Inspection of the Aluminium Alloys Degradation in Aging Aircraft Components Based on Eddy Current Method Application

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Abstract. The majority of modern aircraft maintenance concepts are based mainly on the fatigue defects and corrosion damages detection. But the mechanical parameters changes due to the structural material degradation of aging aircraft components are very significant and needed to be accounted for the residual life estimation and maintenance technologies development. In presented paper the different effects of aluminium alloys degradation mechanisms are analyzed shortly. The special procedure for simulation of aluminium alloy degradation in laboratory conditions identical to the real in-service degradation was developed. The changes of different mechanical parameters such as ultimate strength, elongation, hardness, micro hardness, nominal fatigue threshold, effective fatigue threshold, cyclic fracture toughness and relevant conductivity changes for degraded D16 alloy (Al-Cu-Mg system, analog of 2024 alloy) and B95 (Al-Zn-Mg-Cu system, analog of 7075 alloy) were investigated. The fine structures and microfractographs for B95 and Д16 alloys after simulated and operational degradation also were analyzed.
The new NDT methodology of the structure and mechanical degradation of D16 and B95 aluminium alloys inspection based on eddy current (EC) conductivity measurements is presented. Special experimental conductivity meter possible to be applied in real aircraft conditions with high spatial resolution and without the protected coating removal was developed for EC method implementation. Appropriate software based on special algorithms and local EC probe was implemented into the EDDYCON C type flaw detector for industrial application. Results of the trial application of the developed inspection methodology for ANTONOV aircrafts after long term exploitation show the fruitfulness of proposed approaches.

Introduction

To estimate the technical state and residual life of aging aircraft during long-term operation it is important to distinguish the categories of (1) degradation of aircraft components and (2) degradation of materials [1,2].
Degradation of aircraft components can be associated with the accumulation of corrosion and fatigue damages (e.g. general and intergranular corrosion, macrocracks), which are

detected by nondestructive inspection methods in aircraft maintenance technologies. Some of such defects are eliminated during repair. Others are taken into account when the stress-strain state of the aircraft component with defects is determined and residual life is estimated. At present this approach is mainly used to evaluate the durability of aging aircraft [3-5].

However, due the influence of factors connected with the production technologies and in-service conditions the material mechanical characteristics appropriated to its initial state can be changed because of the material microstructure transformation during long-term operation. Such changes in the phase state and microstructural damages of material (formation of vacancies, pores, clusters of dislocations and microcracks) reduce the functional (service) properties of materials. In today aircraft maintenance practice these degradation phenomena are not taken into account when the residual life of aircraft components is estimated [2]. However, it can be reliably estimated only on the basis of the characteristics of strength, durability and crack growth resistance of the material at the given moment of service life. Therefore, the correction coefficients based on the changes of these characteristics in comparison with the initial state (as-received state) of the material must be established. The number of investigations connected with this problem is insufficient [6,7].

The material degradation can be estimated by destructive and nondestructive methods. In the first approach samples cut out from long exploited aircraft components are used [1] to determine the true characteristics of D16 grade and B95 grade aluminum alloys (Al-Cu-Mg system, analog of 2024 alloys and Al-Zn-Mg-Cu system, analog of 7075 alloys, respectively), which are the main constructional materials for airframe (fuselage and wings). It was shown [1,4] that the most sensitive to these alloys degradation are the characteristics of plasticity (relative elongation δ) and fatigue crack growth resistance (nominal ΔK_{th} and effective ΔK_{theff} fatigue thresholds and cyclic fracture toughness ΔK_{fc}) (Fig. 1).

