https://doi.org/10.37434/tpwj2021.08.09

EDDY CURRENT MONITORING OF ALUMINIUM ALLOY DEGRADATION DURING LONG-TERM OPERATION OF AIRCRAFT

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Monitoring of aluminium alloy degradation is a very important part in ageing aircraft maintenance strategy. Our approach is based on the possibility of finding correlation between the material parameters measurable using nondestructive methods and cyclic crack growth resistance characteristics of the evaluated material. It was revealed that specific conductivity as a structure-sensitive parameter of aluminium alloys, measured by the eddy current method, can be applied as an effective tool for such evaluation. The main advantage of the eddy current method is the possibility to carry out the measurements without a direct contact with the inspected surface. From the point of view of the eddy current method, an aircraft component can be represented by 3-layer object, which consists of dielectric protective coating, anticorrosive layer of about 0.5 mm thickness of pure aluminium cladding and aluminium alloy skin subjected to operational loading. To measure conductivity in this third layer with a high lift-off suppression (up to 0.5 mm), a new eddy current conductivity measuring device of type VEPR-31 was designed. The correlations between elongation, fatigue limit of degraded D16T and B95T1 alloys for different equivalent stresses were obtained. Eddy current measurements of specific conductivity carried out in AN-12 aircrafts (produced in 1966) in different zones of the wing after a long-term operation in aircraft repair plant condition operation confirmed the efficiency of the proposed methodology. 27 Ref., 8 Figures.

Keywords: aircraft, aluminium alloys, degradation, eddy current method, conductivity, fatigue crack growth resistance

Nondestructive testing (NDT) of critical structures during operation is mostly performed in order to detect defects of fatigue and corrosion origin [1–3]. At the same time, the problem of timely evaluation of mechanical characteristics of structural materials, changing in the process of degradation changes of the structure under the influence of operational factors, which can include the effect of elevated temperature, static and cyclic loads, corrosive environment, radiation, etc. [4, 5]. The obtained data are necessary for evaluation of structural reliability of and prediction of their service life.

Operational degradation of structural aluminium alloys (AA) is associated with the action of many factors, among which static and cyclic loads, temperature, exposure to aggressive media, etc. have the highest influence [6-9]. The mentioned factors affect the material of structures in different way, which leads to an increase in the amount of dispersed intermetallics and the density of dislocations, diffusion of alloying elements and their segregation along the grain boundaries, microcracking of secondary phase inclusions, etc. [7, 9]. It is particularly important to note the synergy of operational factors, when each of them separately does not lead to a significant degradation of materials, and their combined action is of crucial importance. Without evaluating the degradation change of mechanical properties of materials it is impossible to reliably evaluate residual life of structures and, in particular, operation of aircraft on the modern principle of admissible damage. Degradation of AA properties can be evaluated by destructive and nondestructive methods [9]. Destructive methods of establishing real life characteristics of materials are based on mechanical tests of witness specimens or specimens cut out from existing structures during the repair and replacement of individual parts of structures. During operation, such an approach is objectively impossible, which stimulates the search for other approaches and makes the need for operational monitoring of degradation changes in the structure of materials by NDT methods relevant.

Our approach is based on the search and use of correlations between physical structure-sensitive parameters of the material, which can be determined by NDT methods and mechanical characteristics of the

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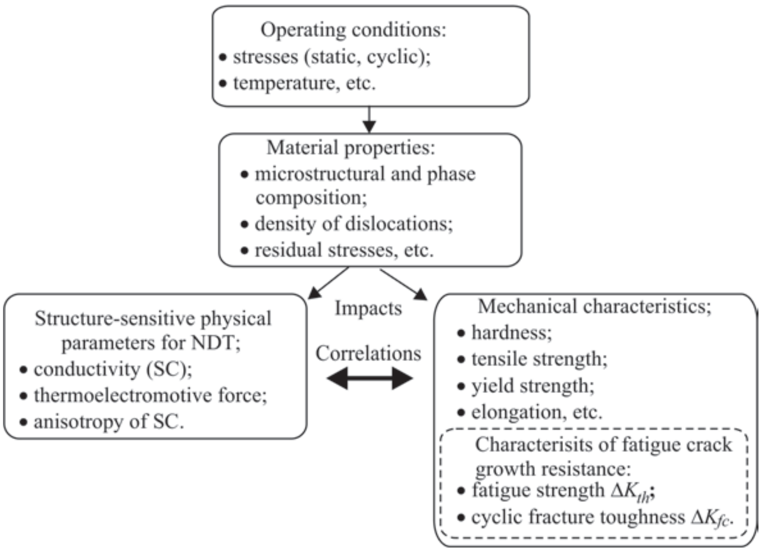

