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INFLUENCE OF THE THERMAL ACTION OF ARTIFICIALLY-INITIATED LIGHTNING CURRENT ON SPECIMENS OF THE METAL SKIN OF AN AIRCRAFT

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This paper presents the results of investigations of the thermal action on sheet specimens of the skin of an aircraft from aluminum alloy AMn with a wall thickness from 2 to 6 mm of the pulse A-component (with a normalized amplitude of 212 kA and an action integral of 2.07·10^6 A^2·sec) and of the long C-component (with a normalized amplitude of 846 A and duration of 1000 msec) of the electric current of the artificially-initiated lightning. It has been shown that the thermal stability of the above sheet specimens is determined by the long C-component of the lightning current causing in them active electrical erosion. The experiments performed and the calculations of the thermal state of the sheet specimens indicate that to provide a thermal lightning resistance of the skin and electromagnetic safety of flights of aircrafts under the conditions of direct action on them of lightning electric discharges, the wall thickness of their skin from aluminum alloy AMn or from another material with similar thermophysical characteristics should be no less than 4 mm.

Keywords: *aircraft, metal skin, direct lightning stroke, pulse and long components of the lightning current, electrical erosion of the skin, thermal stability of the skin.*

Introduction. An important characteristic of the sheet structural materials used for making a metal skin of aircrafts is their resistance to the thermal action in the terrestrial atmosphere of the current of powerful lightning electric discharges (lightnings). Worldwide experience in the operation of these aircrafts shows that because of its thermal action a direct lightning stroke to them may lead to the destruction and loss of sealing of their metal skin and accidents with catastrophic consequences [1–5]. Therefore, in accordance with the existing stringent requirements presented in normative documents of a number of leading aircraft manufacturing countries (e.g., USA, Russian Federation, Ukraine, etc.) [6–9], elements of the metal (composite) skin of the above aircrafts, especially those used in the region of their fuel tanks, are subjected to full-scale electromagnetic tests for thermal resistance to the action of the main current components of the lightning. According to [1, 6–8], the artificially-initiated lightning current used in testing the aircraft skin can include the following components with normalized amplitude-time parameters (ATP): a pulse component A (with an amplitude of 180–220 kA, an action integral J_{dA} = (1.6–2.4)·10^6 A^2·sec and duration t_0 up to 500 μsec), an intermediate component B (with an amplitude of 1.6–2.4 kA, a duration t_0 up to 5 msec, and an electric charge of 9–11 C), a long component C (with an amplitude of 0.2–0.8 kA, a duration t_0 = 250–1000 msec, and a transferred electric charge of 160–240 K), and a repeated pulse component D (with an amplitude of 90–110 kA, an action integral J_{dD} = (0.2–0.3) ·10^6 A^2·sec, and a duration t_0 up to 500 μsec).

These tests aimed at providing flight safety of the above aircrafts with simultaneous application of the pulse component A and the long component C of the lightning current are considered to be the most stringent since they: a) use the maximum values of the lightning current and the maximum levels of the heat flow from this powerful natural energy source due to them, and the largest values of the electrodynamic forces acting on the skin in the region of the zone of connection of the lightning channel; b) provide the largest values of the transferred (flowing) over the aircraft skin electric charge from the atmospheric lightning discharge. The results of [4–10] confirm the determining influence of the given charge on the degree of electro-erosion destruction of the wall of the metal or composite skin of the aircraft under the action of a lightning on it.

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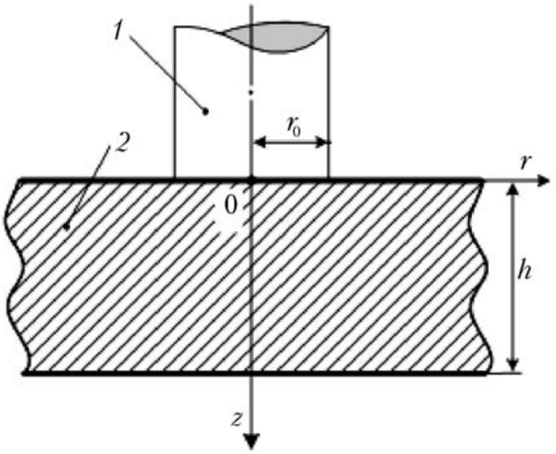

Fig. 1. Schematic view of the action of the current channel of the artificially-initiated lightning on the wall of the metal skin of the aircraft: 1) lightning current channel; 2) wall of the aircraft skin.

Up to now, to estimate experimentally the resistance of sheet metal materials of the skin of aircrafts to the thermal action of an artificially-initiated lightning, low-voltage power plants generating only direct current of strength from 200 to 800 A of its long *C*-component have been used. Such equipment simulates in a few tens or hundreds of milliseconds an electric arc over the tested flat specimens of the metal skin of aircrafts in a two-electrode cathode-specimen or anode-specimen system. This arc glows freely in the air and creates by its plasma channel a heat flow acting locally on the outside surface of the test metal specimens of the skin of aircrafts [10–12]. However, such a method of physical simulation of an electrothermal action of the lightning is based on a rough approximation of this electrophysical phenomenon taking no account of the geometric characteristics of the lightning channel and the ATPs of the heat flow density q_0 in the zone of connection of the lightning channel on the aircraft skin. It completely ignores the sequential dynamic action on the metal wall of the aircraft skin of a number of pulse current components of a real lightning with the above normalized parameters.

