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Influence of Heat Treatment Modes on the Structure and Properties of Large-Sized Products of Advanced Aviation Equipment Made of Alloys of the Al-Zn-Mg-Cu System

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Abstract

Introduction. High-strength aluminum-based alloys of the Al-Zn-Mg-Cu alloying system are commonly used in aircraft manufacturing. However, there is a need to address the issue of achieving the desired level of mechanical properties in large-scale parts made from these alloys during heat treatment. Additionally, studies on the evaluation of corrosion resistance during heat treatment are also essential. The aim of this work was to determine the modes of heat treatment to achieve the necessary values of mechanical properties and resistance to corrosion cracking of parts made of large-sized deformed blanks of alloys of the Al-Zn-Mg-Cu alloying system.

Materials and Methods. The research was conducted on parts made from forged 1933 alloy forgings and B93pch stamped blanks. The influence of heat treatment on the mechanical properties (strength, ductility, hardness) and microstructure, as well as electrical conductivity, was determined. Tensile tests were carried out both on samples subjected to heat treatment after cutting from forgings and stamped blanks, and on samples cut from massive templets that were heat treated together with the products. Electrical conductivity allowed us to assess the level of solid solution supersaturation and predict resistance to corrosion cracking.

Results. The results of the study showed the necessity of a differentiated approach to assigning the duration of aging stages, depending on the alloy grade, configuration, and dimensions of the products, as well as the requirements for the level of properties. Variants and modes of heat treatment were proposed for products made from alloys 1933 and B93pch, providing the necessary level of mechanical properties and resistance to corrosion cracking.

Discussion and Conclusion. Cases of inconsistency in strength properties in the longitudinal and transverse (in width) directions of the fiber of parts made from large-sized blanks of alloys 1933 and B93pch have been established. Modes and options for heat treatment of parts were proposed, allowing the achievement of the required values of mechanical properties and corrosion resistance. This provides for a halving of the aging time for alloy 1933 or an increase of 25% for alloy B95pch.

Keywords: aluminum alloys, large-sized products, heat treatment, structure, properties

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Оригинальное эмпирическое исследование

Влияние режимов термической обработки на структуру и свойства крупногабаритных изделий перспективной авиационной техники из сплавов системы Al-Zn-Mg-Cu

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Аннотация

Введение. Высокопрочные сплавы на алюминиевой основе системы легирования Al-Zn-Mg-Cu широко используются для изготовления деталей авиационной техники. Требует решения проблема достижения необходимого уровня механических свойств крупногабаритных деталей из сплавов этой системы легирования при термической обработке. Актуальны также исследования по оценке особенностей формирования коррозионных свойств в процессе реализации операций термической обработки. Цель данной работы — определить режимы термической обработки для достижения необходимых значений механических свойств и стойкости к коррозионному растрескиванию деталей из крупногабаритных деформированных заготовок сплавов системы легирования Al-Zn-Mg-Cu.

Материалы и методы. Исследования выполнены на деталях, изготавливаемых из поковок сплава 1933 и штампованных заготовок сплава В93пч. Определялось влияние режимов термической обработки на комплекс механических свойств (характеристики прочности, пластичности, твердости), микроструктуру и электропроводность сплавов. Испытания на растяжение реализовывались как на образцах, подвергнутых термической обработке после вырезки из поковок и штампованных заготовок, так и на образцах, вырезанных из массивных темплетов, которые подвергались термической обработке вместе с изделиями. Электропроводность позволяла оценивать степень пересыщенности твердого раствора и прогнозировать сопротивляемость сплава коррозионному растрескиванию.

Результаты исследования. Показана необходимость дифференцированного подхода к назначению длительности ступеней старения в зависимости от марки сплава, конфигурации и габаритов изделий, требований к уровню свойств. Предложены варианты и режимы термической обработки для изделий из сплавов 1933 и В93пч, обеспечивающие необходимый уровень механических свойств и сопротивляемости коррозионному растрескиванию.

Обсуждение и заключение. Установлены случаи несоответствия прочностных свойств в продольном и поперечном (по ширине) направлениях волокна деталей, изготавливаемых из крупногабаритных заготовок сплавов 1933 и В93пч. Предложены режимы и варианты термической обработки деталей, позволяющие достигать требуемых значений механических свойств и коррозионной стойкости, которые предусматривают сокращение в два раза (для сплава 1933) или увеличение на 25 % (для сплава В95пч) времени выдержки при ступенях старения.

