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ALUMINUM ALLOYS IN AIRCRAFT IN THE PERIODS OF 1970 – 2000 AND 2001 – 2015

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INTRODUCTION

Aluminum alloys remain the principal structural material for aircraft parts serving at the turn of the two centuries. The volume of their use at present amounts to about 70% of the total volume of structural materials serving in airframes. Aluminum alloys serve in many types of rockets, seagoing craft and riverboats, automobiles, and carriages of high-speed trains. In order to provide a good weight efficiency in combination with long-term life and service reliability, aluminum alloys should possess a specific set of characteristics, namely, a high strength, a good corrosion resistance, a high resistance to repeated loads, and a low rate of fatigue-crack propagation.

Aluminum alloys and composite materials based on them have been considerably improved in the last 10 – 15 years. New generations of aircraft and rockets will be made of novel alloys and materials.

AIRCRAFT WINGS

In 1970 – 2000, the wings of passenger and transport planes were made of alloy V95pch (the top part) and alloys 1163 or 1161 (the bottom part). The construction departments of Tupolev and Il'yushin used preforms in the form of plates of alloys B95pch and 1163, and the Antonov construction department used pressed panels from alloys 1161 and V95pch. The lengthy discussions of the advantages and disadvantages of these two types of preforms did not affect the preference of each of the departments for the chosen type.

The top and bottom of fighter-plane wings were made of steel V95pch T2. The preforms were pressed panels, pressed waferboards, or plates. At present, alloy B95pch can be replaced by alloy V96ts-3. The latter exceeds alloy V95pch in its strength characteristics (Table 1) [1] and in its low-cycle fatigue preserving the high fracture toughness, corrosion resistance, and ductility.

This alloy was developed in Russia in 1970 and was widely used for the production of frames of solid-propellant rockets 1 m in diameter and 6 m high. The alloy is highly adaptable to manufacturing: rocket frames are fabricated in a vertical press in one pass. However, the designers of aircraft have not used the alloy because the top management of the Central Institute of Aerohydrodynamics and the former Ministry for the Aircraft Industry had a negative opinion on high-strength alloys.

It should be noted that in the last five years, Boeing has been producing wings of the Boeing 777 from plates of alloy 7055 supplied by Alcoa (Table 1); this alloy is an exact copy of alloy V96ts-3. Only the copper content of alloy 7055 produced by Alcoa differs (for patent considerations) from the composition of alloy V96ts-3. Incidentally, the composition of alloy V96ts-3 was long ago published in the journal *Metal Science and Heat Treatment*, translated in the USA. I have found a copy of this journal in the library of the Alcoa Corporation. Boeing 777 has been operating successfully with-

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TABLE 1. Properties of Alloys V96ts-3, V95och, and 7055

Alloy, state	σ_r, MPa	$\sigma_{0.2}$, MPa	$\sigma^c_{0.2}$, MPa	E, GPa	δ, %	K_{Ic}, MPa · m$^{1/2}$	σ_{cc}, MPa	LC, points
V96ts-3 T12	650	625	630	70.4	7	26.5	110	< 5
7055 T77 (plates, U.S.)	630	610	610	70.0 – 73.0	7	24	110	< 5
V95och T2	510	430	640	70.0	7	34	165	< 5

Notations: σ_{cc} is the corrosion-cracking stress; LC is the layer corrosion.

