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STUDIES IN HEAT RESISTANCE OF CAST ALUMINUM ALLOYS

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[This report examines the heat resistance of alloys of the system Al-Cu-Mg-Si-Mn-Cr-Ti, and presents the fundamental concepts used as a basis for the development of the AL20 alloy.] —> 143

CHAPTER VII

EXAMINATION OF THE HEAT RESISTANCE OF ALLOYS OF THE SYSTEM Al-Cu-Mg-Si-Mn-Cr-Ti AND OTHERS

1. Fundamental Concepts Used As Basis For the Development of the AL20 Alloy*

It was shown in the study of V. A. Livanov, D. A. Petrov, V. P. Kozlovskaya and Ye. I. Kutaytseva, carried out in 1944, that an alloy of the system Al-Cu-Mg on a base of solid aluminum solution and containing copper and magnesium in quantities corresponding to the ratio of these elements in the S(Al_2CuMg) phase has the highest short time heat resistance of all the alloys of this system at temperatures of 250-300°C. Therefore an alloy with a content of up to 5% copper and 1.7% Mg was taken as the basis for the development of a new super alloy intended for prolonged operation at 250-300°C. A higher content of these components will lead to a reduction of the alloy's ductility.

Alloys of this system cannot have good casting properties because their base is a solid solution. A definite amount of a eutectic (not less than 30%) is needed for improving their casting properties. The examined alloys were alloyed with silicon for this purpose. It was assumed that elementary silicon would sharply lower the alloy's heat resistance, therefore it should participate in the formation of stable phases of a complex composition.

The investigations showed that the most heat resistant phases containing a silicon are the phases Al_5SiFe, Al_4Si_2Fe and π ($Al_8Si_6Mg_3Fe$). In order to form these phases, iron in ratios corresponding to the composition of the Al_5SiFe phase or the phases indicated above has to be jointly introduced with the silicon into alloys of the system Al-Cu-Mg. The content of each of them should not exceed 2% because in a contrary case the alloy's ductility is lowered.

* In addition to I. F. Kolobnev, D. A. Petrov, G. V. Zakharova, A. V. Korobkov and V. N. Ozepetskovskiy participated in the development of the AL20 alloy.

Alloying with small additions of manganese, chromium and titanium was made use of for reducing the structure and increasing the alloy's ductility. These addition can also cause an increase in the heat resistance.

The chemical composition of the examined alloys is given in Table 70. The test specimens of standard shape were prepared by the usual method with the use of A00 grade aluminum. The test results are given in Table 71. The ultimate strength of the alloy increases in both the cast as well as the heat treated states with an increase in the copper and magnesium content. But the test samples of alloys of the system Al-Cu-Mg are more stable in the heat treated condition than in the cast. It should be noted that alloys containing silicon and iron in a ratio corresponding to the composition of the Al_5SiFe phase have a high heat resistance in the cast state. Alloys with a higher silicon content have a decreased heat resistance which is associated with the presence of elementary silicon in them.

Table 70

Chemical composition of the examined alloys

(1) Номер сплава	(2) Содержание, %, остальное алюминий							
	Cu	Mg	Si	Fe	Ni	Ti	Cr	Mn
1	2,22	0,76	—	—	—	—	—	—
2	3,11	1,24	—	—	—	—	—	—
3	4,46	1,67	—	—	—	—	—	—
4	2,11	0,90	1,35	1,37	—	—	—	—
5	3,32	1,32	1,81	1,52	—	—	—	—
6	4,6	1,75	1,42	1,45	—	0,2	—	—
7	3,78	1,25	1,25	1,31	—	0,2	—	—
8	4,44	1,65	1,26	1,14	—	—	0,2	0,18
9	3,53	1,30	1,27	1,30	—	—	0,25	0,29
10	4,20	1,66	1,37	1,23	—	—	—	—
11	3,03	1,27	2,85	1,35	—	—	—	—
12	3,03	1,24	5,37	1,55	—	—	—	—
13	3,22	1,14	10,39	1,25	(3) Модифицированный			
14	3,18	1,21	10,25	1,25	(4) Немодифицированный			

(5) Примечания. 1. В сплавы № 1—9 медь и магний добавляли в соотношениях образования фазы S (Al_2MgCu).
2. В сплавы № 10—14 железо и кремний добавляются в соотношениях образования фаз Al_5SiFe.

Key: 1--Alloy number; 2--content, % with aluminum remainder; 3--modified; 4--unmodified; 5--Notes. 1. Copper and magnesium was added to alloys 1-9 in ratios corresponding to the formation of the $S(Al_2MgCu)$ phase. 2. Iron and silicon was added to alloys 10-14 in ratios corresponding to the formation of the Al_2SiFe phase.

The data in Table 72 attest to the fact that alloys 7, 8, 9 and 10 have completely satisfactory mechanical properties at room and elevated temperatures in the cast and heat treated states; alloy No 7 is the most ductile, it was therefore taken as the base for the new alloy under the designation AL20 (V14A) and it was checked for ultimate strength at 250°C.

The following composition for the AL20 alloy was established as the result of an all inclusive investigation: 3.5-4.5% Cu, 0.7-1.2% Mg, 1.5-2% Si, 1.2-1.7% Fe, 0.2-0.3% Mn, 0.1-0.18 Cr and 0.1-1.18% Ti with the remainder being aluminum. → 196

In ratio of the basic components of copper, magnesium and silicon the AL20 alloy is found [2] in the region $\alpha + S - Mg_2Si - CuAl_2$ of the two dimensional cross section diagram of the tetrahedron Al-Cu-Si-Mg (at 90% Al) shown on Figure 91.