Figure 1. Relationships between operating conditions, structure and physical and mechanical characteristics of aluminium alloys

material under static and cyclic loading, which, on the one hand, are sensitive to structural changes and degradation of the material, and on the other are necessary to calculate the residual life of structures [10, 11]. The scheme of relationships that lead to the formation of such correlations for AA is shown in Figure 1.

It is obvious that operating conditions, in particular nature of mechanical stresses, temperature, corrosive environment, affect the change of material properties, including microstructural and phase composition, dislocation density and residual stresses, which can be considered to be the most decisive (Figure 1). In turn, the properties of the material simultaneously affect the structure-sensitive physical parameters of the material, which can be determined by means of NDT, and the mechanical characteristics of the material. A similar approach was used by us to test the degradation changes of ferromagnetic steels of steam conductor heat power plants on the basis of measuring the coercive force of the material [12]. Obviously, this approach requires a combination of modern approaches to fracture mechanics with the development of NDT capabilities.

For AA, the structure-sensitive parameters of NDT can be specific conductivity (SC) and thermoelectromotive force (TEMF) [5, 6, 11]. Our previous studies showed that the choice of SC as a structure-sensitive parameter has significant advantages due to the possibility of its contactless measurement by the eddy current method through a layer of paint-and-lacquer coating [13]. SC anisotropy indicated in Figure 1 can also be a promising direction for development of methods for monitoring AA degradation, provided that the means of its determination are created, which are still at the initial stage [14].

The novelty of our approach consists in the search for correlations between SC and fatigue crack growth resistance (FCGR) characteristics, which are needed to calculate the residual life of aircraft structures in contrast to previous works [15, 16], which investigated the correlations of SC with such characteristics of AA as hardness, tensile strength, yield strength and elongation. In Figure 1 FCGR is marked in a dotted line.

It should be noted that characteristics of the existing eddy current structurescopes based on SC measurement do not allow determining SC changes during testing of degradation changes in the material of aircraft structures because of the limited range of tuning out from changes in the thickness of protective dielectric coatings (DC) and a gap, as well as a low depth of testing [15, 18]. The known foreign devices, in particular Sigmatest and Sigmachek, have an insufficient locality of testing due to a large (more than 7 mm) diameter of the working platform of the eddy current converter (ECC) and are used mainly at metallurgical enterprises for quality testing of heat treatment. Therefore, it is necessary to optimize the parameters of eddy current control and develop a new eddy current structurescope with a local ECC and improved metrological characteristics in terms of testing depth and tuning out range from DC thickness and a gap.

Development of means for contactless measurement of specific conductivity of aluminium alloys in the conditions of aircraft operation. To provide NDT of aircraft structures during operation, the eddy current structurescope should meet the following general requirements:

- provide a high locality of testing aircraft structures, characterized by the curvature of the surface with a large number of rivet holes;
- provide testing through the protective DC layer without its removal;

- provide testing of changes of the structure in the inner layers of structural material.

The first requirement can be solved by choosing the working diameter of ECC, which should not exceed 1.2 mm. The second requirement to structurescopes requires realization of the methods that can expand the range of tuning out from the effects of changes in the gap between the working surface of ECC and the surface of the testing object (TO) or DC thickness in the range of up to 0.5 mm. We should note that at the used operating frequencies, the gap (air gap) between ECC and TO surface and the DC layer of the corresponding thickness affect the ECC signal equally. Therefore, we will further use the term «tuning out from the gap», meaning also tuning out from the change in the thickness of the protective DC.