Ключевые слова: алюминиевые сплавы, крупногабаритные изделия, термическая обработка, структура, свойства

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Для цитирования. Муратов В.С., Якимов Н.С. Влияние режимов термической обработки на структуру и свойства крупногабаритных изделий перспективной авиационной техники из сплавов системы Al-Zn-Mg-Cu. *Безопасность техногенных и природных систем.* 2024;8(3):78–87. https://doi.org/10.23947/2541-9129-2024-8-3-78-87

Introduction. In the production of modern and promising aircrafts and helicopters of new generation, first and foremost, attention should be paid to the reliability and safety of flights and transportation [1], as well as the reduction in product weight [2]. This requires the use of high-strength alloys [3] with good fatigue resistance [4], fracture toughness [5], and corrosion resistance [6]. In recent years, high-strength aluminum alloys, in particular alloys 1933 and B93pch, have been widely used for the production of new promising civil aircrafts such as SSJ-NEW, MS-21, Tu-214, Il-96, etc. They are designed for the manufacture of critical power components of the aircraft — frames, traverse, fittings, rods, frames, housings, spars [7]. Aluminum high-strength alloys [8] of Al-Zn-Mg-Cu alloying system [9] are one of the main structural materials [10] for the manufacture of aviation equipment [11]. This group includes alloys of grades B93 [12], B93pch [13], B95 [14], B95och [15], B95pch [16], 1933. Alloy 1933 is a modification of alloy B93, not differing from B93 in terms of content of the main components. Alloy 1933 contains 0.12% Zr instead of Fe as an additive. Such a change in composition provides higher strength, fracture toughness and fatigue resistance, but alloy 1933 has a lower hardenability than alloy B93 [17].

One of the challenges in ensuring the successful operation of products made from alloys based on the Al-Zn-Mg-Cu system is ensuring sufficient corrosion resistance. Analysis of the corrosion damage processes in aluminum alloys has shown that the development of structural deterioration under the main corrosion mechanisms — corrosion cracking (CC) and intergranular damage — occurs in a similar manner. It should be noted that CC is mainly inherent in dispersion-hardened aluminum-based alloys. CC is not typical for alloys characterized by a reduced supersaturation of solid solution. The sensitivity to CC of alloys [15] of a certain alloying system depends on the number of alloying elements [17].

Susceptibility of aluminum alloys to CC reliably correlates with the degree of supersaturation of solid solutions and is significantly less dependent on the electron concentration and inhomogeneity of electrochemical potential that occurs during the decomposition of supersaturated solid solutions. The process of delayed destruction, occurring in mildly aggressive environments (for example, in air having a relative humidity of about 50%), develops at sufficiently high values of atomic concentration of elements used for alloying. Aluminum alloys of the Al-Zn-Mg-Cu alloying system have a 10 CC score, which means corrosion damage in mildly aggressive environments on uncut samples. At the same time, the main way to increase resistance to dangerous types of corrosion is the development and implementation of stepwise modes of softening aging (T2, T3)[1].

According to [18], reliable correlations of mechanical properties (yield strength $\sigma_{0,2}$ strength $\sigma_в$, elongation δ) and values of specific electrical conductivity γ were obtained for aluminum alloys hardened during heat treatment. It has been revealed that with a decrease in the specific electrical conductivity of such alloys, strength increases and ductility decreases. It should be borne in mind that the values of electrical properties are determined not only by the chemical composition of alloys, but also by the peculiarities of the state of the crystal lattice structure, which are formed by the modes of deformation and thermal treatments. All of the above makes it possible to evaluate corrosion resistance based on electrical conductivity values.

There is a problem with the formation of specified properties in large-sized parts made from alloys 1933 and B93pch, which are used for SSJ-NEW and Tu-214 aircraft, after heat treatment. It is also necessary to conduct research to assess the characteristics of how the level of mechanical and corrosion properties is formed in critical power components during heat treatment operations.

The aim of the authors of this article is to determine heat treatment modes to achieve the necessary values of mechanical properties and resistance to corrosion cracking of parts made of large-sized deformed blanks of alloys of the Al-Zn-Mg-Cu alloying system.