It was established that the AL20 alloy with an addition of manganese, chromium and titanium has a higher heat resistance but the ductility of this alloy is lower than that with an addition of titanium.
Changes in small additions do not have any essential effects upon the engineering properties of the alloy.

Table 71

Mechanical properties of the alloys as a function of temperature and composition

(1) Номер сплава	(2) Состояние сплава								
	(3) литое			(6) закаленное и естественно состаренное			(9) закаленное и искусственно состаренное		
	(4) механические свойства при 20° C		(5) длительность испытаний при 200° C и напряжении 6 кг/мм² час.	(7) механические свойства при 20° C		(8) длительность испытаний при 300° C и напряжении 6 кг/мм² час.	(10) свойства при 20° C		(11) длительность испытаний при 300° C и напряжении 6 кг/мм² час.
	σ_b кг/мм²	δ, %		σ_b кг/мм²	δ, %		σ_b кг/мм²	δ, %	
1	12	1,37	1,83	19,6	5,58	6	19,8	2,4	9
2	13,7	0,75	14,3	20,8	1,3	33,5	23,6	1,2	44,6
3	15,4	0,27	23,3	22,5	1,43	45	22,5	0,75	72,6
4	18,8	2,1	27,1	21,4	3,5	31,5	25,1	—	65,7
5	19,9	1,9	66,7	21,6	2,4	70	24,6	1,5	69,3
6	20,0	0,9	94,5	22,7	0,96	82,7	28,4	0,3	78,7
7	18,8	1,57	131	25,9	1,8	113,3	28	1,1	103
8	20,4	1,33	148	23,4	2,18	138	34,4	0,85	121
9	22,2	1,0	128	25,6	1,4	115	26	1,2	108
10	19,9	0,8	157	22,7	0,8	134	27,4	0,7	116
11	16,9	0,45	34	25,6	1,1	33,3	20,9	0,5	20,8
12	18,7	0,5	38	19,85	—	31,8	24,0	0,48	20
13	16,7	0,7	28	20,6	1,0	15	17,7	—	27,3
14	18,9	0,5	59	19,9	0,8	24	17,0	0,2	16

Key: 1--Alloy number; 2--Condition of alloy; 3--Cast; 4--mechanical properties at 20°C; 5--duration of testing at 200°C and load of

Key to Table 71 (continued)

6 kg/mm^2, hours, 6--hardened and naturally aged; 7--mechanical properties at 20°C; 8--duration of testing at 300°C and load of 6 kg/mm^2, hours; 9--hardened and artificially aged; 10--mechanical properties at 20°C; 11--duration of testing at 300°C and load of 6 kg/mm^2, hours.

The AL20 alloy is almost a unique alloy which contains up to 1.7% Fe as the basic alloying constituent. Hence its application in industry promotes a wider use of secondary alloys and industrial scrap which has been contaminated with iron.

Tables 72-74 give the mechanical characteristics of the AL20 alloy as a function of its condition. The heat resistance of the AL20 alloy is adequately high in both the cast as well as in the hardened and artificially aged states. It should be noted that during short time tensile testing the alloy in heat treated condition has a superiority over the cast alloy only up to 250°C. At higher temperatures the tensile strength of the AL20 alloy in both states is practically identical whereas the yield stress in the heat treated condition is higher at all test temperatures. This is a characteristic peculiarity for all multicomponent alloys with a strongly alloyed solid solution.

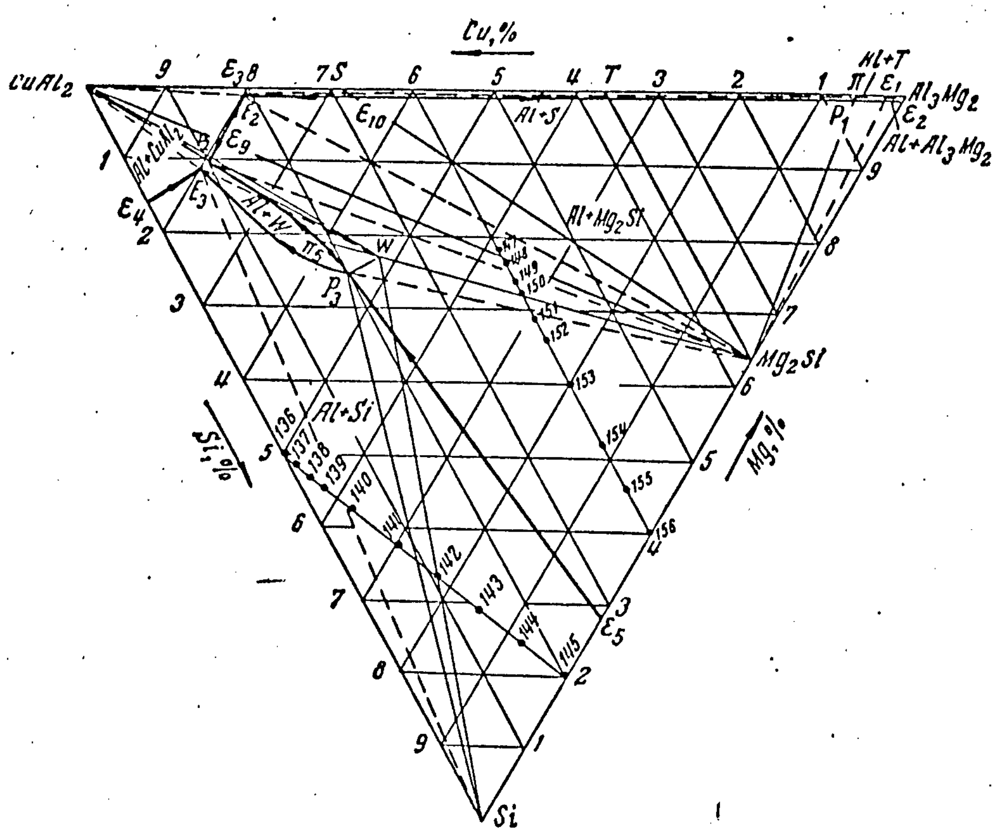


Figure 91. Two dimensional diagram for 90% Al of the tetrahedron Al-Si-Cu-Mg.