Therefore, as we see it, the most reliable experimental data on the thermal resistance of the metal skin of an aircraft to the artificially-initiated lightning current can be obtained by using the combined action on it of the pulse *A*-component (mainly at the initial stage) and the long *C*-component (at the final stage) of the lightning current simulating by a powerful high-voltage electrophysical equipment with normalized values of their ATPs. Up to now, these important investigations of the lightning-heat resistance of various sheet metal (composite) materials of the aircraft skin have not been carried out because of the lack of the electrophysical equipment required for these purposes. This equipment should simulate, according to [8–9], pulse components of the lightning current closest to the real current components and thermal shocks of lightning discharges. Owing to the development, with the participation of the authors, in 2007 at the Scientific-Research and Structural-Design Institute "Molniya" of the National Technical University "Kharkov Polytechnical Institute" (Ukraine) on its experimental-testing ground near Kharkov of a unique powerful electrophysical equipment [13, 14] for forming a lightning with the given ATPs in the required (in accordance with the international documents [6–9]) temporal order of flow of all its basic current components, such investigations became possible.

Experimental Results. Test elements of the aircraft skin under investigation represented sheet specimens of thickness h from 2 to 6 mm with dimensions in plan 0.5×0.5 m^2 made from aluminum alloy AMn. Figure 1 shows the scheme of action in the cylindrical coordinate system of the imitated lightning channel 1 of radius r_0 on a flat metal aircraft skin wall 2 of finite thickness h situated in the air. In the experiments performed, the pulse *A*-component and the long *C*-component of the artificially-initiated lightning current were generated by a discharge to the tested flat specimens of precharged high-voltage capacitive energy storages (CES) through the air gaps of two- and three electrode atmospheric-pressure dischargers. In tests, these specimens were brought into the discharge circuit of the above electric energy storages. Simultaneous (or separate) operation of the powerful CESs of the lightning generator for combined (or single) action on the test specimens of the skin of the considered current components of the lightning was

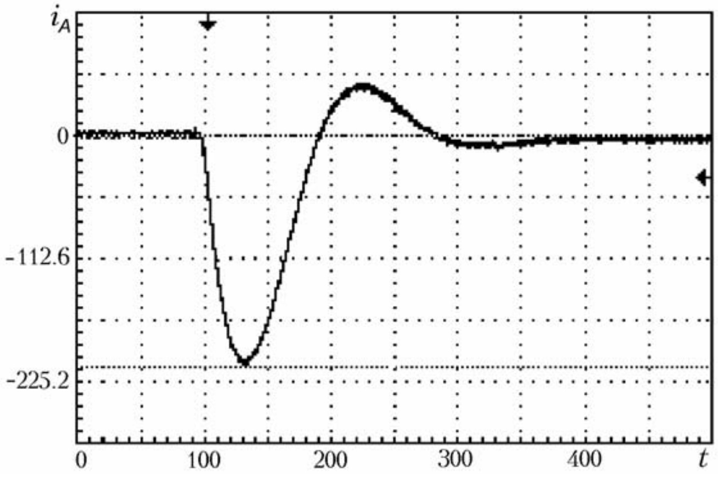

Fig. 2. Oscillogram of the pulse A-component of the artificially-initiated lightning current (I_{mA} = 212 kA, $J_{dA} = 2.07 \cdot 10^6$ A^2·sec, t_{mA} = 34 μsec, t_0 = 300 μsec, vertical scale, 56.3 kA/cell, horizontal scale 50 μsec/cell). i_A, kA; t, μsec.

provided by simultaneous (or time-shifted) supply to their high-voltage dischargers of control microsecond voltage pulses of amplitude up to 100 kV from one GVPI-100-type trigger generator [13, 15]. In experiments on the electrothermal action of the imitated current components of the lightning on flat aluminum specimens, we used the spark channel of electric discharge in the air oriented vertically with respect to the specimens. The given channel was created by an electric discharge to the specimens of the corresponding CESs and acted on the central zone of the sheet specimens-anodes. This discharge imitated the plasma current-conducting lightning channel over horizontally arranged test sheet specimens of the aircraft skin formed here as a result of the high-voltage electrical breakdown over them of an air gap of length 10 mm or electrical explosion (EE) over the test specimens of a thin bare copper wire of diameter 0.2 mm and length 50 mm. Note that conveying lightning current components that are negative with respect to the electric potential of the specimens-anodes provided resolution in the test specimens of the largest values of specific Joule energy losses and realization of the most severe thermal conditions for the aircraft skin under the action on it of a lightning discharge [7, 11]. Test specimens of the aircraft skin on the working table of the lightning current generator [13] were connected electrically to the break of the flat current-conducting buses of the discharge circuit of its powerful CESs. The rigidly fixed opposite edges of the test specimens of the aircraft skin provided practically uniform radial spread of the negative current components of the artificially-initiated lightning over the given specimens.