Materials and Methods. The research was conducted on parts made from large-sized forgings of the 1933 alloy produced at the Kamensk-Ural Metallurgical Plant, and stamped blanks made of the B93pch alloy produced at the Arkonik SMP (Samara). Figure 1 provides the dimensions of the forgings. The overall dimensions of the stamped blanks were 1790x980 mm. Chemical composition of the studied alloys is shown in Table 1.

Heat treatment of the products was carried out in electric furnaces PA-56 and PA-54. Microstructural studies were performed using an Olympus GX71 light microscope. Electrical conductivity measurements were conducted with a Constant K6 device. Mechanical properties were tested in accordance with GOST 1497-84. The test samples were made from templets (cut from blanks) of sizes 70×70×140 mm, which were heat-treated together with the products. Proportional cylindrical W type samples with initial diameters of 5 mm or 15 mm were used. Tensile tests of the samples were performed on a GURM-20 installation. The Brinell method was used to determine their hardness (GOST 9012–9, ISO 410–82)[2].

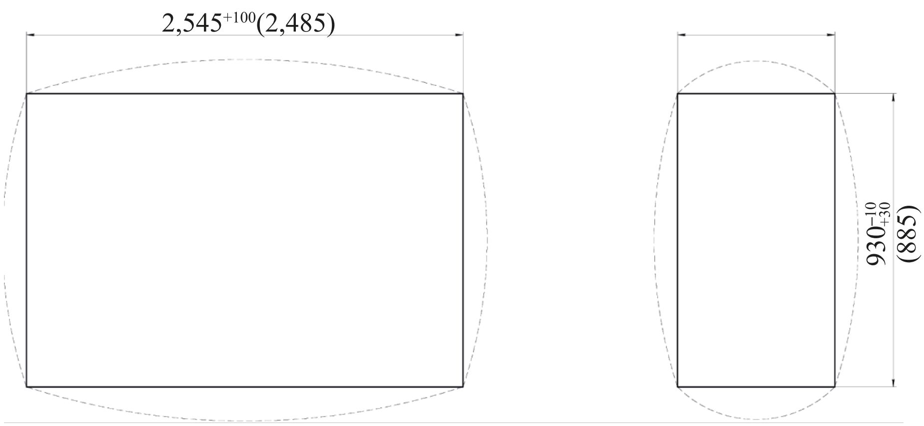


Fig. 1. Sketch of a large-sized forging made of alloy 1933

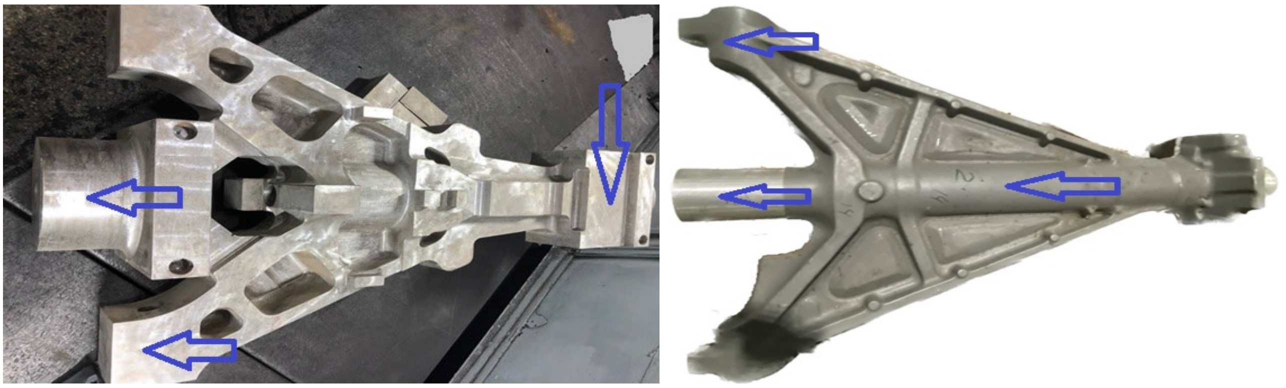
[1] GOST 1497–84. *Metals. Methods o f tension test.* Moscow: Standartinform; 2008. 26 p. URL: https://files.stroyinf.ru/Data2/1/4294852/4294852801.pdf (accessed: 29.04.2024). (In Russ.)
[2] GOST 9012–59. ISO 410–82 *Metals. Method of Brinell hardness measurement.* Moscow: Standartinform; 2008. 40 p URL: https://files.stroyinf.ru/Data2/1/4294850/4294850482.pdf (accessed: 29.04.2024). (In Russ.)