To perform the third requirement, it is necessary to reduce the working testing frequency in such a way that output ECC signal was influenced by SC changes in the lower layers of TO.

In terms of the eddy current method, each element of the surface of the aircraft structure can be presented in the form of a three-layer structure (Figure 2) [19]. The upper layer represents a protective DC. The second layer is an anticorrosion cladded layer of pure aluminium. And the third layer is the base aluminium material that bears operating loads and structural degradation changes of the material, which should be tested with tuning out from variable parameters that may affect the testing results.

It is obvious that the problem specified in the complete statement is quite complex and therefore for its solution it is rational to apply methods of mathematical modeling along with experimental means. In particular, in [19] the optimal choice of the operating testing frequency depending on the thickness of DC was analyzed. The dependence of sensitivity of the eddy current method to the change of SC on the operating testing frequency for different values of the gap (DC thickness) was investigated. The existence of an optimal operating frequency depending on DC thickness is shown, which drops with an increase in DC thickness. To obtain the maximum sensitivity to SC change during testing through the DC layer of 0.5 mm thickness, the optimal frequency should be 30 kHz, which is three times lower than the operating frequencies of previously developed devices for measuring SC in AA.

To reduce the SC measurement error associated with a possible change in the gap (or DC thickness), it is promising to use the phase method for ECC signal processing [20]. The phase structurescope (SC measuring device) consists of two channels: a measuring and a reference one. To increase the range of tuning out from the impact of changes in the gap, the output ECC signal is summed up with a compensation signal, which actually leads to a displacement of the reference point in the complex plane of the signal. We used the method of dynamic compensation, when the compensation signal changes only on one component depending on the SC value, which simplifies the realization of the phase method and expands the range of tuning out from the change in the gap [21]. In the reference channel from the signal of the generator, a reference signal for the operation of the phase detector is formed. In order to set a zero signal at the output of the phase detector when setting ECC on the specimen with SC, which corresponds to the lower values of the measured range, the phase shifter of a reference channel was introduced in the circuit. The characteristics of the phase detector have a key importance to achieving a high accuracy of the SC measuring device as a whole and its development requires a special attention. In the device an updated circuit is used, that reduces the errors associated with the conversion of the signal phase into a time interval, which is used as an indication parameter [22]. At the output of the phase detector a signal is extracted, proportional to the phase shift between the measuring and reference signals. For digital indication of the measured value directly in SC units (MSm/m), into the SC measuring circuit, a scaling and linearization unit was introduced according to our invention [23]. Figure 3 shows the dependences of the signal at the output of the phase detector from the gap, which were obtained without tuning out from it and with realization of the proposed method of eddy current testing with tuning out from the impact of the gap [21]. The results are given for the beginning, middle and end of the SC measurement range (14.0; 24.7 and 37.1 MSm/m, respectively). These dependences show that the signal at the output of the phase detector does not depend on the size of the gap in the range of up to 0.5 mm, which provides the possibility of testing through the DC layer of appropriate thickness.

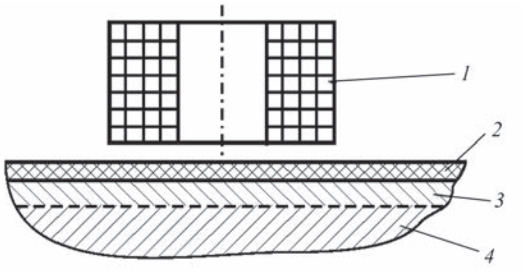

Figure 2. ECC over the element of aircraft structure in the form of a 3-layer electric conductive TO: *1* — ECC; *2* — DC; *3* — cladding layer of aluminium; *4* — aluminium alloy

The set of technical solutions presented above is used to create an eddy current structurescope-SC