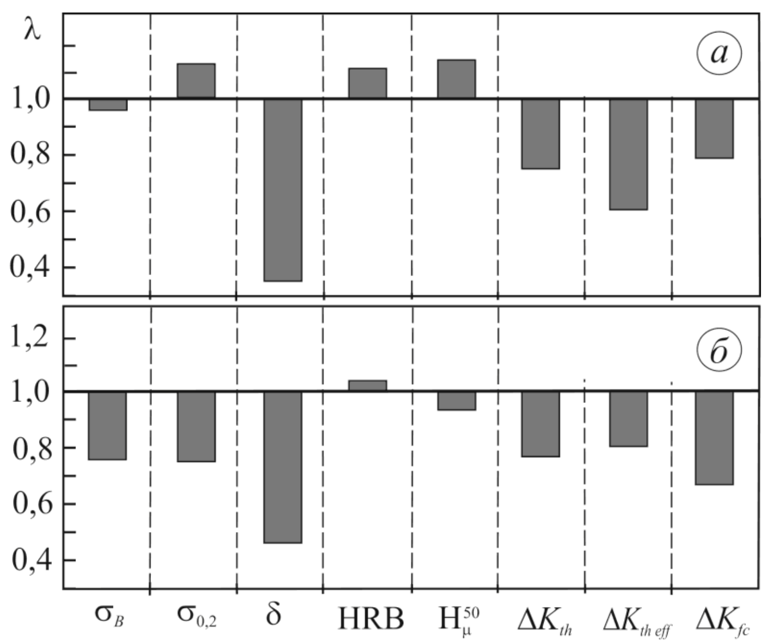

Fig. 1. The influence of simulated degradation on the mechanical characteristics of D16 (a) and B95 (b) aluminum alloys: λ - related characteristics of the material in its initial and degraded conditions.

The characteristics of fatigue crack growth resistance can be applied for estimation of the fatigue life N_f [1,2,8] and relevant reducing correction factor $\eta = N_f^{degr} / N_f^{init}$ (N_f^{degr} and

N_f^{init} are life time of notched specimens for degraded and as-received materials, respectively), which is needed for calculation of the residual life of the aircraft components taking into account the influence of the material degradation.

There is no way to apply presented above destructive approach during aircraft exploitation. Therefore, the estimation of their in-service material degradation can be carried out only by NDT methods. The degradation is determined by the structural and phase state and microstructural damages of materials. Therefore the NDT methods based on structure sensitive characteristics of material can be applied. For nonferrous materials (such as aluminum alloys) monitoring technologies can be developed on the base of material electrical conductivity measurement. It is known that electrical conductivity measured by eddy current (EC) method is sensitive to structural state and mechanical characteristic of aluminum alloys [2, 9]. But in practice EC method is applied for estimation of the heat treatment influence on aluminum alloys parameters mainly. There is known only one opportunity of the conductivity measurements application for aircraft maintenance when the weakened zones in aircraft components due to the heat damage caused by fire incident are detected [9,10]. The influence of microstructure transformation of aluminum alloys during long-term exploitation on both mechanical characteristic and conductivity is not investigated.

All aluminum alloy aircraft components can be represented as 3-layer structures: upper layer – nonconductive protective coating with up to 0.5 mm thickness; middle layer – pure aluminum plating with thickness about 0.5 mm; bottom layer – the greatest and specially heat treated for aluminum alloy hardening in which conductivity changes must be investigated. That is why the main demands to EC conductivity meter are:

- High lift-off suppression for in-service measurements through nonconductive protective coating with changed thickness.
- High eddy current penetration to ensure high enough sensitivity to conductivity changes in the 3-d layer.
- High locality for inspection of aircraft components with large number of rivets and holes.

This article present the results of experimental investigations of mechanical characteristics changes in combination with corresponding electric conductivity values of aluminum alloys degraded in in-service and laboratory conditions. The main purpose of such investigations is the development of new concept for aging aircraft monitoring and maintenance.