Table 1

Chemical composition of the studied alloys (wt., %)

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	Be	Al
1933	0.020	0.090	0.900	0.010	1.800	0.010	6.500	0.400	0.040	0.001	Base
B93pch	–	0.310	1.000	–	1.900	–	6.700	0.010	–	–	Base

Figure 2 shows the parts subjected to hardening heat treatment (arrows indicate the places where the electrical conductivity of the alloy was measured).



a) *b)*

Fig. 2. Heat-treated parts: *a* — traverse made of 1933 alloy; *b* — frame of the shock-absorbing strut made of B93pch alloy

Results. Studies in the state as received (after annealing) of the macrostructure of forgings and stamped workpieces, fractures, and performed ultrasonic inspection did not reveal unacceptable deviations. The electrical conductivity of alloy 1933 was 24.7 mSm/m, and for alloy B93h — 23.5 mSm/m. Figure 3 shows the microstructure of the 1933 alloy in the delivery state. The grain structure of the alloy did not have a pronounced oriented character.

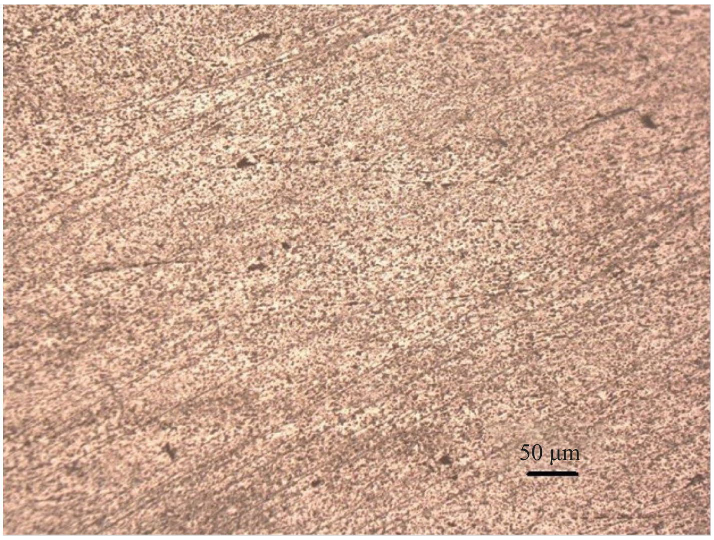


Fig. 3. Microstructure of alloy 1933 in the state as received

The characteristics of mechanical properties on longitudinal and transverse in width and transverse in thickness samples, which were made from forged and stamped blanks, were determined. Heat treatment of samples (standard version) was performed according to the following modes: alloy 1933 — the temperature of heating for quenching was 470 °C, cooling in water with a temperature of 75–85 °C, artificial aging: 1 stage — 110 °C (holding time 24 hours, air cooling), 2 stage — 180 °C (holding time 10–12 hours, cooling outdoors); alloy B93pch — quenching heating temperature 460 °C, holding time 180 minutes, cooling in water at a temperature of 75–85 °C, artificial aging: 1 stage — 120 °C (holding time — 8 hours, air cooling), 2 stage — 170 °C (holding time — 8 hours, air cooling). The results of the studies are shown in Table 2. It follows from the presented data that the values obtained after heat treatment of samples cut from forgings and stamped blanks comply with the requirements of regulatory documents (RD).

Table 2

Values of mechanical properties of heat-treated samples cut from forgings (alloy 1933) and stamped blanks (alloy B93pch)

Results of mechanical properties					RD Standard			
Fiber direction	$\sigma_в$, MPa	$\sigma_{0,2}$, MPa	δ, %	HB	$\sigma_в$, MPa	$\sigma_{0,2}$, MPa	δ,%, not less than	HB, not less than
Longitudinal	480 / 480	— / 433	17.0 / 11.2	149 / 163	440–530 / 430–500	390–470	7.0 / 7.0	110
Transverse in width	480 / 500	— / 457	12.2 / 8.0		430–530 / 430–500	390–470	5.0 / 5.0	
Transverse in thickness	490 / 470	–	8.1 / 3.5		420–500 / 430–500	–	3.0 / 3.0	

Note. The numerator contains the property values for alloy 1933, and the denominator — for alloy B93pch.