The powerful CES used in the first set of experiments to create the pulse A-component of the artificially-initiated lightning current i_A with the normalized ATPs given above was assembled from 112 parallel high-voltage low-inductance pulse capacitors of the type of IK-50-3 (capacity of 3 μF) as the classical electrical circuit of the pulse current generator (PCG) [16] for nominal voltage of ±50 kV (PCG-A) and had the following main characteristics: capacity of 336 μF, inductance of 2.05 μH, active resistance of 0.061 Ω, nominal electric energy stored in the CES of 420 kJ. Figure 2 shows an oscillogram of the pulse component A of the simulated lightning current of negative polarity with an amplitude $I_{mA} = 18.8 \cdot 11{,}261 = 212$ kA and a duration of no less than t_0 = 300 μsec (the charging negative voltage of the capacitors was 27 kV, the electric energy stored in the CES was 123 kJ, t_{mA} = 34 μsec). The oscillogram was obtained in the discharge circuit of the PCG-A generator. In this case, the action integral of current for the A-component had a normalized value of $J_{dA} = \int_0^{t_0} i_A^2 dt = 2.07 \cdot 10^6$ A^2·sec. Measurements of the ATPs of the pulse A-component of the simulated lightning current used in the first set of experiments were made with the aid of the digital storage oscilloscope of the type of *Tektronix* TDS 1012 developed at the Scientific-Research and Structural-Design Institute "Molniya" of the National Technical University "Kharkov Polytechnical Institute." This oscilloscope passed a state metrological attestation of an instrument coaxial shunt of the type of ShK-300 [13] having an active re-

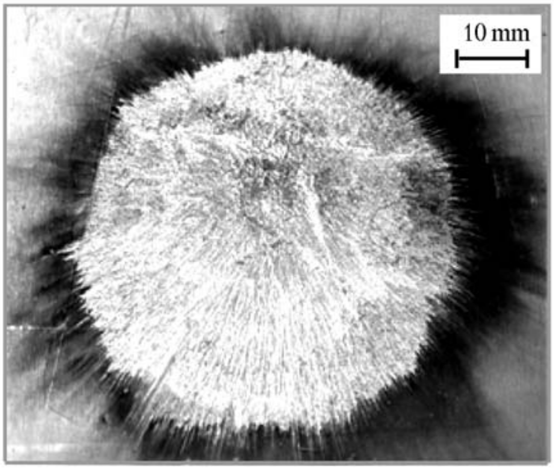

Fig. 3. General view of the damage zone of the sheet specimen-anode of the aircraft skin from aluminum alloy AMn of thickness $h = (2–6)\cdot 10^{-3}$ m under the action on it of the pulse A-component of the artificially-initiated lightning current (I_{mA} = 212 kA, $J_{dA} = 2.07\cdot 10^6$ $A^2\cdot$sec, t_{mA} = 34 μsec, t_0 = 300 μsec, over the specimen an electrical breakdown of an air gap of length 10 mm) by an imitated high-current lightning discharge was realized.

sistance of 0.185 mΩ and two matched outlets with transformation coefficients of 5642 A/V (outlet No. 1 for the current component C) and 11,261 A/V (outlet No. 2 for the current component A).

Figure 3 shows the general view of the typical zone of electrothermal damage of the outer layer of test specimens of the aircraft skin with a wall thickness $h = (2–6)\cdot 10^{-3}$ m subjected to the action of the pulse component A of the lightning current i_A with the above ATPs. Examination of the local destruction zone of the test specimens at the site of the thermal shock delivered by the given component of the artificially-initiated lightning has shown that in the case under consideration the largest depth of penetration at the center of the plate-shaped hollow formed in them is approximately $h_p = 0.15\cdot 10^{-3}$ m, and the radius of the penetrated hollow $r_{p.out}$ on the outside surface of the specimens is about $26\cdot 10^{-3}$ m. The experimental data obtained point to the fact that in the local zone of connection on the surface of the test specimens of a high-current channel of radius r_0 with the current component A of the lightning the temperature of the aluminum alloy AMn is much higher than its melting temperature T_{melt} = 658°C [17, 18]. This leads to an intensive superheating followed by EE (to the phenomenon of sublimation [19]) in the give zone of the thin surface metal layer of the wall of the test specimens of the aircraft skin [5].