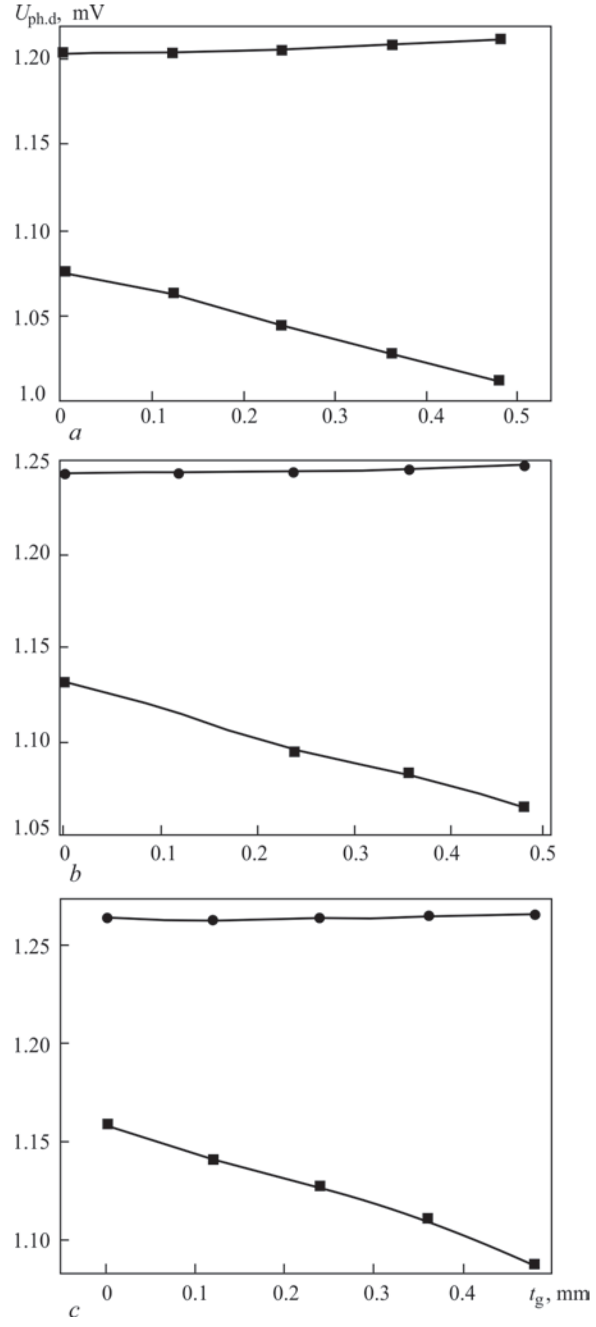

Figure 3. Dependence of stress at the output of phase detector U_{PhD} on the gap t_g without tuning out (●) and with tuning out (■) for ECC mounted on the specimens of the material with SC of 14.0 MSm/m (*a*), 24.7 (*b*) and 37.1 (*c*)

meter (Figure 4), which solves the problem of local measurement of the specific SC of aluminium alloys in the range of 14.0–37 MSm/m with an error of up to 2 % with tuning out from the impact of change of a gap to 0.5 mm.

The eddy current structurescope of type VEPR-31 (Figure 4), unlike previously created devices of type VEP-21 and VEP-22 [6, 9], has a larger range of tuning out from the value (change) of the gap or thickness of paint and varnish coating and an autonomous power supply. In addition, in the device a reduced operating frequency of 60 kHz was used,

Figure 4. Eddy current structurescope of type VEPR-31

which allows testing the change in the structure of AA through the DC layer and cladding. We should note that during the final choice of operating frequency, it is also necessary to have a sufficient sensitivity of measuring the phase of the output signal of ECC, which drops with a decrease in the operating frequency. The device uses a local ECC, the windings of which are mounted on a ferrite core with a diameter of 1.1 mm, which allows testing aircraft structures with a large number of holes.

Basic technical characteristics of the structurescope of type VEPR-31

SC measurement range, MSm/m	14.0–37.1
Main measurement error in normal conditions,%	not more than ± 2
Admissible gap between ECC and testing surface, mm	not more than 0.5
Device power supply: • from the mains of 50–60 Hz, voltage 220 V • from a built-in battery	
Power consumption, W	not more than 1.0
Overall dimensions, mm	not more than 60×160×14
Mass of device, kg	not more than 1.5

Metrological and operational characteristics of the structurescope of type VEPR-31 allow monitoring degradation changes of AA structure under operating conditions, which is confirmed by the experience of its use at the SE «Antonov».