The technological process of manufacturing the products in question was multi-stage. After mechanical processing, hardening heat treatment was carried out on large-sized parts with complex geometries. After heat treatment of the parts according to traditional modes, a discrepancy in the indicators of RD mechanical properties was revealed. In this regard, a number of modes and options of heat treatment have been investigated (Table 3):

Mode No. 1 (1933) — a typical version of heat treatment of a “traverse” part made of alloy 1933 according to the production instructions;

Mode No. 2 (1933) — either a variant of repeated heat treatment carried out to correct the discrepancy in the level of properties after Mode No. 1 (1933), or a variant of heat treatment instead of Mode No. 1 (1933);

Mode No. 1 (B93) — a typical variant of heat treatment of a “frame” part made of B93pch alloy according to the production instructions;

Mode No. 2 (B93) — either a variant of repeated heat treatment carried out to correct the discrepancy in the level of properties after Mode No. 1 (B93), or a variant of heat treatment instead of Mode No. 1 (B93).

Table 3

Hardening heat treatment modes of “traverse” parts made of alloy 1933 and “frame” parts made of alloy B93

Heat treatment mode	Tempering	First stage of aging	Second stage of aging
Mode No. 1 (1933)	T = 470°C, starting point temperature — 455°C, holding time — 250 min., cooling medium — water, t_{water} = 75–85°C	T = 110°C, holding time — 24 h., cooling medium — air	T = 180°C, holding time — 10–12 h., cooling medium — air
Mode No. 2 (1933)	T = 470°C, starting point temperature — 455°C, holding time — 250 min., cooling medium — water, t_{water} = 75–85°C	T = 110°C, holding time — 12 h., cooling medium — air	T = 180°C, holding time — 6 h., cooling medium — air
Mode No. 1 (B93)	T = 460°C, starting point temperature — 445°C, holding time — 180 min., cooling medium — water, t_{water} = 75–85°C	T = 120°C, holding time 8 h., cooling medium — air	T = 170°C, holding time — 8 h., cooling medium —air
Mode No. 2 (B93)	T = 460 ºC, starting point temperature — 445 ºC, holding time — 180 min., cooling medium — water, t_{water} = 75–85°C	T = 120°C, holding time — 10 h., cooling medium — air	T = 175°C, holding time — 10 h., cooling medium — air

Table 4 shows the results of evaluating the mechanical properties after the studied modes and heat treatment options for alloy 1933. Mode No. 2 (1933), presented in Table 3, allows you to obtain the required mechanical properties corresponding to RD, and this mode can also be used as a repeated heat treatment to eliminate negative results after processing according to Mode No. 1 (1933) — an unacceptably low level of alloy strength in the longitudinal and transverse (width) direction of fiber.

Table 4

Results of mechanical properties tests after hardening heat treatment of the "traverse" part made of alloy 1933

Heat treatment mode	Mechanical properties			
	$\sigma_в$, MPa	$\sigma_{0,2}$, MPa	δ, %	HB
Longitudinal direction of fiber				
Mode No. 1 (1933)	430	370	10.1	129
Mode No. 2 (1933) (in re-processing option)	480	430	12.2	–
Mode No. 2 (1933) (in option of replacing Mode No. 1)	480	400	16.1	138
RD requirement	440–530	380–480	Not less than 7.0	Not less than 110
Transverse direction of fiber (in width)				
Mode No. 1 (1933)	420	370	13.2	129
Mode No. 2 (1933) (in re-processing option)	470	450	11.3	–
Mode No. 2 (1933) (in option of replacing Mode No. 1)	480	410	11.1	138
RD requirement	430–530	370–470	Not less than 4.0	Not less than 110
Transverse direction of fiber (in thickness)				
Mode No. (1933)	430	–	16.3	129
Mode No. 2 (1933) (in re-processing option)	480	–	16.2	–
Mode No. 2 (1933) (in option of replacing Mode No. 1)	460	–	10.4	138
RD requirement	420–500	–	Not less than 2.5	Not less than 110

Table 5 shows the results of evaluating the mechanical properties after the studied modes and heat treatment options for B93pch alloy.