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TABLE 2. Properties of Sheets from Alloys 1163 and 2524

Alloy	h, mm	$\frac{h_{cl}}{h}$, %	σ_r, MPa		δ, %	E, GPa	K_c^f, MPa · $m^{1/2}$	GRFC, mm/kcycles	N_f, kcycles	σ_{cc}, MPa
			T	L	T	L, T	L – T	L, T	L	T – L
1163	0.5 – 1.9	4.5 – 6.0	405	–	13	66.6 – 71.0	–	–	–	–
	2.0 – 10.0	2.0 – 4.5	425	–	11		130	2.2	100	≥ 250 (90 days)
2524	1.6 – 8.0	2	420	420	15	67.0 – 71.0	130	3.0	100	≥ 250 (30 days)

Notations: h is the thickness of the preform; h_{cl} is the thickness of the cladding; L is the longitudinal direction; T is the transverse direction; K_c^f is the fracture toughness; GRFC is the growth rate of the fatigue crack at $\Delta K = 30$ MPa · $m^{1/2}$; N_f is the number of cycles before failure in tests of specimens with concentrator ($K_t = 2.6$) at $\sigma = 160$ MPa for low-cycle fatigue.

out any trouble. This gives us grounds to pass in the future from alloy V95pch T2 to alloy V96ts-3 in the production of the tops of wings of large aircraft and the tops and bottoms of fighter-plane wings.

However, though the production of pressed panels and preforms from this alloy for fighter planes does not cause much difficulty in metallurgical plants, the situation with plates (which are very important semiproducts) is different. In order to solve this problem, the Samara Metallurgical Plant (SMP) is determined to pass to the production of large-size flat ingots. The problem is quite solvable though complicated.

At the present time, the Verkhne-Saldinskoe Metallurgical Production Association (VSMPA, Verkhnyaya Salda) has stopped manufacturing ingots 680 mm in diameter from alloy V96ts-3. By an order of British Aerospace Airbus, the ingots have been used to produce rolled plates 15 and 30 mm thick and pressed panels 12 m long with tips. Their heat treatment is being optimized; the structure and properties are being studied together with the All-Russian Institute of Aircraft Materials. The alternative to alloy V96ts-3 is an aluminum-lithium alloy of the type 1464 suitable for the production of the tops and bottoms of some aircraft variants.

Thus, in 2001 – 2015, alloys V95, 1163, and 1161 will be replaced by the more promising V96ts-3 and 1464.

FUSELAGES

In 1970 – 2000, aircraft fuselages were produced in the form of riveted structures, i.e., sheet jackets from alloy 1163 analogous to American alloy 2524 (Table 2) or from alloy D19 for warming planes. The stringers were made of alloys 1163 and V95pch T2, and aluminum-lithium alloy 1420, depending on the type of the aircraft. Fuselages of YAK36 and YAK38 were completely made of alloy 1420, which provided a high gain in the weight. A still higher gain in the weight (24%) has been provided by the use of the aluminum-lithium alloy for the welded fuselage of the MIG 29.

The DaimlerChrysler Corporation in cooperation with the All-Russia Institute of Aircraft Materials (ARIAM), the Kamensk-Uralsky Metallurgical Plant (KUMP), and the Hugovens Metallurgical Plant (Germany), is testing alloy 1424 for fuselages of a large European passenger plane (novel modification of alloy 1420) [2] (Table 3) with the use of laser welding for attaching stringers. Ingots produced by KUMP are used in the Hugovens Plant for making fuselage sheets 4 mm thick and 2600 mm wide. The sheets are certified in Germany and by the ARIAM. The well-processable and long-life alloy 1441 is widely used for making fuselages by the Russian Beriev Company. This is the only aluminum-lithium alloy easily rolled into sheets with a thickness of up to 0.4 – 0.5 mm.

A variant of alloy AD37 (6013) in the Al – Mg – Si system (Table 3) is being tested in parallel with alloy 1424 by the DaimlerChrysler Corporation together with the All-Russia Institute of Aircraft Materials and the All-Russia Institute of Light Alloys. Alloys of this type have long been used by the Russian aircraft industry for helicopter blades. However, intercrystalline corrosion can develop in long-term operation of alloy 613 (AD37 type), which should be eliminated.

One more very promising variant for fuselage sheeting is a layered composite material consisting of alternating thin aluminum sheets and layers of glued prepreg with glass fibers, which is known as SIAL [3] (Table 3). A similar material used abroad is graded GLARE. SIAL possesses a high specific strength and rigidity and a satisfactory corrosion resistance. This material is quite adaptable to manufacturing and can be used for making fuselage sections of virtually any requisite size.