Correlation dependencies between mechanical characteristics and SC of degraded aluminium alloys. It is shown [24] that the processes of degradation of AA depend on the load of structural elements and are displayed in the change of SC value. It was found that a compatible long-term effect of mechanical stresses and elevated temperatures causes changes in the fine structure, significant local inner stresses and determines the special mechanical behavior of structural AA of type D16 and B95. At the same time, their tendency to brittle fracture grows (plasticity Δ drops) and FCGR (ΔK_{th}, ΔK_{fc}) decrease, which determine fatigue life (N_f) of structural elements [9], and SC σ

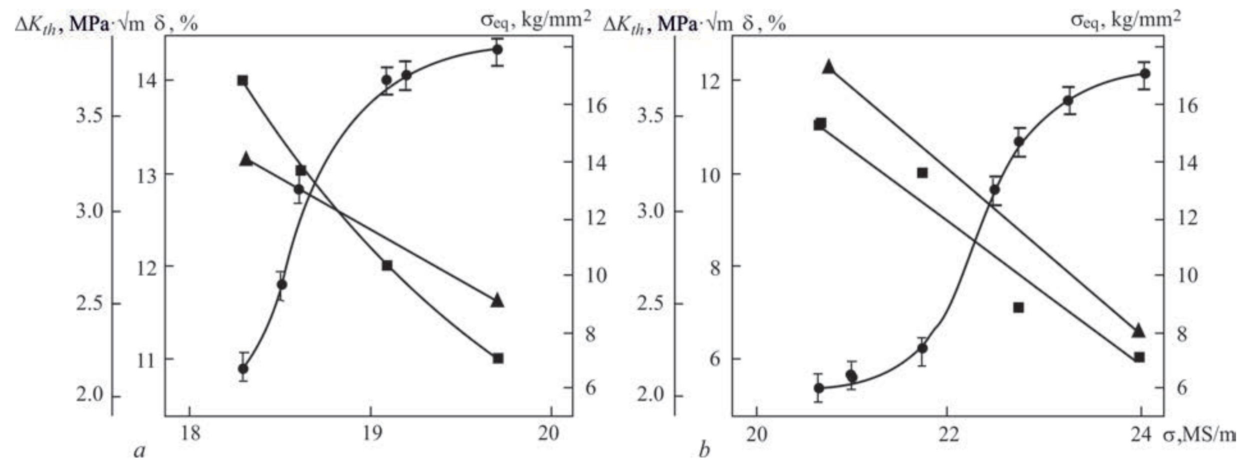

Figure 5. Dependencies between elongation δ (■), fatigue threshold ΔK_{th} (▲), level of operating equivalent stresses σ_{eq} (•) and SC (σ) of degraded D16ATNV (*a*) and B95T1 (*b*) alloys

increases. It was found that to a 1.5–2 times drop of fatigue threshold ΔK_{th} and fatigue strength N_f of the specimens of degraded alloys of type D16 and B95, a 20–30 % growth of SC σ (3–4 MSm/m with a measurement error of 2 %) corresponds [10].

The results of investigations on the specimens cut out from the skin zones with different operating equivalent stresses showed that based on SC values, the change in mechanical properties of the material, the degree of its degradation can be evaluated, comparing them with the data obtained by destruction methods (Figure 5). It is obvious that an increase in SC values indicates the degradation of the material in the local areas of the skin, which is manifested in depletion of ductility in the material (reduction of its elongation) and a drop of resistance to fatigue crack propagation (fatigue threshold).

The obtained results create a basis for monitoring the degradation of structural aluminium alloys during long-term operation [25–27]. It is important that realization of these approaches by means of eddy current structuroscopy allows carrying out measurement of SC of materials of aircraft structures without removal of lacquer coatings.