1. Investigated Materials, Specimens and Experimental Procedures

Aluminum alloys identified as D16ATHB (similar to 2024T3) and B95T1 (similar to 7075T6) used respectively for lower and upper wing skins of AN-12 type aircraft were investigated. The chemical compositions of investigated alloy are Cu-4.64 Mg-1.62 Mn-0.72 Si-0.48 Fe-0.46 for D16ATHB alloy and Cu-1.85 Mg-2.43 Zn - 6.35 Mn-0.41 Si- 0.49 Fe-0.48 for B95T1 alloy. Specimens were cut out from the aircraft 3-5 mm thick skins after 40 years of operation in various areas of the wing (Fig. 2a), in which different operating stresses occurred: in the area from the 2nd to the 14th ribs of the wing (marked in Fig. 2a as 2RW and 14RW, respectively) between the 4th and the 6th stringers (marked in Fig. 1a as 4St and 6St, respectively). Tensometric data show that the wing skins are working in a biaxial loading mode (Fig. 2a) with prevailing loading direction along the wings. The equivalent stresses σ_{eqv} are maximal near the root of the wing in 2RW area and gradually decrease 3.0 and 2.6 times towards 14RW area in the bottom and upper wing skins, respectively (Fig. 2b). Therefore specimens were cut in two directions (longitudinal and transverse) with regard to the sheet rolling direction L (see Fig. 2a): (LT) and (TL) specimens, respectively.

The characteristics of static strength (0.2% yield strength σ_Y and ultimate strength σ_U) and plasticity (elongation δ) were determined on specimens sized 20×3…5×140 mm. Materials fatigue crack growth resistance is determined using compact tension specimens (base size W = 64 mm, thickness t = 3-5 mm) based on fatigue crack growth rates diagrams (da/dN – ΔK) established at stress ratio R = 0.1 and frequency f = 10 Hz of loading cycle using testing machine "BISS" in load control mode. The environments involved were: laboratory air at 20°C and – 60 °C and 3.5% NaCl solution as a model corrosion environment. These thin specimens were loaded through specially tempered bushings pressed to either side of the specimen [11].

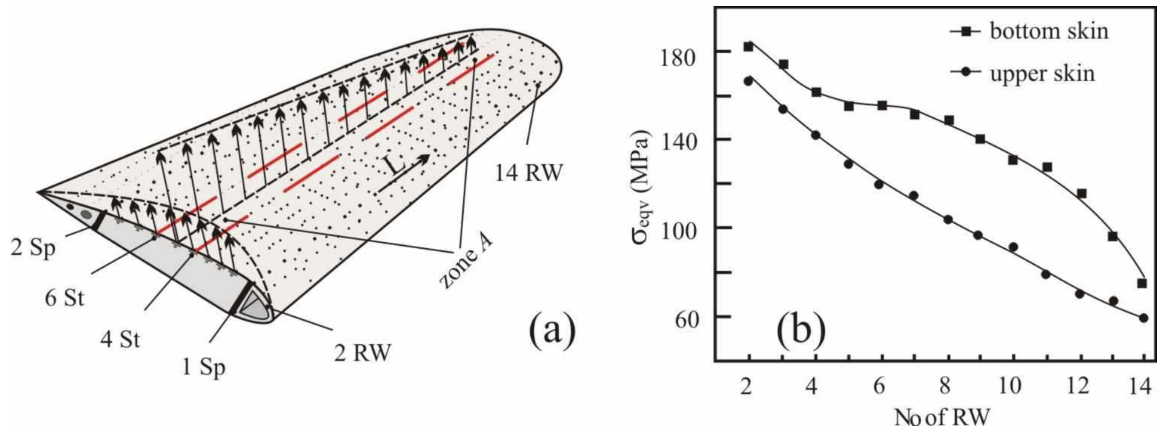

Fig. 2. Zone A of specimens cut out from aircraft wing skins (a) and (b) level of applied equivalent stresses in the bottom and upper skins: RW – rib of the wing; St – stringer; Sp – spar; L – sheet rolling direction.