Table 72

Duration of testing in hours of individually cast test specimens of AL20 alloy

(1) Номер сплава	(9) Состояние сплава					
	(2) литое			(5) закаленное и искусственно состаренное		
	(3) механические свойства при 20° С		(4) длительность испытаний при 250° С σ_b= 9 кг/мм² час.	(6) механические свойства при 20° С		(7) длительность испытаний при 250° С σ_b= 8 кг/мм² час.
	σ_b кг/мм²	δ, %		σ_b кг/мм²	δ, %	
1	20	1,8	100*	27,5	1,3	100*
2	18,2	1,3	100*	28,4	0,7	100*
3	18,3	1,6	100*	28,4	1,3	100*
4	—	—	96	—	—	100*
5	—	—	100*	—	—	100*
6	—	—	—	—	—	—
7	—	—	—	—	—	—
8	—	—	—	—	—	—

(8)* Образцы были сняты без разрушения и переведены на следукщее напряжение.

Key: 1--Alloy number; 2--Cast; 3--mechanical properties at 20°C; 4--duration of testing at 250°C, σ_b = 9 kg/mm², hours; 5--hardened and artificially aged; 6--mechanical properties at 20°C; 7--duration of testing at 250°C, σ_b + 8 kg/mm², hours; 8--* The test specimens were removed without failure and then carried over to the following load; 9--Condition of alloy.

Table 73

Short time testing of AL20 alloy

(1) Температура испытания, °С	(2) Состояние сплава													
	(3) литой							закаленный и искусственно состаренный (4)						
	σ_b кг/мм²	$S_к$ кг/мм²	δ, %	ψ, %	$\sigma_{пр}$ кг/мм²	$\sigma_{0,2}$ кг/мм²	E, кг/мм²	σ_b кг/мм²	$S_к$ кг/мм²	δ, %	ψ, %	$\sigma_{пр}$ кг/мм²	$\sigma_{0,2}$ кг/мм²	E, кг/мм²
20	17,2	17,3	0,4	0,3	5,0	13,88	7590	23,6	23,8	0,8	0,9	10,7	19,9	7070
100	17,0	17,1	0,1	0,1	7,5	15,25	7635	21,75	22,0	0,9	1,1	10,45	17,6	7035
150	16,7	16,75	0,1	0,1	7,0	14,40	6855	20,6	20,8	0,82	0,8	10,2	16,6	6670
200	16,2	16,22	0,2	0,2	6,8	12,20	6715	20,8	21,2	1,5	1,4	10,0	17,9	6590
250	15,0	15,1	0,7	0,6	4,2	8,9	6585	14,9	15,3	2,6	2,75	6,7	13,0	6300
300	12,6	12,7	1,85	2,1	2,9	5,9	6300	12,7	13,0	3,4	7,1	6,5	11,0	6020

Key: 1--Test temperature, °C; 2--condition of alloy; 3--cast; 4--hardened and artificially aged.

Table 74

Ultimate strength of AL20 and other alloys at 300°C
(Individually cast test specimens)

(1) Марка сплава	(2) Длительность испытаний до разрушения при напряжении 6 кг/мм², час., в состоянии		
	(3) литом	(4) закаленном	(5) закаленном и состаренном
АЛ1	89	125*	114
АЛ3	5	4	4
АЛ5	5	8	11
АЛ4	1	(6) Разрушился при нагружении	
АЛ20	140	125*	115

(7) Примечание. Сплав АЛ20 термически обрабатывали по режиму: нагрев под закалку при 515° С в течение 3 час.; закалка в воде; старение при 250° С в течение 10 час.

(8) * Сняты без разрушения.

Key: 1--Designation of alloy; 2--Duration of testing to failure at a load of 6 kg/mm², hours, in condition; 3--cast; 4--hardened; 5--hardened and aged; 6--Failed at load of; 7--Note. The AL20 alloy was heat treated according to the regime: heating to below hardening at 515°C for 3 hours; water quenching; aging at 250°C for 10 hours; 8--* Removed without failure.

2. Heat Treatment Conditions For the AL20 Alloy

The optimum heat treatment conditions were selected not for the purpose of obtaining casting with a maximum strength but rather for assuring minimum volumetric changes in the parts during their service at elevated temperatures. In this case hardening and aging with the attainment of a maximum strength are harmful.

The mechanical properties as a function of heat treatment conditions are given in Table 75. The best heat treating regime is shown in Figure 92.

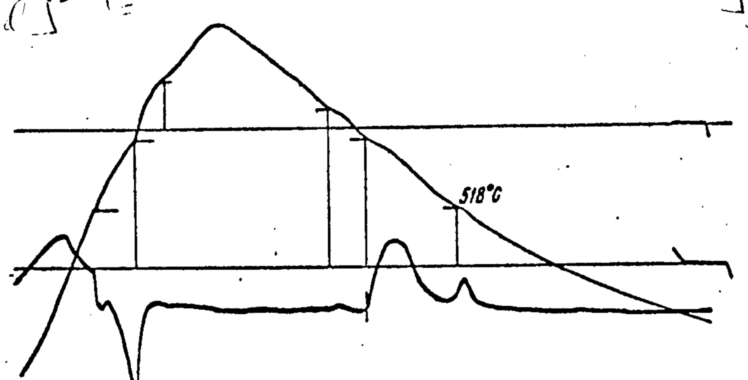


Figure 92. Heating and cooling curve for the AL20 alloy.