At the same time, fuselages can possibly be produced from wide thin panels welded together by the laser method. In this case, suitable grades are 1441 and AD37 (6013) (Table 3). It should be noted that the fracture toughness of alloy 1424 diminishes after 4000-h tests at 85°C, which simulate the action of solar heating for the entire service life of a plane. In addition, the rate of propagation of a fatigue crack in the alloy increases noticeably when it is placed into a corrosive ambient. The causes of this phenomenon are being studied, and researchers are searching for a suitable heat-treatment regime stabilizing the properties of alloy 1424.

The frames of the majority of aircraft types are produced from alloys B93 and 1933. In some rare cases, they are made

TABLE 3. Properties of Sheets from Aluminum Alloys and Composite Material SIAL (Sheathing)

Alloy	h, mm	ρ, g/cm^3	State	E, GPa	E_c, GPa	σ_r, MPa	$\sigma_{0.2}$, MPa	$\sigma^c_{0.2}$, MPa	δ, %	K^f_c, MPa · m$^{1/2}$	GRFC, mm/kcycles	σ_{cc}, MPa	DIC,* mm
1163AT	1.5	2.78	T	70	–	435 / 435	310 / 300	–	22 / 21	104 / –	1.6	– / 265 (30 days)	No
			T + 85°C 1000 h			435 / 440	315 / 310	–	22 / 21	103 / –	1.6	–	–
AD37 (6013)	1.6	2.71	T6	70	74	400 / 395	365 / 345	400 / 390	15.0 / 15.5	120 / 102	2.6	– / 350 (30 days)	120
			T6 + 85°C 1000 h			410 / 400	370 / 355	–	14.8 / 15.8	–	–	–	140
1424	4.8	2.52	TKh	77	–	475 / 480	350 / 310	–	6.8 / 11.8	91 / 93	2.0	– / 300 (30 days)	No
			TKh + 95°C 300 h			490 / 495	365 / 335	–	6.8 / 9.9	– / 93	–	–	No
SIAL-2	1.5 – 2.0	2.45	–	55	57	830 / 530	300 / 240	320 / 250	4.5 / 4.5	99 / 53	0.2	Non-susceptible	–
SIAL-3	1.5 – 2.0	2.50	–	55	–	630 / 600	280 / 260	280 / –	5.0 / 4.5	–	0.4	Non-susceptible	–

* Depth of intercrystalline corrosion.

Notes: 1. SIAL-2: 70 and 30% glass reinforcement in directions L and T, respectively; SIAL-3: 50% glass reinforcement in directions L and T. 2. K^f_c of SIAL-2 was determined at B = 140 mm; that of the aluminum alloys was determined at B = 400 mm.

of an old alloy, AK6, whose mechanical properties and corrosion resistance are worse than those of V93 and 1933 [4] (Table 4). Alloy 1933 has a high fracture toughness that exceeds that of American counterparts (7050 T74, 7175 T73) and of the new French alloy 7040 [4, 5] (Table 5). In cooperation with ARIAM, Aerospatiale, and Airbus Industry, the Samara Metallurgical Plant produced in 1998 a large-size, complex-geometry fitting connecting the wing with the center section. The fitting has been tested successfully and certified by ARIAM. At present, Aerospatiale is preparing to use fittings from alloy 1933 for commercial European plants A340 and A320 [6].

The active cooperation with Airbus Industry involves other native alloys, i.e., V96ts-3, 1468, and 1424, the suitability of which for European airbuses is reflected in Fig. 1.