Table 5

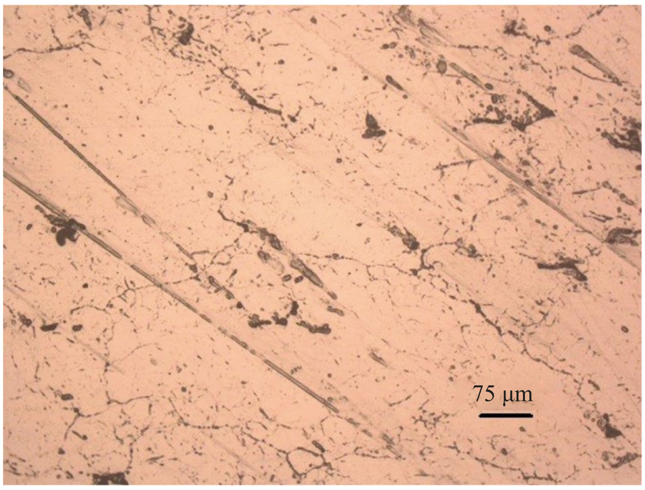
Results of mechanical properties test after hardening heat treatment of the "frame" part made of B93pch alloy

Heat treatment mode	Mechanical properties		
	$\sigma_в$, MPa	δ, %	HB
Longitudinal direction of fiber			
Mode No. 1 (B93)	510	12.4	163
Mode No. 2 (B93) (in re-processing option)	450	15.5	121
Mode No. 2 (B93) (in option of replacing Mode No. 1)	480	13.0	143
RD requirement	440–500	Not less than 7.0	Not less than 110
Transverse direction of fiber (in width)			
Mode No. 1 (B93)	510	7.2	163
Mode No. 2 (B93) (in re-processing option)	440	13.5	121
Mode No. 2 (B93) (in option of replacing Mode No. 1)	480	8.0	143
RD requirement	430–500	Not less than 4.0	Not less than 110
Transverse direction of fiber (in thickness)			
Mode No.1 (B93)	490	4.0	163
Mode No. 2 (B93) (in re-processing option)	431	9.0	121
Mode No. 2 (B93) (in option of replacing Mode No. 1)	480	8.0	143
RD requirement	420–500	Not less than 3.0	Not less than 110

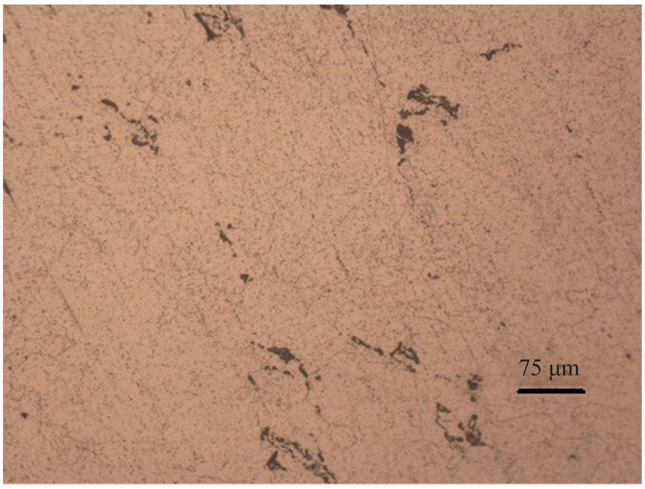
As it can be seen from the presented data, Mode No. 1 (B93) does not provide the required level of strength properties in the longitudinal and transverse (in width) directions of the fiber of the part. The level of properties is overestimated. At the same time, Mode No. 2 (B93) allows you to achieve the necessary property values when it is implemented both in the re-processing option and in the replacement option of Mode No. 1.

Thus, the longitudinal and transverse (in width) directions of fiber are the most sensitive to the influence of heat treatment modes in large-sized products made of alloys of the Al-Zn-Mg-Cu system. It is possible to achieve the required level of strength properties by correcting the aging modes of alloys — either by reduction (alloy 1933) or by increase (alloy B93pch) of duration.