The heating to below hardening was gradual; 2-3 hours at 500°C, then 2-3 hours at 515°C. Under conditions of slow heating to 525°C one step heating will also assure high properties. Water quenching was at 80-100°C. Aging at 250°C for 10 hours.

This heat treating regime assures (for individually cast test specimens) a tensile strength of 25 kg/mm^2 and a relative elongation of 1.5%.

Table 75

Mechanical properties of AL20 alloy as function of heat treatment conditions

(1) Режим термической обработки	(2) Механические свойства	
	σ_b, кг/мм²	δ, %
(3) Литой	18,3	1,1
(4) Литой + отжиг при 250° С в течение 3 час.	18,2	1,0
(5) Литой + отжиг при 250° С в течение 35 час.	21,4	0,7
(6) Нагрев под закалку при 520° С в течение 3 час.	29,5	1,3
(7) Нагрев под закалку при 520° С в течение 10 час.	29,3	1,3
(8) Нагрев под закалку при 520° С в течение 10 час. + старение при 250° С в течение 10 час.	25,7	1,4
(9) Нагрев под закалку при 520° С в течение 10 час. + старение при 250° С в течение 10 час.	27,5	0,9
(10) Нагрев под закалку при 515° С в течение 10 час.	29,5	1,13
(11) Нагрев под закалку при 515° С в течение 10 час. + старение при 250° С в течение 5 час.	27,2	1,3
(12) Нагрев под закалку при 515° С в течение 10 час. + старение при 250° С в течение 10 час.	24,1	1,0
(13) Нагрев под закалку при 515° С в течение 10 час. + старение при 300° С в течение 10 час.	19,2	1,6
(14) Нагрев под закалку при 515° С в течение 10 час. + старение 170° С в течение 10 час.	27,7	0,6
(15) Нагрев под закалку при 515° С в течение 10 час. + старение 170° С в течение 15 час.	33,3	0,8
(16) Нагрев под закалку при 515° С в течение 10 час. + старение при 150° С в течение 10 час.	23,8	1,5
(17) Нагрев под закалку при 515° С в течение 10 час. + старение при 150° С в течение 15 час.	29,2	1,7
(18) Нагрев под закалку при 515° С в течение 13 час. + старение при 150° С в течение 50 час.	33,5	0,4
(19) Нагрев под закалку при 515° С в течение 3 час. + старение при 250° С в течение 5 час.	25,8	1,1
(20) Нагрев под закалку при 515° С в течение 3 час. + старение при 250° С в течение 10 час.	23,5	1,2
(21) Ступенчатый режим закалки: нагрев при 500° С в течение 3 час. В 515° С 3 час. + старение при 250° С в течение 5 час.	31,2	1,1
(22) Ступенчатый режим закалки: нагрев при 500° С в течение 3 час. + 520° С в течение 3 час. + старение при 150° С в течение 35 час.	36,3	1,5

Key: (Table 75)

1--Heat treatment conditions; 2--Mechanical properties; 3--Cast; 4--Cast + annealing at 250°C for 3 hours; 5--Cast + annealing at 250°C for 35 hours; 6--Heating to below hardening at 520°C for 3 hours; 7--Heating to below hardening;at 520°C for 10 hours; 8--Heating to below hardening at 520°C for 10 hours + aging at 250°C for 10 hours; 9--Heating to below hardening at 520°C for 10 hours + aging at 250°C for 10 hours; 10--Heating to below hardening at 515°C for 10 hours; 11--Heating to below hardening at 515°C for 10 hours + aging at 250°C for 5 hours; 12--Heating to below hardening at 515°C for 10 hours + aging at 250°C for 10 hours; 13--Heating to below hardening at 515°C for 10 hours + aging at 300°C for 10 hours; 14--Heating to below hardening at 515°C for 10 hours + aging at 170°C for 10 hours; 15--Heating to below hardening at 515°C for 10 hours + aging at 170°C for 15 hours; 16--heating to below hardening at 515°C for 10 hours + aging at 150°C for 10 hours; 17--heating to below hardening at 515°C for 10 hours + aging at 150°C for 15 hours; 18--Heating to below hardening at 515°C for 13 hours + aging at 150°C for 50 hours; 19--Heating to below hardening at 515°C for 3 hours + aging at 250°C for 5 hours; 20--Heating to below hardening at 515°C for 3 hours + aging at 250°C for 10 hours; 21--Step by step hardening regime; heating at 500°C for 3 hours. At 515°C for 3 hours + aging at 250°C for 5 hours; 22--Step by step hardening regime: heating at 500°C for 3 hours + 520°C for 3 hours + aging at 150°C for 35 hours.

3. Mechanical Properties of the AL20 Alloy

The effects of low temperatures on the mechanical properties of the AL20 alloy in annealed condition after casting are given in Table 76.

Table 76

Mechanical properties of AL20 alloy at low temperatures (according to S. Ye. Belyayev)

(1) Вид образца	(4) Температура испытания °C	σ_b кг/мм²	$S_к$ кг/мм²	ψ, %	δ, %	$\frac{\sigma_{b_n}}{\sigma_b}$	$\frac{S_{K_n}}{S_к}$
(2) Гладкий	+20	17,2	17,7	2,1	0,5	—	—
	—40	17,6	17,7	1,0	0,2	—	—
	—70	18,6	18,6	0	0	—	—
(3) С надрезом	+20	16,1	16,1	0	—	0,935	0,910
	—40	16,2	16,2	0	—	0,915	0,915
	—70	16,6	16,6	0	—	0,890	0,890

(5) Примечание. $\frac{S_{к_п}}{S_к}$; $\frac{\sigma_{b_п}}{\sigma_b}$ — коэффициенты действия надреза.