Thus, in 2001 – 2015, aircraft wings will be produced from superhard aluminum alloy V96ts-3 and superlight Al – Si alloys, whereas the fuselage will be made of compo-

TABLE 4. Minimum Properties of Stampings from Aluminum Alloys 1933, V93pch, and AK6pch

Alloy, state	σ_r, MPa	$\sigma_{0.2}$, MPa	δ, %	K_{Ic}, MPa · m$^{1/2}$	σ_{cc}, MPa
1933 T2	490 / 460	440 / 430	7 / 3	39 / 24	– / 171
1933 T3	440 / 410	385 / 365	8 / 3	43.5 / 25	– / 245
V93pch T2	440 / 440	400 / 400	8 / 3	30.1 / 20.3	– / 196
V93pch T3	410 / 410	335 / 335	9 / 4	34.5 / 25	– / 295
AK6pch T1	380 / 345	275 / 245	10 / 5	35.9 / 25	– / 98

Note. The numerators give the properties in the longitudinal direction; the denominators give the properties in the transverse direction.

TABLE 5. Typical Properties of Massive Semiproducts (h = 150 mm) from High-Strength Alloys Used for the Production of Frame Parts

Alloy, state	σ_r, MPa	$\sigma_{0.2}$, MPa	δ, %	K_{Ic}, MPa · m$^{1/2}$
1933 T3	500 / 470	450 / 440	10 / 5	48 / 32
7040 TXX	–	450 / 440	–	33.5 / 26.0
7050 T74	500 / 470	450 / 440	8 / 5	30 / 25
7175 T73	450 / 350	370 / 350	7 / 5	40 / 28

Notes. 1. σ_r, $\sigma_{0.2}$, and δ were determined in the longitudinal direction (numerators) and in the altitudinal direction (denominators). 2. K_{Ic} was evaluated in the longitudinal-transverse direction (numerators) and in the altitudinal-longitudinal direction (denominators).

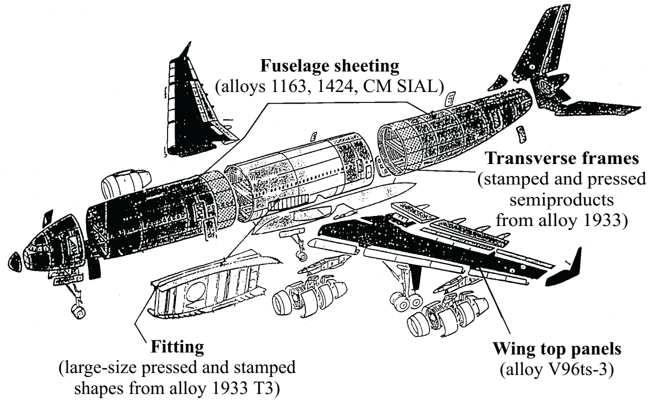

Fig. 1. European Airbus A3XX. Joint work of ARIAM, SMP, and Airbus Industry on alloys 1933, V96ts-3, and 1421.

site materials such as SIAL and welded thin pressed panels from Al – Li alloys.

TANKS OF LIQUID-PROPELLANT ROCKETS

Tanks of large rockets for liquid oxygen and liquid hydrogen are produced from alloys of the magnalium type (AMg6) and alloy 1201 in the Al – Cu – Mg system. However, in recent years, the world's cosmonautics and astronautics have passed radically to aluminum-lithium alloys. By 1998, 91 tanks for the Space Shuttle system 8 m in diameter and 40 m high were produced from alloy 2219 (1201) (Fig. 2) and 29 tanks were produced additionally from aluminum-lithium alloys. In 1998, the Energiya Company, guided by ARIAM, produced several tanks for liquid oxygen 4.5 m in diameter for the McDonald Douglas Corporation (U.S.) from aluminum-lithium alloy of type 1460. These tanks have successfully passed ground tests at room temperature and the temperature of liquid nitrogen and flight tests in the USA. The use of aluminum-lithium alloy 1460 decreased the weight of the tank by 37% (7500 kilopounds) [7]. Still better results were obtained for alloy 1464. Comparison of the properties of alloys AMg6, 1201, and 1464 (Table 6) shows the obvious advantages of alloy 1464.