Monitoring of degradation of aluminium alloys during long-term operation of aircraft. The developed approaches were tested during the measurement of SC distribution in different zones of the upper (B95T1 alloy) and lower (D16ATNV alloy) wing skin of AN-12 aircraft, which has been in operation since 1966 [10, 11]. Measurements were carried out using the eddy current structurescope of type VEPR-31 (Figure 4). The distribution of SC values (σ) of the material of the upper and lower wing skin of AN-12 aircraft in the area between the 4 and 5 stringer along the wing from the root of the wing to its end by the numbers of ribs is shown in Figure 6. The values of σ_k (▲) on the end element of the wing are also indicated. The values of SC gradually drop from the wing root with an increase in the number of a rib, which is associated with a decrease in the level of equivalent stresses [9, 10]. It is seen that SC on the end element of the wing has the lowest value, which is easily explained by the absence of loads in this area required for degradation process. AA in this zone can be conditionally considered to be one that has not undergone degradation. This allows using the value of SC in the end zones in the cases when information about SC of the material in the state of delivery is absent, which is typical for aircrafts of a long-term operation. Therefore, the value σ_k on the end element of the wing is proposed to be used as a comparative value to determine the level of degradation of the material [27].

As a criterion of local degradation of the material, it is proposed to use three different parameters, which is confirmed by their distribution by the numbers of

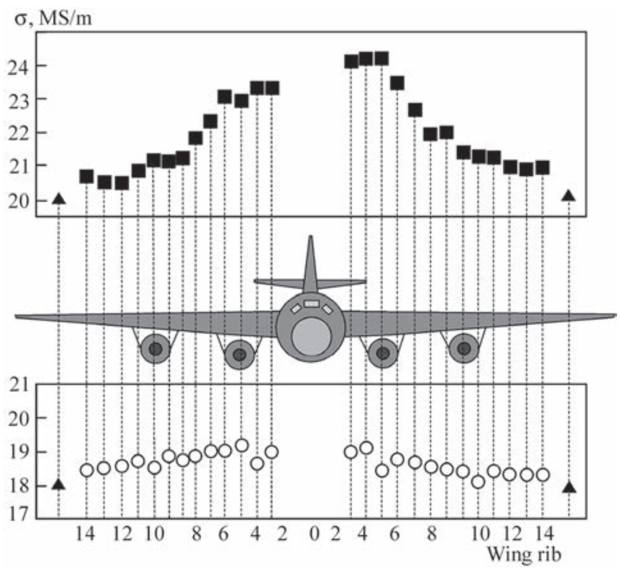

Figure 6. Distribution of SC (σ) of the upper (■) and lower (○) skin of the wing of AN-12 aircraft after many years of operation along the wing by the number of ribs (▲ is the value of SC σ_k on the end element of the wing)

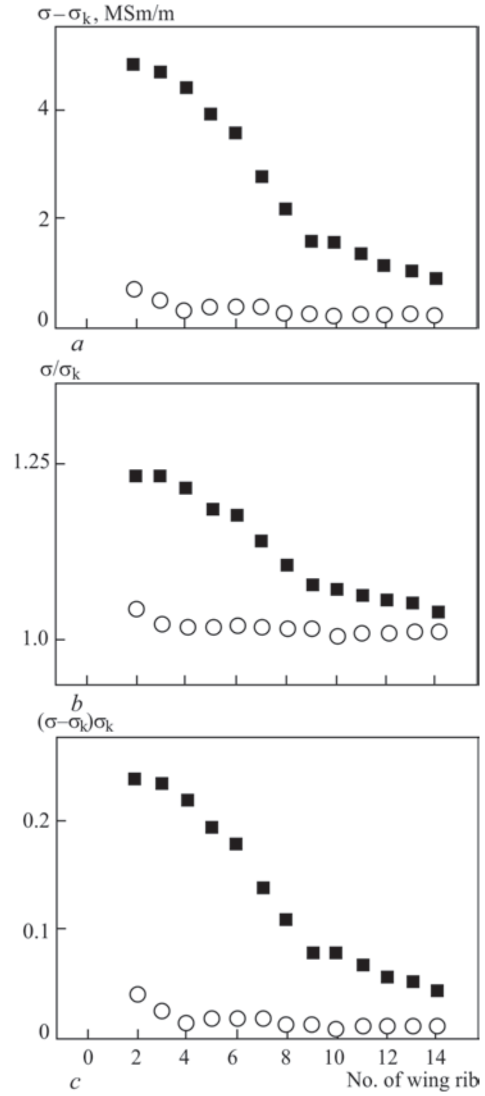

Figure 7. Distribution of parameters of local degradation of AA on the upper (■) and lower (○) skins of the wing depending on the number of a rib: *a* — for the parameter $\sigma-\sigma_k$; *b* — for the parameter σ/σ_k; *c* — for the parameter $\sigma-\sigma_k)/\sigma_k$