As the characteristics of fatigue crack growth resistance the fatigue threshold $\Delta K_{th} = \Delta K_{10^{-10}}$ for low-amplitude region of (da/dN – ΔK) diagram and cyclic fracture toughness $\Delta K_{fc} = \Delta K_{10^{-5}}$ for high-amplitude region (herein ΔK - range for fatigue crack growth rate da/dN=10^{-10} and 10^{-5} m/cycle, respectively) were chosen.

The microstructure of alloys was investigated by a light microscope "Neophot-21" with 800 times magnification. The fine structure was observed by TEM "JEOL-200CX" with 30000 times magnification. Microfractographic analysis was performed by SEM "Zeis-EVO 40" with up to 1000 times magnification.

Electrical conductivity of aluminum alloys was measured by EC method by the specially developed experimental instrument both for investigations of conductivity changes of specimens in laboratory condition and during the evaluation of the real aircraft components in repair plant. More details about conductivity measurements will be presented in next section of this paper.

2. Results and Discussion

2.1 Mechanical Behavior, Microstructure and Fatigue Fracture Mechanisms

The mechanical characteristics of alloys after long-term service are dependent on the wing area, where different levels of equivalent stresses exist. There are known no data on the properties of investigated alloys in the as-received state. Therefore, the properties of degraded materials were evaluated by the change in 2RW area comparatively with the same parameter in 14RW area, where operational stresses have the smallest value and the material in this area is similar to the material in as-received state. It was determined that the alloys strength changed slightly (only 2 - 4%), but plasticity decreased noticeably (21 - 45%), especially for B95T1 alloy of Al-Zn-Mg-Cu system. This is reflected on the fatigue crack growth resistance value of these alloys and the diagrams (da/dN – ΔK) for both alloys are shifted to the left indicating the higher level of material degradation in 2RW area in comparison to the material properties in 14RW area. Furthermore, fatigue threshold ΔK_{th} decreases more intensive (22-39%) than cyclic fracture toughness ΔK_{fc} (6-20%), where higher values are for B95T1 alloy. Thus, this alloy is more inclined to in-service degradation in comparison with D16ATHB alloy. Besides, the degradation degree is influenced by the mechanical stress level during long-term exploitation. These results coincide with the data estimated for such aluminum alloys after model degradation [1,12].

Degradation of aluminum alloys is appeared also on their specific mechanical behavior under the operational factors influence. In particular, the influence of structural anisotropy due to sheet rolling, climatic low temperature and corrosion environment on the fatigue crack growth resistance of degraded alloys is cardinally different than for these alloys in as-received state. Long-term operation of the studied alloys leads to the appearance of the "inverse anisotropy", when the fatigue crack growth resistance for (L-T) specimens is lower than for (T-L) specimens. As a rule, for aluminum alloy in as-received state it is vice versa [13]. Low-temperature embrittlement of degraded B95T1 alloy is revealed contrary to D16ATHB alloy. It is known [14] that practically all aluminum alloys of Al-Cu-Mg and Al-Zn-Mg-Cu systems in as-received state have better fatigue crack growth resistance at low temperature (up to – 60°C) than at room temperature in the range from $\Delta K=\Delta K_{th}$ to $\Delta K=\Delta K_{fc}$. Specific sensitivity to corrosion environment is also shown: negative influence grows with ΔK-range increase. Such an effect for as-received aluminum alloy decreases when ΔK-range becomes large [15].

The microstructure investigated by the optical microscope for alloys with different level of mechanical property degradation is very similar. There are some differences in the fine structure studied in the foils by TEM microscope caused first of all by the prolonged exposure of mechanical factors. In specimens obtained from 2RW area some changes can be observed in comparison with low degraded alloy in 14RW area: the increase of the dislocation density in the matrix and the increase of dispersed intermetallic inclusions quantity and their microcracking. The exfoliation along the inclusion-matrix boundaries and cracking of large inclusions of the second phase also occur. These microstructural changes determine the susceptibility to brittle fracture of degraded alloys (plasticity δ and fatigue crack growth resistance ΔK_{th} , ΔK_{fc} are reduced), particularly for B95T1 alloy. The changes in the fine structure of this alloy and the resulting significant increase in the internal local stresses [11] lead to functionability reduction at the low temperature and in corrosive environment because the tough dimple mechanism of fatigue fracture is changed to trans- and intergranular cleavage.