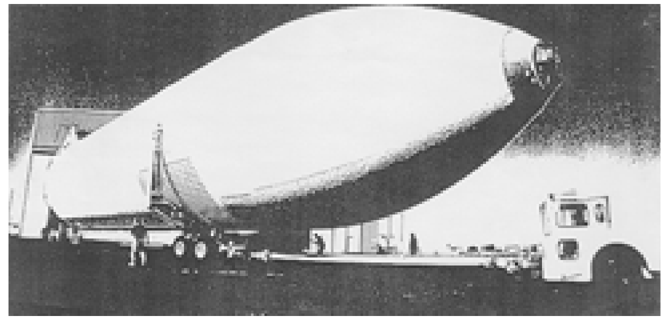

Fig. 2. Shuttle fuel tanks.

The future of materials for tanks of large rockets belongs to aluminum-lithium alloys.

A NEW TECHNOLOGY: SUPERPLASTIC SHAPING

The advanced process of superplastic shaping (SPS) makes it possible to produce parts with high degrees of drawing from aluminum sheets under a low gas pressure in one operation, which is impossible for traditional multipass forging. This resource-saving process opens up new approaches to the design and fabrication of parts with a complex shape with a decreased number of joints.

However, in order to realize SPS, the composition of the alloy and its production technology should provide sheets with ultrafine grains (less than 10 μm) and high parameters

TABLE 6. Properties of Aluminum Alloys for Rocket Cryogenic Tanks

Alloy, state	t_{test}, °C	Direction of cutting	σ_r, MPa	$\sigma_{0.2}$, MPa	δ, %	K_c^f, MPa · m$^{1/2}$
AMg6 (M)	20	T	320	160	15	–
	– 196	L, T	470	180	24	–
AMg6 (cold-hardened with ε = 20%)	20	T	400	300	9.0	–
1201	20	L	420	325	6.0	–
		T	420	325	6.0	40
	– 196	L, T	530	450	12	–
1464	20	L	5.0	535	9.5	65
		T	530	495	10.0	–
		45°	500	460	13.5	–
	– 196	L, T	615	525	17.5	–

Note. The values of δ at – 196°C were determined only in the longitudinal (L) direction.

TABLE 7. Typical Characteristics of Aluminum Alloys for Superplastic Shaping

Alloy	σ_r, MPa	$\sigma_{0.2}$, MPa	E, GPa	δ, %	ρ, g/cm^3	Parameters of superplasticity				
						δ_{al}, %	σ, MPa	m	$\dot{\varepsilon}$, sec^{-1}	t, °C
Type V95och	500 – 580	450 – 450	72	10 – 12	2.8	400 – 1000	5.0 – 8.0	0.35 – 0.45	$10^{-4} – 10^{-3}$	480 – 500
Type 1570	380 – 420	280 – 300	71	15 – 20	2.64	400 – 1000	4.0 – 6.0	0.35 – 0.50	$10^{-2} – 10^{-3}$	400 – 480

of superplasticity, i.e., a low yield stress σ, a high elongation δ_{al}, and a coefficient of speed sensitivity $m > 0.3$.

At present, ARIAM possesses alloys (with special additions of transition metals) for various purposes, namely, high-strength alloys of type V95 and not heat-treated alloys of type 1570 (Table 7). They have been tested and recommended for production of aircraft sheet parts with 100 – 200% deformation, front wing edges, internal partitions, door walls, and seats, and for multilayer parts obtained by combining SPS with diffusion annealing.

CONCLUSIONS

Russian aluminum alloys and semiproducts are not inferior to similar foreign materials in the level of their properties and can be used successfully in various structures. However, we should work further on improving the quality of semiproducts with respect to metallurgical defects, tolerances, and range of products, as well as service life, reliability, and weight efficiency for the purposes of aircraft and spacecraft engineering and conveyance.

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