_{resM}, cycles	Mean value of the residual fatigue life according to the damage parameter *D*, n_{resD}, cycles	Mean value of the residual fatigue life according to the experiment, n_{res}, cycles	Mean value of the prediction error when using Miner's rule	Mean prediction error when using the damage parameter *D*
79MPa-108 MPa	61596	69547	68380	9,82	-1,806
108 MPa -79 MPa	119 148	131488	166800	28,36	20,78
133 MPa -79 MPa	115 582	131501	216933	45,36	37,3
79 MPa - 133 MPa	34 531	34654	27166	-52,43	51,21

The results of the residual life calculations presented in Table 1: a) according to the Miner rule; b) according to the damage parameter D determined by the developed methodology after two stages of programmed loading and the corresponding regression model of life consumption, as well as the actual fatigue lives obtained experimentally, make it possible to conclude that within a certain range of loading regimes the obtained regression model of life consumption allows the residual life to be determined with an accuracy that exceeds the accuracy of life estimation according to the Miner rule. The agreement of the residual life calculation methods, both according to the Miner rule and according to the prediction methodology based on the damage parameter D, decreases with increasing levels of the applied stresses.

At the same time, the prediction obtained by both methods gives an overestimated result for loading according to the "low–high" scheme and an underestimated result for loading according to the "high–low" scheme. Thus, the regression model of life consumption developed on the basis of regular fatigue tests makes it possible to evaluate the residual life of aircraft structural elements without the use of additional calculations within a certain range of programmed loading regimes.

4. Implementation of the Surface Deformation Relief Phenomenon in Fatigue Damage Indicators for Metal Structures

One of the applications of data concerning the evolution of the surface deformation relief of clad aluminum alloys is a method that involves installing fatigue indicators for metal structures (FIMS) on loaded structural elements of various purposes. The need to use such indicators arises from the fact that a significant number of structural materials do not exhibit the formation of surface deformation relief under cyclic loading and do not possess a cladding layer that belongs to PSB (Persistent Slip Band) metals, i.e., metals on whose surface extrusions, intrusions, and slip bands can be observed during cyclic loading. The results of this work demonstrated that the surface deformation relief can be considered an indicator of fatigue damage. When such an indicator is attached to the surface of loaded structural elements, a correlation can be established between the damage in the indicator and the damage in the structure, making it possible to assess the exhaustion of the fatigue life of the structure. For many structures, another solution is more optimal, namely, the use of structural alloys with a cladding layer instead of single crystals. The basic configuration is an indicator specifically developed for aircraft fatigue monitoring (Fig. 6). In this case, the cladding layer of the indicator serves as the fatigue damage indicator, whose sensitivity to cyclic loading was demonstrated above. The sensitivity of the indicators is determined by their geometry. The loading regimes of some other engineering structures indicate the possibility and expediency of using structurally-sensitive fatigue damage indicators.

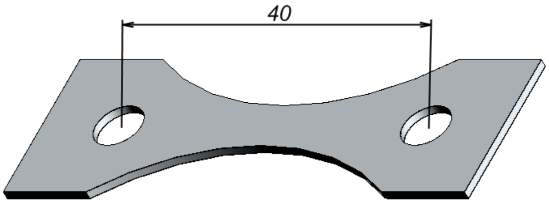


Fig. 6. Basic configuration of the Fatigue Indicator for Metal Structures

After analyzing the deformation of elements of steel bridges [10], it was established that indicators manufactured from 2024-T3 clad alloy (Alclad) are capable of responding to the service deformations of bridge elements made of S275 and S355 steels through the formation of a surface deformation relief [18]. Another potential application of fatigue indicators for metal structures is the monitoring of fatigue damage in oil and gas transportation systems, for example for Compressed Natural Gas (PNG) pressure cylinders [12, 13].

Conclusions

The study of the evolution of the surface deformation relief of clad aluminum structural alloys indicates a close correlation between the density of the deformation relief and the accumulated fatigue damage within a certain range of cyclic stresses and the corresponding strains. Under irregular two steps cyclic loading, this phenomenon makes it possible to predict the residual life with an accuracy that is not inferior to, and within a certain range even exceeds, the accuracy of prediction based on the Miner rule.

The obtained conclusions can be implemented both in the direct monitoring of the technical condition of structures made of clad aluminum alloys and in the application of fatigue indicators for metal structures.

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Карускевич М.В. , Маслак Т.П. , Карускевич О.М. , Корчук В.І. Деформаційний рельєф поверхні як індикатор втомного пошкодження при ступінчатому циклічному навантажуванні

У роботі досліджено можливість прогнозування залишкового ресурсу втоми плакованих конструкційних алюмінієвих сплавів на основі кількісної оцінки поверхневого деформаційного рельєфу, що формується під час циклічного навантаження. Накопичення втомних пошкоджень у металевих конструкціях супроводжується мікроструктурними перетвореннями, зумовленими рухом дислокацій уздовж кристалографічних площин. У результаті цих процесів на поверхні металу утворюються характерні структурні елементи, зокрема смуги ковзання, екструзії та інтрузії. Хоча ці структури мають тривимірний характер, їх розвиток може ефективно оцінюватися за допомогою двовимірних оптичних зображень, отриманих за допомогою металографічного мікроскопа, що дозволяє кількісно аналізувати еволюцію деформаційного рельєфу під час втомного навантаження. Дослідження присвячене плакованим алюмінієвим сплавам, які широко застосовуються в авіаційних конструкціях, зокрема сплавам Д16АТВ, В95, 2024-Т3 та 7075-Т6. Для характеристики ступеня насичення деформаційного рельєфу було введено параметр пошкодження *D*. Цей параметр визначається як відношення площі поверхні, зайнятої елементами деформаційного рельєфу, до загальної площі спостереження. Експериментальні спостереження проводилися за допомогою металографічної мікроскопії при збільшенні 200–400$^{\times}$. Отримані експериментальні дані дали змогу побудувати регресійні моделі, що пов’язують параметр пошкодження з відносним залишковим ресурсом втоми. Запропонований підхід було поширено з умов регулярного циклічного навантаження на прості режими нерегулярного навантаження, зокрема на двоступеневі програми навантаження типу «низький–високий» та «високий–низький». Отримані результати порівнювалися з прогнозами, виконаними за правилом лінійного підсумовування втомних пошкоджень Майнера. Експериментальні випробування зразків зі сплаву Д16АТВ показали, що точність прогнозування залишкового ресурсу на основі параметра деформаційного рельєфу залежить від діапазону напружень. У певному інтервалі циклічних напружень розроблена регресійна модель забезпечує точність прогнозування, яка є не гіршою, а в окремих випадках навіть перевищує точність оцінювання за правилом Майнера. Отримані результати підтверджують, що ступінь насичення поверхневого деформаційного рельєфу може розглядатися як структурно чутливий індикатор накопичених втомних пошкоджень. Запропонована методика може бути використана як для безпосереднього моніторингу технічного стану конструкцій із плакованих алюмінієвих сплавів, так і для індикаторів втоми металевих конструкцій літаків, мостів, посудин під тиском.

Ключові слова: втома, плаковані сплави, деформаційний рельєф, залишковий ресурс, індикатори втоми.