2.2 Influence of Microstructure and Mechanical Characteristics on Electrical Conductivity

Microstructural and mechanical properties of aluminum alloys are correlated with their electrical conductivity. This creates the essential principle for operational aluminum alloy nondestructive inspection.

The influence of the chemical and phase composition and the heat treatment (annealing, quenching and aging, over aging, overheating, RRA - treatment etc.) on electrical conductivity of D16 (2024) and B95 (7075) aluminum alloys was shown in many publications [1,9,10,15-24]. Analysis of this data shows that for heat-treated aluminum alloy in as-received state the reduction of the strength σ_U and the increase of the plasticity δ is accompanied by the increase of the electrical conductivity χ in most cases (Fig. 3, dashed regions).

The data obtained for long-term exploited D16ATHB and B95T1 alloys and also for these alloys after artificially simulated degradation [25] show (Fig. 3, symbols) a radically different relationship: strength σ_U is changed slightly and at the same time plasticity δ is decreased significantly. Such change of material plasticity due to degradation is accompanied by the increasing of electrical conductivity χ and not by its reduction as for heat-treated not degraded alloys (dashed regions). Thus, the conjoint long-term influence of operating mechanical stresses and elevated temperature causes the special microstructure and determines the specific changes in physical and mechanical properties of degraded aluminum alloys. So, the creation of a new database on the correlation of physical and mechanical characteristics of these materials after long-term operation is required because a known database [2,10,17] collected for aluminum alloys in as-received state cannot be applied to monitor the operational degradation.

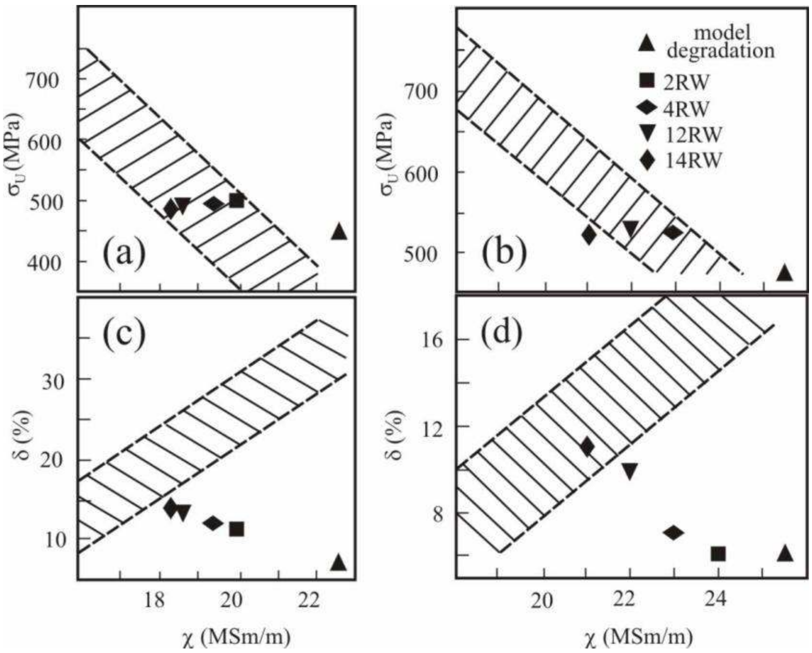

Fig. 3. Relationships between ultimate strength σ_U, elongation δ and conductivity χ of (a, c) D16 type and (b, d) B95 type aluminum alloys: dashed regions represent the literature data for alloys in as-received state; symbols are given for such alloys after long-term exploitation in areas from 2 RW to 14RW and after model degradation.