In the second set of our experiments, the considered new sheet specimens of the aircraft skin were subjected to a separate pulsed action of the long C-component of the artificially-initiated lightning current with the above normalized ATPs. The powerful CES used to create the long C-component of the lightning current i_C was also realized as GIT-type current generators [16] on the basis of 324 parallel high-voltage low-inductance pulse capacitors of the type of IM2-5-140 (capacity of 140 μF) for nominal voltage of ±5 kV. This generator received the name GIT-C. It had the following main characteristics: capacity of 45.36 mF, inductance of 11.43 mH, active resistance of 4.74 Ω, nominal stored electric energy of 567 kJ. Figure 4 shows an oscillogram of the long C-component of the lightning current i_C of duration t_0 = 1000 msec of negative polarity with an amplitude $I_{mC} = 0.15\cdot 5642 = 846$ A (the charging negative voltage of capacitors is 4.1 kV, the electric energy stored in the CES is 381 kJ, τ_{pulse} = 160). In this case, the C-component of the lightning current had a normalized value of the transferred electric charge equal to about $q_C = \int_0^{t_0} i_C dt = 207$ C. In recording this component of the lightning current on a digital oscilloscope of the type of *Tektronix* TDS 1012, we used the above-mentioned instrument coaxial shunt of the type of ShK-300 with outlet No. 1 and a transformation coefficient equal to 5642 A/V.

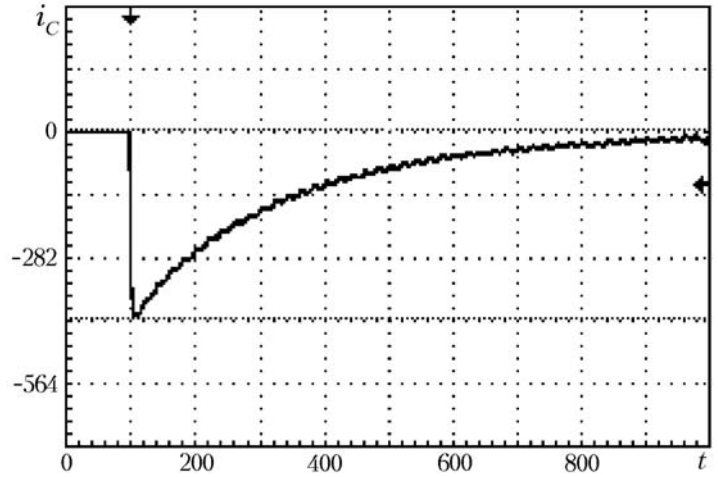

Fig. 4. Oscillogram of the long C-component of the artificially-initiated lightning current (t_{mC} = 11 msec, vertical scale, 282 A/cell, horizontal scale 100 msec/cell). i_A, A; t, msec.

Figure 5a shows the general view of the zone of through penetration of the investigated flat specimen of the skin of thickness $h = 2 \cdot 10^{-3}$ m formed as a result of the action on it of the long C-component of the simulated lightning current with the above ATPs. According to the measurements made, the radius of the penetration zone on the outside surface of the wall of this specimen is about $r_{\text{p.out}} = 3 \cdot 10^{-3}$ m, and on the inner surface it is about $r_{\text{p.int}} = 1 \cdot 10^{-3}$ m. Further experiments have shown that under the action of the GIT-C-imitated long component C of the lightning current i_C with analogous ATPs (I_{mC} = 846 A, τ_{pulse} = 160 msec, t_0 = 1000 msec, q_C = 207 C) on test specimens from aluminum alloy AMn of thickness $h = (4–6) \cdot 10^{-3}$ m, the conical hollow of their penetration with an almost round base on the outside surface of the specimens is characterized by an input radius of about $r_{\text{p.out}} = 2 \cdot 10^{-3}$ m and a depth of no more than $h_{\text{p}} = 4 \cdot 10^{-3}$ m (Fig. 5b, $h = 6 \cdot 10^{-3}$ m). Moreover, these experiments on determining the lightning-heat-resistance of the investigated sheet specimens of the aircraft skin have demonstrated that the initiation in the discharge circuits of high-voltage spark-channel generators GIT-A or GIT-C of current components A and C of the artificially-initiated lightning by means of thin copper conductors having the above-mentioned dimensions that are exploded electrically over the specimens has a weak influence on the change in the values of $r_{\text{p.out}}$, $r_{\text{p.int}}$, and h_{p}. Compared to the electrical breakdown over specimens of short air gaps (of length of the order of 10^{-2} m) in the two-electrode system metal cathode-specimen (anode), such initiation of a plasma channel over specimens only causes an insignificant decrease in the above values of $r_{\text{p.out}}$, $r_{\text{p.int}}$, and h_{p}. Initiating over sheet specimens an EE of thin copper wires whose explosion products form over the specimens a current-conducting plasma lightning channel leads mainly to additional multiside local burns of diameter no more than $2 \cdot 10^{-3}$ m of the outside surface of test specimens (Fig. 5c, $h = 6 \cdot 10^{-3}$ m). These point burns of the surface of specimens located around the connection zone of a discharge channel of radius r_0 were caused by the action on it of superheated fine-disperse parts of the electrically exploded (in the atmospheric) thin copper conductors (diameter $2 \cdot 10^{-4}$ m, length 0.05 m), whose temperature, according to [20, 21], can exceed the boiling temperature of copper $T_{\text{b}} = 2590^{\circ}$C [22] and attain values of the order of $10^{-4\circ}$C. Examination of the local zones affected by the artificially-initiated lightning of the investigated specimens of the aircraft skin upon simultaneous combined action on them, in accordance with the requirements [1, 6–8] of the leading (in time t) A-component and of the following C-component of the lightning current with the ATPs used in the previous experiments has shown that in these experiments (Fig. 6) the results of their simultaneous thermal action on the sheet specimens from aluminum alloy AMn with a wall thickness $h = (2–6) \cdot 10^{-3}$ m differ slightly from the cases of a single electrothermal action of these current components of the aircraft skin described above and presented in Figs. 3 and 5. Note that with such an order of tests of specimens, the A- and C-components of the simulated lightning current are formed as a result of the simultaneous discharge to the two-electrode system cathode–specimen (anode) of the powerful CESs of the GIT-A and GIT-C generators.