The performed microstructural studies confirmed the absence of signs of burnout after quenching during processing in all modes and variants of heat treatment. Figure 4 shows the microstructure of the studied alloys after hardening heat treatment according to Mode No. 2 (1933) and Mode No. 2 (B93pch) (in options of replacing Mode No. 1). Since significantly longer aging was used during heat treatment of alloy B93pch, dispersed particles of strengthening phases are detected in the microstructure.



a)



b)

Fig. 4. Structure of alloys after hardening heat treatment according to the modes:
a — Mode No. 2 (1933); *b* — Mode No. 2 (B93pch) (in options of replacing Mode No. 1)

The authors conducted studies on electrical conductivity of alloys 1933 and B93pch after different modes and variants of heat treatment. Based on the results of these studies, it was possible to evaluate the P.1.22 extent of decomposition of the supersaturated solid solution under different aging conditions, as well as the corrosion resistance of the alloy, according to TU 1-804-475-2008. According to the RD requirements, in order to confirm satisfactory corrosion resistance on semi-finished products made of alloy 1933 in the T2 and T3 states, electrical conductivity index (ϒ) should be at least 22.5 mSm/m in the T2 state and at least 23.5 mSm/m in the T3 state; for alloy B93pch, the electrical conductivity index should be within the range of 21–25 mSm/m. Electrical conductivity measurements were carried out by the device on the most massive parts of the part (indicated by arrows in Fig. 2). In the state of delivery, the electrical conductivity of alloy B93pch was 22.7–23.8 mSm/m. The measurement results are presented in Table 6.

Table 6

Values of electrical conductivity at various stages of hardening heat treatment of alloys 1933 and B93pch

Heat treatment mode	Condition of the workpiece during heat treatment	Electrical conductivity, mSm/m
Mode No. 1 (1933) Mode No. 1 (B95)	After tempering	18.5–18.6
	After the 1st stage of aging	19.6–19.8
	After the 2nd stage of aging	25.1–25.9 23.5–23.6
Mode No. 2 (1933) Mode No. 2 (B95) (in re-processing option)	After tempering	18.5–18.6
	After the 1st stage of aging	19.6–19.7
	After the 2nd stage of aging	25.1–25.7 24.2–25.0
Mode No. 2 (1933) Mode No. 2 (B95) (in option of replacing Mode No. 1)	After tempering	18.5–18.7
	After the 1st stage of aging	19.6–19.7
	After the 2nd stage of aging	25.2–25.7 24.3–25.0

As follows from the above data, as the processes of decomposition of a supersaturated solid solution develop during aging, there is an increase in the electrical conductivity of the alloy, which is associated with a decrease in supersaturation of a crystal lattice with atoms of alloying elements. At the same time, despite the shortened duration of aging in the first and second stages, when implementing Mode No. 2 (1933), the values of electrical conductivity practically coincide with the values after Mode No. 1 (1933). This indicates a sufficiently high degree of decomposition of the supersaturated solid solution at the stages of aging during treatment according to Mode No. 2 (1933). The values of electrical conductivity of the alloy confirm its sufficient CC resistance. The electrical conductivity of alloy B93pch also meets the RD requirements.

Discussion and Conclusion. During hardening heat treatment of SSJ-NEW and TU 214 aircraft parts made from large-sized forgings of the 1933 alloy and stamped blanks of the B93pch alloy, cases of inconsistency of strength properties in the longitudinal and transverse (in width) directions of fiber of the parts were revealed.

It is shown that, depending on the configuration and dimensions of parts, the levels of the required characteristics of mechanical properties of aging stages duration should be assigned differentially. The modes and options of heat treatment of parts using a shortened (for alloy 1933) or increased (for alloy B95pch) holding time at aging stages are proposed, which allows you to ensure the necessary level of mechanical properties and resistance to corrosion cracking of large-sized products.

The studies conducted to investigate the effect of implementing different heat treatment stages on the electrical conductivity of the 1933 alloy have confirmed the achievement of an adequate level of decomposition of the supersaturated solid solution with the use of a shortened aging period for this alloy. This approach provides the necessary strength and corrosion resistance levels. By extending the aging time for the B93pch alloy, a higher level of electrical conductivity can be achieved.

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