Key: 1--Type of sample; 2--Smooth; 3--Notched; 4--Test temperature °C; 5--Note. $\frac{S_{k_n}}{S_k}$; $\frac{\sigma_{b_n}}{\sigma_b}$ - These are the coefficients of notch effect.

Tests were carried out for tension and mechanical shock resistance at a temperature of +20, -40 and -70°C on small and notched test specimens[1].

The samples were cooled down to a temperature of -70° with a mixture of carbonic acid and acetone and were then held at the test temperature for 15 minutes.

Fatigue tests[2] were carried out at a vibration frequency of 20 x 10^6 cycles in the case of testing at normal temperature. The fatigue data for the AL20 alloy in comparison with other alloys is given in Table 77.

With respect to fatigue strength at 20°C the AL20 alloy is not inferior to the AL4 alloy and it surpasses the latter in ultimate strength at 250°C (see Table 74).

Table 77

Fatigue test data for AL20 alloy in comparison with other alloys (sand cast test specimens)

(1) Марка сплава	(2) Предел усталости сплава при температуре. °C $\sigma_{0,2}$ кг/мм²		
	20		250
	(3) литой 20·10⁶ циклов	(4) термически обработанного (2·10⁷ циклов)	(5) термически обработанного (2·10⁷ циклов)
AL1	—	6,5	—
AL4	—	7,0	4,5
AL5	—	—	4,5
AL20	7	7,5	6,5

Key: 1--Alloy designation; 2--Alloy's fatigue limit at temperature, °C, $\sigma_{0.2}$ kg/mm²; 3--Cast, 20 x 10^6 cycles; 4--Heat treated (2 x 10^7 cycles).

[1] The tests were carried out under the directorship of Ye. S. Belyayev.

[2] The tests were carried out under the directorship of L. S. Zhukov.

Table 78

Creep test data for AL20 alloy in comparison with other alloys

(1) Марка сплава	(2) $\sigma_{0,2}$ за 100 час. при 250° С кг/мм²		(5) $\sigma_{0,2}$ за 100 час. при 300° С кг/мм²	
	(3) литой	(4) термически обработанный	(6) литой	(7) термически обработанный
AL1	—	6,2	—	3,0
AL4	—	2,0	—	1,2
AL5	—	3,0	—	2,4
AL20	4,5	—	3,2	4,0
	—	6,0	—	—

Key: 1--Alloy designation; 2--$\sigma_{0.2}$ for 100 hours at 250°C kg/mm²; 3--Cast; 4--Heat treated; 5--$\sigma_{0.2}$ for 100 hours at 300°C kg/mm²; 6--Cast; 7--Heat treated.

The minimum creep values for the AL20 alloy (with $\sigma_{0.2}$ = 100 hours) in comparison with other alloys are given in Table 78. Data for prolonged tension and compression tests for the AL20 alloy on individually sand cast test specimens are given in Table 79.

Table 79

Data for tension and compression tests of AL20 alloy test specimens

(1) Состояние сплава	(2) Вид испытания	(3) σ_b, кг/мм²	(4) $S_к$, кг/мм² истин.	δ, %	ψ, %	(5) Испытание ускорения в % $E_к$	ψ_p, %	(6) $\sigma_{пр}$, кг/мм²	(7) Предел текучести, кг/мм² при $\sigma_{0,2}$	$\sigma_{0,1}$	$\sigma_{0,05}$	E, кг/мм²
(8) Отожженный при 250° С в течение 5 час	(10) На растяжение	19,0	19,5	0,5	2.4	—	1,4	7,8	15;0	13,3	12,0	7080
	(11) На сжатие	116,7	5,12	—	—	56,0	—	—	—	—	—	6800
(9) После закалки и старения	(12) На растяжение	25,3	—	—	—	—	—	13,6	24,7	—	21,7	7080
	(13) На сжатие	76,8	38,7	—	—	48	—	—	—	—	—	—

Key: 1--Condition of alloy; 2--Type of test; 3--σ_b, kg/mm²; 4--S_K, kg/mm² ture; 5--acceleration test in % E_K; 6--$\sigma_{proportionality}$ kg/mm²; 7--Yield stress, kg/mm², at; 8--annealed at 250°C for 5 hours; 9--after hardening and aging; 10--tension; 11--compression; 12--tension; 13--compression.

The AL20 alloy is considerably superior to the AL4 and AL5 alloys and is practically equal in strength to the AL1 alloy.

Short time testing of the AL20 alloy for portion and shear are given in Table 80.

Figure 93 shows the microstructures of the AL20 alloy. Comparative characteristics of the basic alloys are given in Figures 94 and 95.