Comparison of the Experimental Results with the Thermal Calculations. Along with full-scale tests for choosing the sheet material and the thickness h of the metal wall of the skin of aircrafts with regard for the consequence of a direct lightning stroke to it, as well as for predicting the behavior of such aircrafts under the action on them of shock thermal loads from the main components of the lightning current, adequate computational thermal models are needed. For the investigated cases, we have developed two-dimensional models on the basis of the theory of heat conductivity of solids [23, 24] with the use of a number of assumptions substantiated by experimental data [25]. They describe approximately the nonstationary thermal processes in the flat metal elements of the aircraft skin subjected to the action of the above-mentioned pulse component A and long component C of the lightning current. These models are based on the fundamental analytical solution of the thermal problem, known from [23], for a thick (massive) metal conductor with a disc-shaped instantaneous surface point heat source of radius r_0 acting in the pulsed mode in the region of the connection zone of the current lightning channel with an averaged heat flow density $q_0(t)$ in time $0 \le t \le t_0$ on the flat outside surface of the wall of the considered aircraft skin. According to these models, in the cylindrical coordinate system for the spatial-temporal change in the temperature excess $\theta(r, z, t_0) = (\theta_t - \theta_0)$ of a homogeneous material with invariable thermophysical characteristics of investigated flat wall of the metal skin of an aircraft with a finite thickness h in the circular zone of action on it in the air in time t of a surface heat flow of density $q_0(t)$ from the plasma channel of the current lightning components, the following approximate analytical expression [23, 25] holds:

$$\theta\,(r, z, t_0) = \frac{1}{(\pi\lambda_0 c_0)^{1/2}} \int\limits_0^{t_0} r_0\,(\tau)\, q_0\,(\tau)\, F\,(r, z, t_0 - \tau)\, d\tau\,, \tag{1}$$

where r is a radial coordinate directed from the lightning channel axis along the skin wall; z is a longitudinal coordinate directed from the center of the site of the thermal action of the lightning current into the skin wall; $q_0(\tau)$ is the averaged density of the surface heat flow acting on the metal wall of the aircraft skin which is caused by the plasma cylindrical channel of the current components of the lightning electric spark discharge (lightning); $F(r, z, t_0 - \tau) = \exp\left[-\frac{z^2 c_0}{4\lambda_0(t_0-\tau)}\right](t_0-\tau)^{-1/2}\int\limits_0^{\infty} \exp\,[-\lambda_0(t_0-\tau)\nu^2 c_0^{-1}]J_0(\nu r)J_1(\nu r_0)d\nu$; $r_0(\tau)$ is the current value of the channel radius for the pulse component A or the long component C of the lightning current characterized by the flowing time t_0.

For the pulse $i_A(\tau)$ and long $i_C(\tau)$ components of the lightning current, the calculation expressions for $r_0(\tau)$ and $q_0(\tau)$ used in (1) have the form, respectively [11, 12, 25]

$$r_{0A}\,(\tau) = r_{0\mathrm{m}} i_A^{1/2}\,(\tau)\, I_{\mathrm{m}A}^{-1/2}\,, \tag{2}$$

$$r_{0C}\,(\tau) = 0.11 \cdot 10^{-3}\,(I_{\mathrm{m}C})^{1/2}\,, \tag{3}$$

$$q_{0A}\,(\tau) = i_A\,(\tau)\, U_0\, [\pi r_{0A}^2\,(\tau)]^{-1}\,, \tag{4}$$

$$q_{0C}\,(\tau) = i_C\,(\tau)\, U_0\, [\pi r_{0C}^2\,(\tau)]^{-1}\,, \tag{5}$$

where $r_{0\mathrm{m}} = 0.093(\rho_H \rho_0^{-1})^{-1/6}(I_{\mathrm{m}A})^{1/3}(I_{\mathrm{m}A})^{1/2}$ is the maximum value of the spark channel radius for the pulse component A of the lightning current defined by the Braginskii formula [26], m; ρ_H is the air density at the flight H altitude of the aircraft above sea level, kg/m^3; ρ_0 is the air density at sea level at an atmospheric pressure of $1.013 \cdot 10^5$ Pa and a temperature of 0°C equal to 1.293 kg/m^3 (in our case, $\rho_H \rho_0^{-1} = 1$) [22]; U_0 = 5–10 V is the near-electrode voltage drop in the connection zone of the artificially-initiated lightning channel on the metal skin of the aircraft depending weakly on the kind of its current component as well as on the two-electrode system used and the