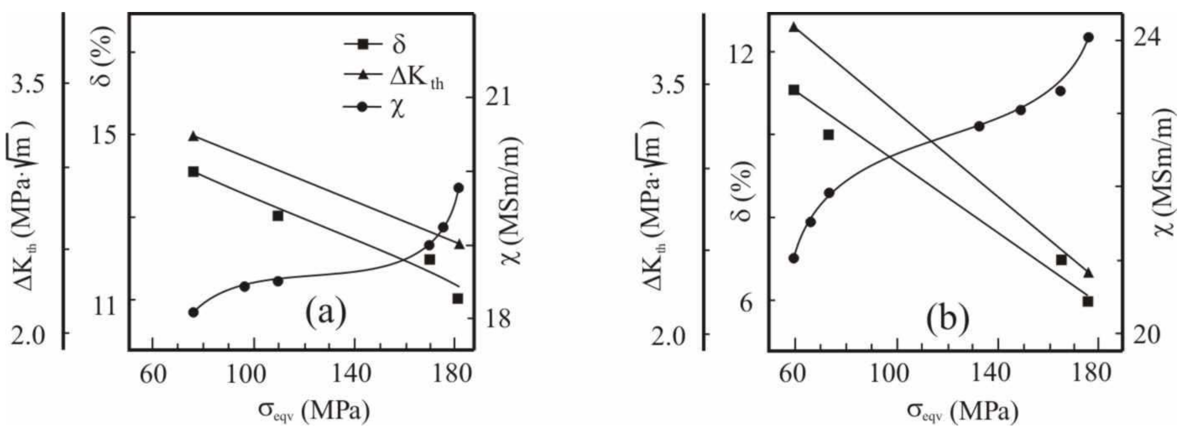

Fig. 4. Dependences of elongation δ, fatigue threshold ΔK_{th} and electrical conductivity χ of degraded (a) D16ATHB and (b) B95T1 alloys on equivalent stresses in various areas of the bottom and upper wing skins, respectively.

The results obtained (Fig. 4) show that such monitoring can be successfully implemented into maintenance practice, because the 1.5 - 2.0 time reduction of the fatigue threshold ΔK_{th} (as well as fatigue durability N_f [25,26]) corresponds to 20 - 30% conductivity χ growth. This degradation process depends on the level of operational stress σ_{eqv}. Thus, it is possible to determine the critical zones in aircraft wing during long-term exploitation by EC conductivity χ measurement.

3. Instrumentation for EC Measurements of Conductivity Changes in Aging Aircraft

High level of lift-off suppression (up to 0.5 mm) for local EC probe was achieved due to the new processing algorithm based on phase measurements of EC probe signal response [27]. In accordance with proposed method for every phase value $\varphi_{к}$ the point of summarized signal parameters reading are replaced into the point $O_{К}$ by summation to compensating signal U_0 the additional signal $\dot{U}_{к}$, the phase of which is equal to the phase of signal $\dot{U}_{н}$, and amplitude is determined by formula $U_{к} = U_{н} + \lambda(\Delta U)$, where $\lambda = (\varphi_{К} - \varphi_{Н})/(\varphi_{в} - \varphi_{Н})$ and $\Delta U = U_{в} - U_{н}$ (Fig. 5).