Table 80

Results of portion and shear tests

(1) Состояние сплава	(2) $\tau_p = 12$ кг/мм² с учетом пластического кручения	(3) $\tau_p = 16$ кг/мм² с учетом упругого кручения	$\tau_в = 12$ кг/мм²	$\tau_з = 16$ кг/мм²	(4) $\tau = 12$ кг/мм² максимальное, касательное напряжение	(5) $\tau = 16$ кг/мм², максимальное напряжение	(6) Средний угол закручивания, град.	(7) $\tau_{сред}$ касательное напряжение при срезе	(8) Модуль сдвига при кручении E кг/мм²
(9) Отожженный при 250° С в течение 5 час.	4,1	5,5	7,9	10,4	14,5	19,4	110	14,5	2660
(10) Закаленный и состаренный	—	11,9	—	17,7	—	25,6	—	17,6	2600

Key: 1--Condition of alloy; 2--$\tau_p = 12$ kg/mm² with consideration of plastic tortion; 3--$\tau_p = 16$ kg/mm² with consideration of elastic tortion; 4--$\tau = 12$ kg/mm² maximum, tangential stress; 5--$\tau = 16$ kg/mm² maximum stress; 6--average angle of tortion, degrees; 7--τ average tangential stress at shear; 8--shear modulus in tortion E kg/mm²; 9--annealed at 250°C for 5 hours; 10--hardened and aged.

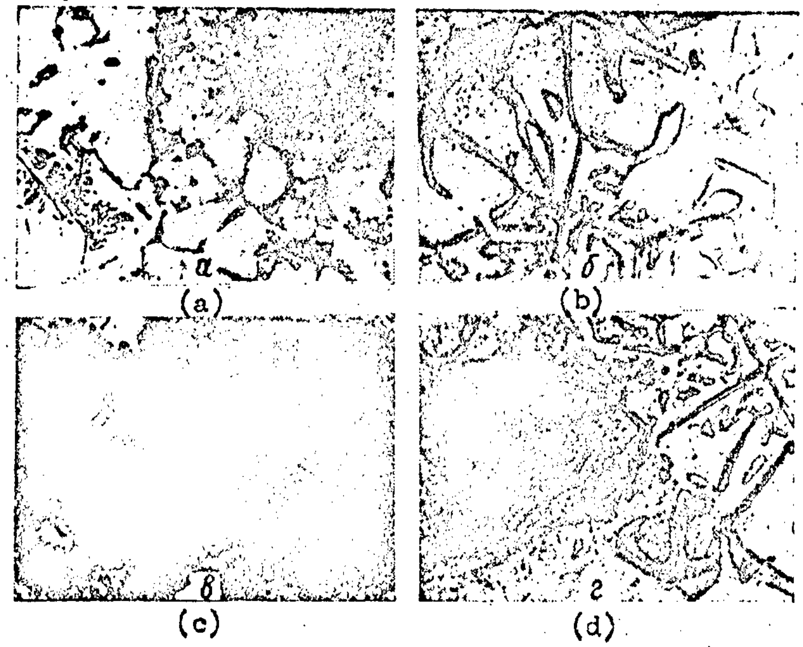
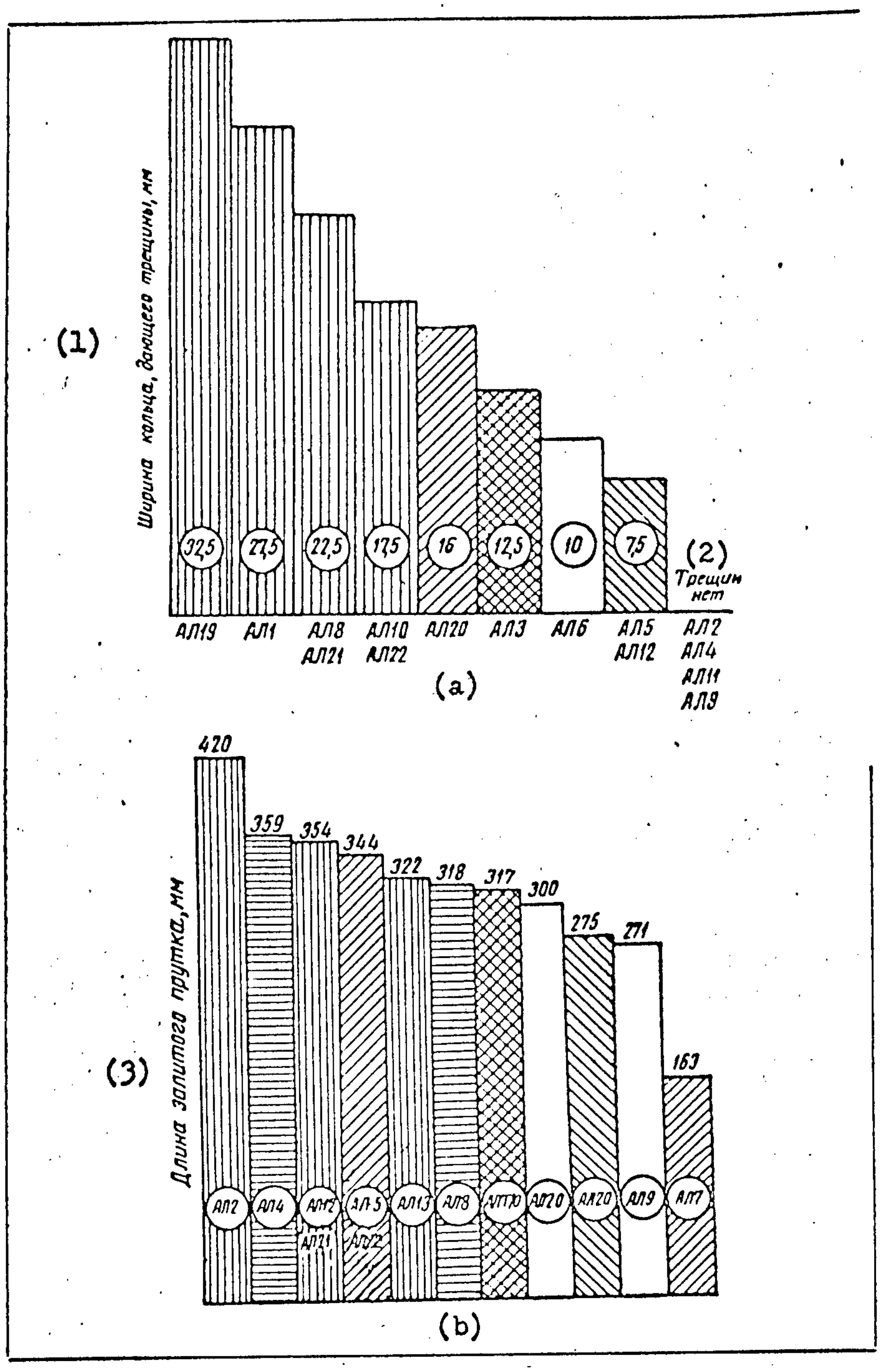