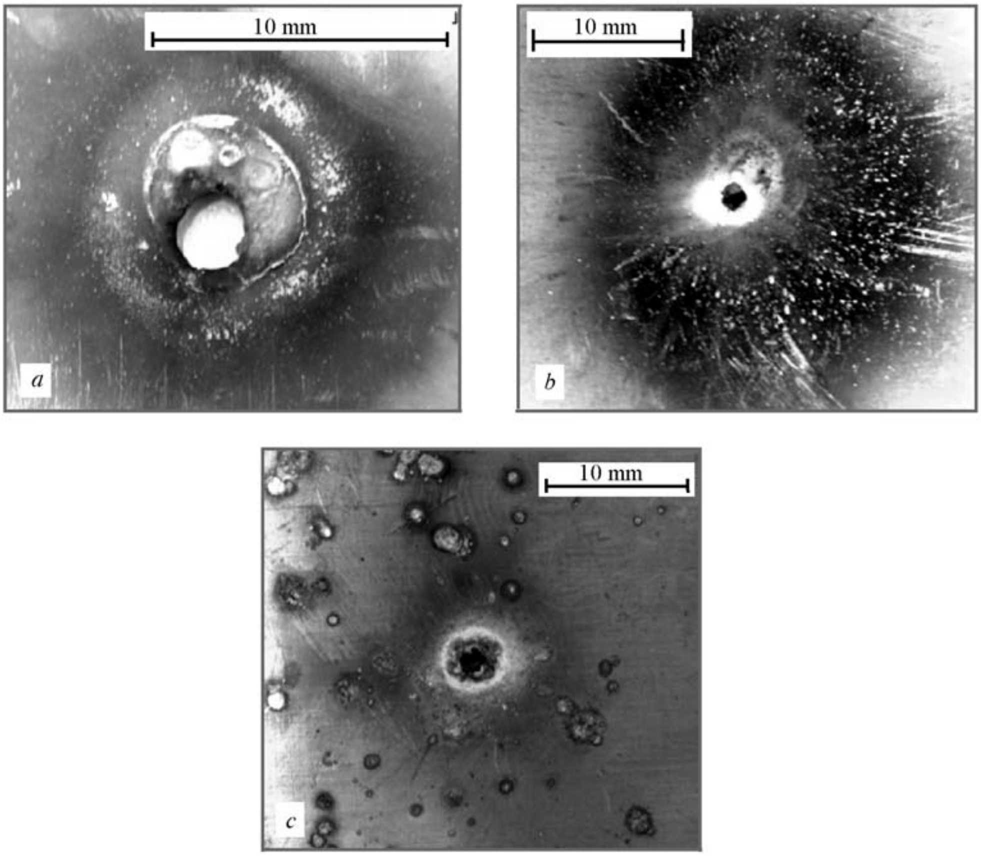

Fig. 5. General view of the penetration zone of the test sheet specimens-anodes of the aircraft skin of different thicknesses h from aluminum alloy AMn under the action on them of the long C-component of the artificially-initiated lightning current (t_{mC} = 11 msec): a) through penetration of the wall of thickness $2 \cdot 10^{-3}$ m; b) partial penetration of the wall of thickness $6 \cdot 10^{-3}$ m, over the specimen an electrical breakdown of an air gap of length 10 mm was realized; c) partial penetration of the wall of thickness $6 \cdot 10^{-3}$ m, over the specimen an electrical breakdown was produced by the EE of a copper wire of diameter 0.2 mm and length 0.05 m.

material of the electrodes in it (for the aluminum specimen in the system cathode–specimen (anode) it is about 8 V, and in the anode–specimen (cathode) system it is equal to about 10 V) [1, 11].

Note that in integrating numerically in (1) with a calculation accuracy of the order of 10^{-8} of the internal improper integral, we used the Simpson method, and in calculating the external definite integral with a similar accuracy, the Gauss–Legendre quadrature formula [27]. Our recommendations for practical use of the given mathematical apparatus as applied to numerical calculations in accordance with (1) of the two-dimensional temperature field in the metal wall of the aircraft sheeting created in it by the action of the considered current components of the artificially-initiated lightning are given in [25]. It should be noted that in the calculated estimate of the temperature excess $\theta(r, z, t_0)$ in the investigated specimens-anodes of the aircraft sheeting from aluminum alloy AMn due to the action of the pulse component A and the long component C of the lightning current the thermophysical characteristics λ_0 and c_0 of the material of the investigated specimens had the following constant numerical values [17–19]: $\lambda_0 = 180$ J/(m·sec·°C), $c_0 = 2.97 \cdot 10^6$ J/(m^3·°C).