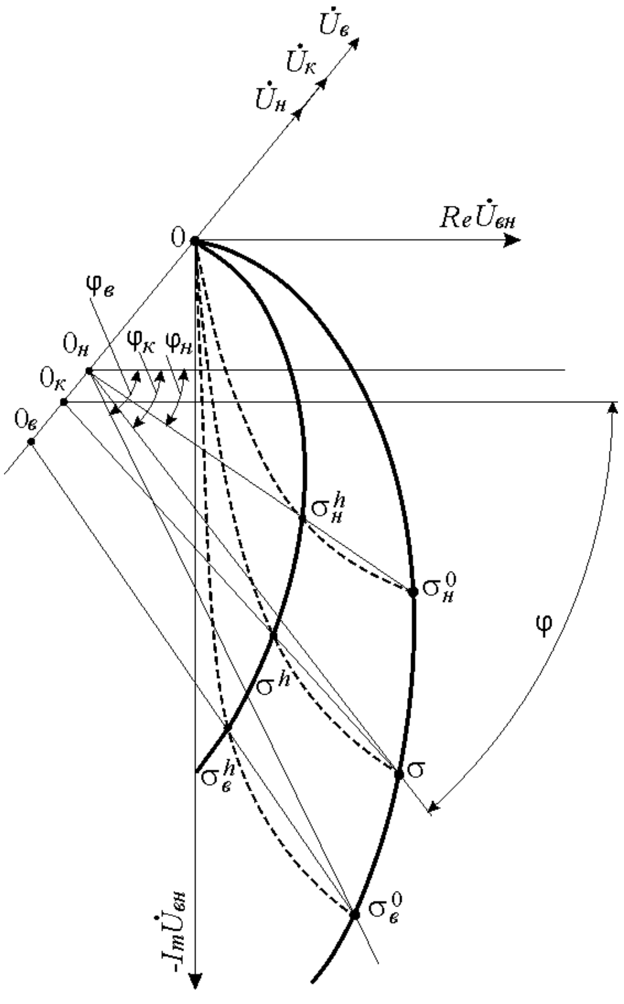

Fig. 5. Diagram of proposed EC algorithm for conductivity measurements with lift-off influence suppression.

The developed conductivity meter gives the possibility to measure conductivity of aluminum alloys components at operational frequency 60 kHz with high locality due to small size of EC probe application (only 1.2 mm in diameter) [28, 29] and high lift-off

influence suppression (Fig. 6). Conductivity meter was scaled by calibrated set of special reference standards with conductivity in the range from 14.0 to 37.1 MSm/m.
In addition, the appropriate software based on proposed algorithms was implemented into the EDDYCON C type flaw detector [30].

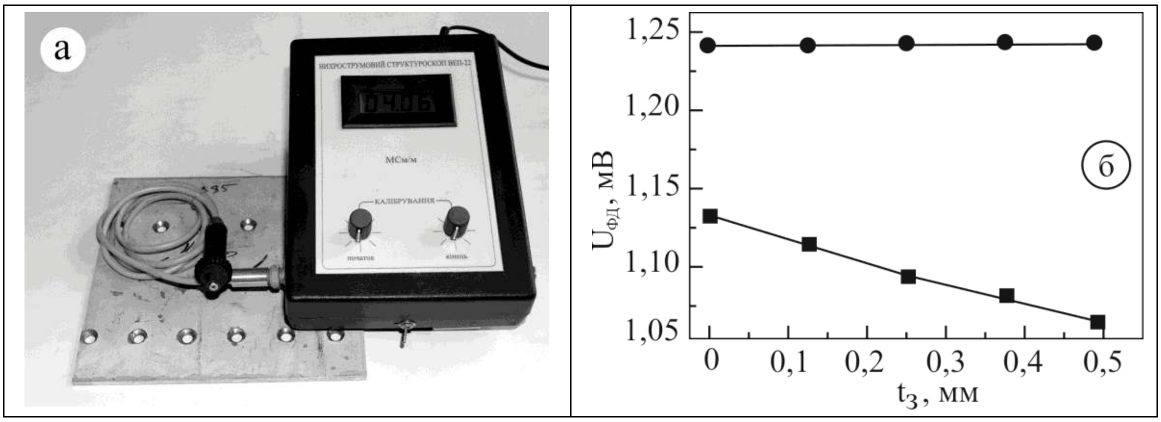

Fig. 6. Eddy current conductivity meter VEPR-22 (a) and the dependence of the output voltage on the lift-off distance t_z without lift-off suppression (■) and with suppression algorithm application (●) (b).