Figure 93. Microstructure of the AL20 alloy: 1 - 300°C; 2 - 350°C a - in cast state, 100X; b - the same, 500X; c - in hardened and annealed state, 100X; d - the same, 500X.

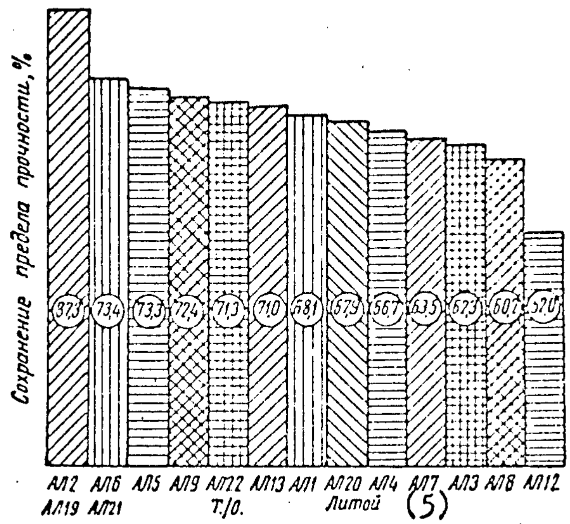
It was established as a result of the examination that the AL20 alloy surpasses the AL1 alloy with respect to prolonged heat resistance in the cast state but it is practically equal to the latter in the heat treated condition. The AL20 alloy is less inclined to crack formation during crystallization and quenching than the AL1, AL7, AL8, AL9, AL21 and other alloys (See Figure 94a).

The flowability of the alloy at 730-780°C is fully adequate for the casting of complex and irregular parts (Figure 94c).

The ability to retain its strength in relation to cross section thickness is higher than in the cases of the AL1, AL4, AL7, AL3, AL8 and AL12 alloys (Figure 94b).


(1)
Ширина кольца, дающего трещины, мм
32,5
27,5
22,5
17,5
16
12,5
10
7,5
(2)
Трещин нет
АЛ19
АЛ1
АЛ8
АЛ21
АЛ10
АЛ22
АЛ20
АЛ3
АЛ6
АЛ5
АЛ12
АЛ2
АЛ4
АЛ11
АЛ9
(a)
(3)
Длина залитого прутка, мм
420
359
354
344
322
318
317
300
275
271
163
АЛ2
АЛ4
АЛ13
АЛ8
АЛ9
АЛ7
(b)

(4)



(c)

Figure 94. Comparative characteristics of the alloys: a - hot shortness of AL19 and AL20 alloys in comparison with other alloys; b - (retention of tensile strength in the alloys with an increase in the casting diameter from 15 to 60 mm; c - flowability of alloys at 700°C temperature. 1--width of ring producing cracks, mm; 2--no cracks; 3--length of cast bar, mm; 4--retention of tensile strength, %; 5--cast.

The parts made out of the AL20 alloy are distinguished by a high air tightness (water pressure above 100 at. is withstood without failure).

The coefficients of thermal expansion and heat conduction at high temperatures are practically the same as those in the AL4 and AL5 alloys.

The mechanical properties at room temperature in the cast and heat treated states are practically the same as those in many alloys (AL6, AL9 and others) with the exception of a decreased elongation in cast state.

The optimum heat treating conditions which have been developed for the AL20 alloy assure a relatively high level of heat resistance with retention of satisfactory strength at room temperature. The following heat treatment conditions are recommended for parts which operate at elevated temperatures.

Heating to below hardening at 515°C for 3-5 hours, water quenching 80-100°C and aging at 250° for 5-10° per hour. The given regime provides for a tensile strength in the alloy of 25 kg/mm^2 and a relative elongation of not less than 1.0% as well as a rupture strength for 100 hours at 300° of 5 kg/mm^2.