ribs in Figure 7 [27]. The difference $\sigma-\sigma_k$ between SC of the material in the tested zone and SC of the material of the end element of the wing, respectively, can be used (Figure 7, *a*). The value of this parameter for the nondegraded material corresponds to $\sigma-\sigma_k = 0$. Also the ratio σ/σ_k (Figure 7, *b*) can be used, which for nondegraded material will correspond to $\sigma/\sigma_k = 1$. The ratio $(\sigma-\sigma_k)/\sigma_k$ can also be used, which for nondegraded material will correspond to $(\sigma-\sigma_k)/\sigma_k = 0$ (Figure 7, *c*).

The proposed methodology was used to test the technical condition (including the degree of degradation of the material) of aluminium longerons of helicopter blades. Investigation of blades after different operation time (till 1100 h) in assembled and disassembled states was carried out at the JSC «Motor-Sich». SC measurements performed on «open» longerons revealed critical places of damage in the longerons, which correspond to the areas of the maximum operating load.

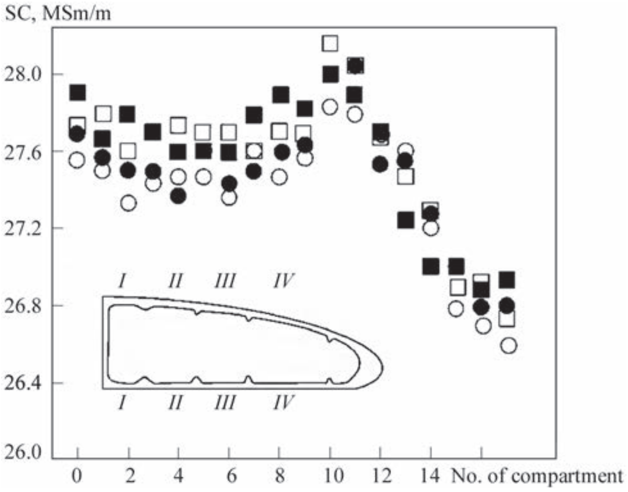

Figure 8. SC distribution on the upper (□ and ○) and lower (■ and ●) sides of the helicopter blade longeron in the zones I (□ and ■) and II (○ and ●)

Figure 8 shows, that SC has a maximum value near the root of the blade, and a minimum one at its end, similarly to the distribution of SC along the wing of the aircraft in Figure 6. In the zone of compartments Nos 10, 11 the area of growing SC is observed, which corresponds to the zone of maximum action of tensile, bending and torsional stresses. Thus, according to SC distribution, it is possible to find critical zones of a maximum damage of the helicopter blade longerons.

The presented methodology for evaluation of the level of local degradation of aircraft structures during long-term operation will increase the reliability of prediction of their residual life, and may also become an important component in realizing the concept of safe damage.

Conclusions

1. The problem of degradation of aluminium alloys during a long-term operation of aircraft is considered. The significance of correlation dependencies between the physical structure-sensitive parameters of the material (which can be determined by NDT methods), and mechanical characteristics of the material during cyclic loading are shown.

2. Peculiarities of monitoring aircraft alloy degradation based on contactless measurement of specific conductivity are analyzed. The eddy current structurescope for measuring specific conductivity is presented to test damage of materials of aircraft in the operation conditions.

3. It is shown that an increase in the values of specific conductivity indicates degradation of the material in the local areas of the structure, which is manifested in depletion of ductility of the material (reduction of its elongation) and drop in resistance to fatigue crack propagation (fatigue threshold).

4. The methodology of eddy current monitoring of degradation of aircraft aluminium alloys in the conditions of a long-term operation of aircraft structures is offered. The results of effective use of the developed methods and means for determination of critical zones in skins of aircraft and longerons of helicopter blades of aluminium alloys are given.

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Received 22.01.2021

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