As a result of the mathematical modeling on the basis of the calculation relations (1), (2), and (4), it has been established that the calculated depth of the largest penetration of the wall of the flat specimen-anode of the aircraft skin form aluminum alloy AMn of thickness $h = (2–6) \cdot 10^{-3}$ m due to the action of the decaying sinusoidal pulse A-

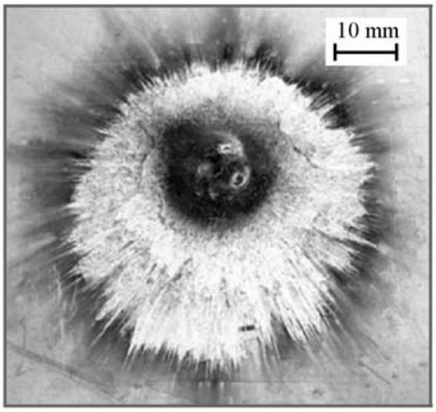

Fig. 6. External view of the damage zone of the sheet specimen-anode of the aircraft skin from aluminum alloy AMn of thickness $h = 4 \cdot 10^{-3}$ m under simultaneous action on it first of the pulse *A*-component ($I_{mA} = 212$ kA, $J_{dA} = 2.07 \cdot 10^6$ A^2·sec, $t_{mA} = 34$ μsec, $t_0 = 300$ μsec) and then immediately of the long *C*-component of the artificially-initiated lightning current ($I_{mC} = 846$ A, $t_{mC} = 11$ msec, $\tau_{\text{pulse}} = 160$ msec, $t_0 = 1000$ msec, $q_C = 207$ C) in the case of electrical breakdown by the imitated lightning discharge over the specimen of an air gap of length 10 mm.

component of the lightning current i_A with the normalized ATPs used in the experiment ($I_{mA} = 212$ kA, $J_{dA} = 2.07 \cdot 10^6$ A^2·sec; $t_{mA} = 34$ μsec; $t_0 = 300$ μsec; $r_{0m} = 32$ mm) at the epicenter of the thermal shock ($r = 0$) is about $h_p = 0.1 \cdot 10^{-3}$ m. It should be noted that in so doing, for convenience of calculations of the temperature excess $\theta(r, z, t_0)$ of Eq. (1), we preliminarily switched from the decaying sinusoidal pulse current i_A to a current equivalent in the value of the discharge of the electric charge in the channel to the aperiodic current pulse for the *A*-component of the lightning current. In the case under consideration, the latter had the following ATPs: $I_{mA} = 212$ kA, $J_{dA} = 2.25 \cdot 10^6$ A^2·sec; $t_{mA} = 26.3$ μsec; $\tau_{\text{pulse}} = 72.2$ μsec; $r_{0m} = 28.4$ mm. Such switching provided, in the first approximation equivalency, for the given temporal forms of the pulse current i_A to the thermal energy input into the test aluminum specimen [10]. The calculated radius of the plate-shaped hollow penetrated in this case by the current channel of the pulse *A*-component of the imitated lightning discharge on the outside surface of the specimen wall takes the maximum value equal to about $r_{\text{p.out}} = 28 \cdot 10^{-3}$ m. Because of the short-time thermal process ($t_0 = 300$ μsec), this value of $r_{\text{p.out}}$ turns out to be close to the value of the maximum radius $r_{0m} = 32$ mm of the current channel, as well as to the experimental radius of penetration of the surface layer of the wall (see Fig. 3, where $r_{\text{p.out}} = 26 \cdot 10^{-3}$ m and $h_p = 0.15 \cdot 10^{-3}$ m). The results of comparison between the above calculation data and the experimental data for penetration hollows in the wall of the aluminum skin of the aircraft (parameters r_{0m}, $r_{\text{p.out}}$, and h_p) point to the efficiency of the approximate thermal mathematical model used here in accordance with relations (1), (2), (4) and [25] for determining the thermal action on the metal wall of the aircraft skin of the normalized pulse *A*-component of the artificially-initiated lightning current.

The results of the mathematical modeling of the thermal action of the aperiodic long *C*-component of the artificially-initiated lightning current i_C with its normalized ATPs obtained in the experiments performed ($I_{mC} = 846$ A, $t_{mC} = 11$ msec, $\tau_{\text{pulse}} = 160$ msec, $t_0 = 1000$ msec, $q_C = 207$ C) on the investigated specimen-anode of the skin from aluminum alloy AMn ($h = 2 \cdot 10^{-3}$ m) with the use of expressions (1), (3), and (5) point to the fact that for this electrothermal case the calculated values of the radii of the through penetration in its wall are: $r_{\text{p.out}} = 2.6 \cdot 10^{-3}$ m and $r_{\text{p.int}} = 0.9 \cdot 10^{-3}$ m. It is seen that these calculation data are in good agreement with the above experimental data obtained by us in the course of the experiment on the lightning-heat-resistance of the investigated specimen of the aircraft skin to the action of the imitated normalized long *C*-component of the lightning current. The experiment was performed with the aid of a powerful GIT-C generator. In so doing, in accordance with the data of Fig. 5a the parameters of the experimental penetration of the above specimen for the radius were $r_{\text{p.out}} = 2.6 \cdot 10^{-3}$ m and $r_{\text{p.int}} = 1 \cdot 10^{-3}$ m. The estimation calculation of the consequences of the action of a powerful thermal shock on the investigated specimen-anode of the aircraft skin of thickness $h = 6 \cdot 10^{-3}$ m from the experimental artificially-initiated lightning at the final stage of the imitated lightning spark discharge with a flow of the normalized long *C*-component of the lightning current shows that in this case the depth of the conical penetration hollow in the wall of the specimen is about $h_{\text{p}} = 3{\cdot}10^{-3}$ m. This calculation result is in good agreement with our experimental results (see Fig. 5b and c), according to which the value of h_{p} for the above specimen of the aircraft skin reaches a numerical value of about $4{\cdot}10^{-3}$ m.