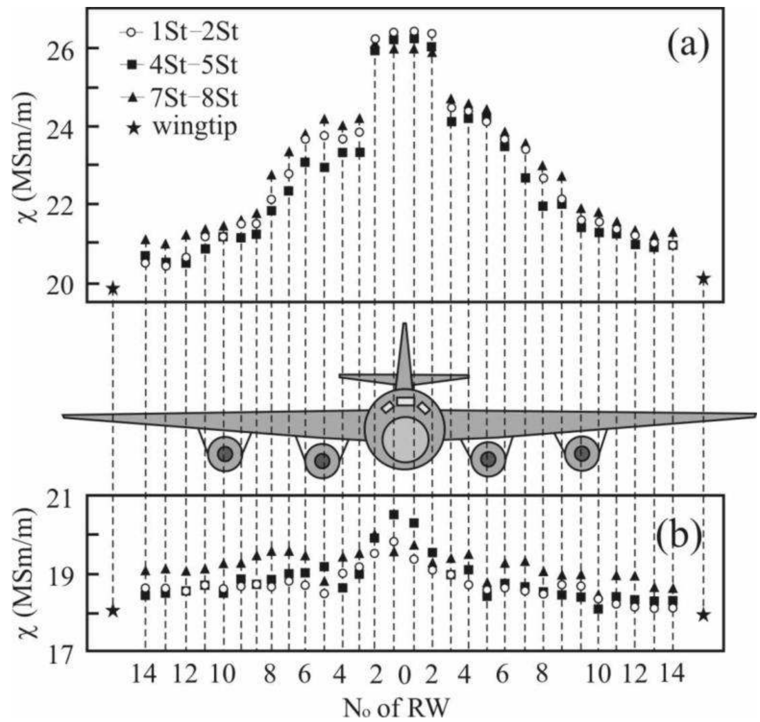

Fig. 7. The change of material conductivity in various areas of (a) upper (B95T1 alloy) and (b) bottom (D16ATHB alloy) wing and center section skins of AN-12 type aircraft after long-term exploitation.

5. Monitoring of Aging Aircraft Components Degradation

The EC electrical conductivity measurements (Fig. 7) carried out in real aircraft repair plant conditions in different wing skin areas of long-term exploited aircraft "ANTONOV-12B" (produced in 1966) show that the upper skin material degradation occurs more intensive in the zone between 9RW and 2 RW areas and in the center section area (Fig. 7a). The protective dielectric coatings on inspected aircraft components were not removed.

Therefore, the conductivity measurements were executed by placing EC probe directly on skin coating taking into consideration high lift-off suppression in the range of coating thicknesses (0.15-0.3 mm).

The bottom skin material degrades much less (Fig.7b) in-spite of the higher level of equivalent stresses (Fig.2b). This confirms mentioned above high sensitivity of B95T1 alloy to in-service degradation. The wingtip material has the smallest conductivity due to insignificant loading. So, aluminum alloy in this area can be assumed to be identical to the material in as-received state and conductivity in this area can be applied for comparative measurements during monitoring in accordance with proposed methodology [31].

6. Conclusions

Microstructure, mechanical characteristics and electrical conductivity of aluminum alloys after long-term exploitation have been studied to form the base for new nondestructive inspection technology development in aircraft industry.

The results obtained show that it is necessary to take into account the operational degradation of aluminum alloys for aging aircraft functionality and residual life estimation.

Known correlations between microstructure features, mechanical characteristics and electric conductivity for aluminum alloys in as-received state are different in comparison with these estimated for in-service degraded aluminum alloys.

Proposed methodology for monitoring of aluminum alloys degradation can be realized by EC measurements of electrical conductivity. Such inspection can be executed with high locality through dielectric protective coating due to high lift-off suppression.

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