Conclusions. The experimental and theoretical investigations of the thermal resistance of sheet specimens of the aircraft from aluminum alloy AMn with a thickness of the flat wall $h = (2–6){\cdot}10^{-3}$ m and dimensions in plan 0.5×0.5 m^2 to the action on them in the atmospheric air of the dangerous (from the electromagnetic point of view) pulse component *A* and long component *C* of the artificially-initiated lightning current with normalized ATPs indicates that to provide lightning-heat-resistance of the metal skin of aviation objects under the conditions of powerful lightning electric discharges (lightnings) in the terrestrial atmosphere, the wall thickness of their skin from materials whose thermophysical characteristics λ_0 and c_0 are close to the corresponding characteristics for aluminum alloy AMn should be no less than $4{\cdot}10^{-3}$ m.

The experiments performed on the unique powerful electrophysical equipment simulating, in compliance with the international requirements in force, the main current components of lightning electric discharges (lightnings) and described in [13, 14] confirm the efficiency of the calculation two-dimensional thermal models used here for an approximate mathematical description of the nonstationary thermal processes in the metal wall of the aircraft skin under the direct action on it of the plasma channel of the two main components *A* and *C* of the artificially-initiated lightning current.

NOTATION

c_0, specific volume heat capacity of the material of the aircraft skin, J/(m^3·$^{\text{o}}$C); h, thickness of the wall of the aircraft skin, m; h_{p}, depth of the penetration hollow in the wall of the aircraft skin, m; H, flight altitude of the aircraft, m; i_A and i_C, electric current for the pulse *A*-component and the long *C*-component of the lightning current, respectively, A; $I_{\text{m}A}$, $I_{\text{m}C}$, amplitudes, respectively, for the pulse *A*-component and the long *C*-component of the lightning current, A; $J_{\text{d}A}$, $J_{\text{d}D}$, action integral of the current, respectively, for the pulse component *A* and the repeated pulse component *D* of the lightning current, A^2·sec; J_0, J_1, zeroth- and first-order Bessel functions of the first kind; q_0, heat flow density, W/m^2; $q_{0A}(\tau)$, $q_{0C}(\tau)$, heat flow density, respectively, for the pulse *A*-component and the long *C*-component of the lightning current, W/m^2; q_C, electric charge for the long *C*-component of the lightning current, C; r, radial coordinate in the wall of the aircraft skin, m; r_0, radius of the current channel for the air electric discharge, m; $r_{0\text{m}}$, maximum value of the channel radius for the pulse *A*-component of the lightning current, m; $r_{0A}(\tau)$, $r_{0C}(\tau)$, current value of the channel radius, respectively, for the pulse *A*-component and the long *C*-component of the lightning current, m; $r_{\text{p.out}}$, $r_{\text{p.int}}$, radius of the penetration hollow, respectively, on the outer and internal surfaces of the wall of the aircraft skin, m; t, current time, sec; t_0, duration of the main components of the lightning current, sec; $t_{\text{m}A}$, $t_{\text{m}C}$, time corresponding to the amplitude of the pulse *A*-component and the long *C*-component of the lightning current, sec; T_{melt}, T_{b}, melting and boiling temperature for the material of the aircraft skin, $^{\text{o}}$C; U_0, near-electrode electric voltage drop for the main components of the lightning current, V; z, longitudinal coordinate in the mass of the aircraft skin, m; λ_0, heat conductivity coefficient of the aircraft skin material, J/(m·sec·$^{\text{o}}$C); ν, auxiliary variable, m^{-1}; $\theta(r, z, t)$, temperature excess of the aircraft skin material, $^{\text{o}}$C; θ_t, current temperature of the aircraft skin material, $^{\text{o}}$C; θ_0, temperature of the air surrounding the aircraft skin taken in the work to be $\theta_0 = 0^{\text{o}}$C; ρ_H, ρ_0, air density, respectively, at the flight altitude of the aircraft and at sea level, kg/m^3; τ, auxiliary variable, sec; τ_{pulse}, duration of the aperiodic pulse of the lightning current at the level of a half of its amplitude, sec. Subscripts: p, penetration; d, direct; melt, melting; b, boiling; p.out, outside penetration; p.int, internal penetration; t, time; *H*, for altitude *H*; pulse, pulse.

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