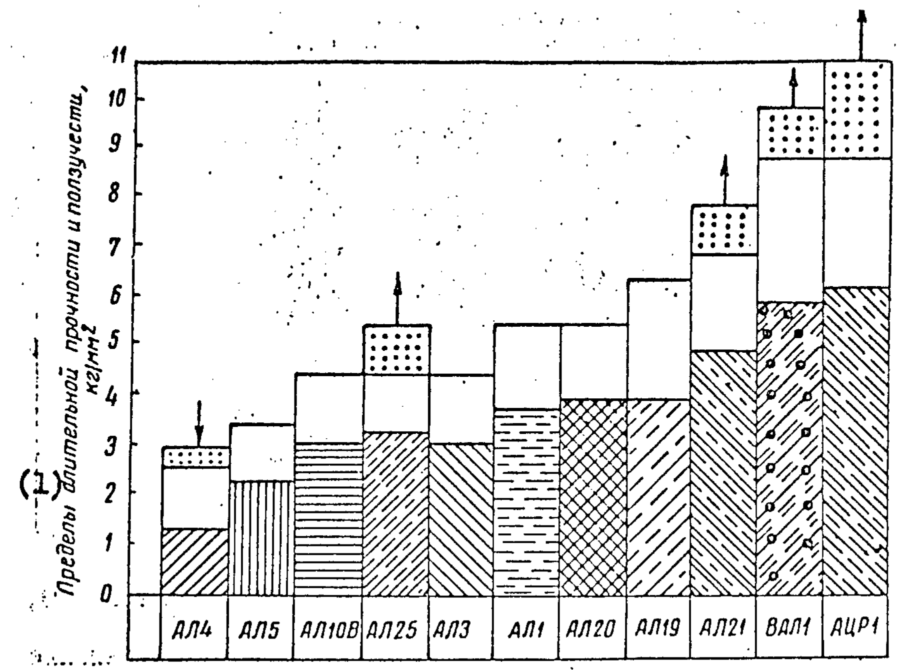


Figure 95. Rupture strength and creep limits for the alloys at 300°C. The creep limit is cross hatched; the ultimate strength is cross hatched and unshaded; increase in the rupture strengths at optimum chemical composition — dots with the arrow pointing upwards; the same, reduction — arrow pointing downwards. 1--Rupture strength and creep limit, kg/mm².

CONCLUSION

A generalization of the source material as well as the comprehensive material in the present work make it possible to draw a conclusion concerning the possibility of the development of still more heat resistant aluminum casting alloys than the alloys shown in Table 5 for prolonged services at temperatures of 0.8-0.85 from their absolute melting point. The following propositions have to be considered in the development of the new alloys:

1. A binary system should be taken as the basis for the development of a new highly heat resistant casting alloy. This system should have: a) a eutectic with a high melting point; b) a second phase which practically does not react with aluminum at working temperature.

2. The melting point of the new alloy should be above 600°C which will enable to increase its working temperature to 400-500°C.

3. The alloy should contain not less than 35% of the eutectic and have a relatively narrow interval of crystallization (not more than 30°C) in order to assure high casting properties and to obtain extra airtight parts.

4. The basic alloying constituents should be the elements of the transition group of the periodic table in order to obtain a relatively stable α solid solution and a high temperature eutectic. The most suitable are those elements which have a low coefficient of diffusion in aluminum, a high melting point and the capability of forming complex and dispersed decomposition products at working temperatures which then create a stable microheterogeneity of the second quarter within the grains. For example an alloy intended for prolonged service at 400°C should be alloyed by the following most effective constituents: cerium, manganese, chromium, vanadium, zirconium and other analogous elements.

5. The higher the alloy's working temperature to a greater degree is it necessary to strengthen the grain boundaries with phases which are stable at working temperatures [for instance Al_4CuCe, Al_8Mn_4Ce, $Al_3(NiCu)_2$, Al_6Cu_3Ni] which crystallize in a branched form and for all practical purposes do not react with the α solid solution. Generally these phases form a stable lattice blocking the grains of the solid solution.

6. The sizes of the particles of the second phases as well as their quantity should not be very high so that a concentration of stresses, leading to a reduction in the alloy's ductility, would not occur.

The size and quantity of the particles of the second phase, optimal for a given alloy and service conditions, are found experimentally.

Data are given below which characterize the heat resistance of the alloy composition as a function of the nature of the alloying constituents. Silumin type alloys can operate for a long time only at temperatures up 200-275°C on account of the increased diffusion mobility of the silicon and aluminum alloys. Silicon does not form complex compounds with aluminum therefore the formation of the silicon particles proceeds rather rapidly during the decomposition of the α solid solution. When the Silumin type alloys are alloyed with elements of the transition group their heat resistance is raised considerably. This is explained by the strengthening of the α solid solution and the grain blocking force owing to the formation of a stable framework of complex phases. Examples of similar alloys are the alloys AL25 (ZhLS-1) and AL26 (VKZhLS) which are used for the pistons of automobile and tractor engines. It is of advantage to employe the systems Al-Mg and Al-Cu as the base when developing a high strength alloy for brief service at elevated temperatures or one which is subjected to the prolonged action of low gas or fluid pressures at temperatures which are below the aging temperatures. The alloys should have a fine grain structure with a minimum quantity of particles of second phases distributed among the grain boundaries. The degree of supersaturation of the α solid solution of the alloy by the alloying constituents should be maximum.

The most suitable systems are the Al-Ce, Al-C and Al-Ni as the basis for an alloy intended for prolonged service at temperatures around 400°C. The alloy structure should be multiphase and particles of the second phases should reliably block the grain boundaries of the solid solution. A solid solution should answer the requirements set forth in section 4.

The role of the transition type alloying constituents, increasing the interatomic bond and stability of the α solid solution of aluminum, can be evaluated by Raynor's data (See page 64). The pausitive effects of the transition elements on the heat resistance of the alloys has also been noted by M. V. Zakharov (page 64).

The data of our investigations confirms the very positive effect of the transition group elements on the heat resistance of aluminum alloys (page 64).

Their effects can basically be reduced to the following: a) strengthening of the interatomic bond owing to the complexing of the electron structure of the multicomponent solid solution (a partial filling up of the electron shells by valance electrons, for example d in the case of atoms of manganese, chromium, nickel and others) as well as the low mobility of the transition element atoms. Presence of metallic atoms with a low coefficient of diffusion in the solid solution promotes the appearance of Cottrell "atmospheres," inhibiting the movement of dislocations; b) the formation of dispersed particles of complex phases, having a favorable effect upon the origination of microheterogeneity within the grains of the solid solution and stable at working temperatures; c) strengthening of the grain boundaries by second phases which crystallize in a branched form. These considerations found confirmation in our examinations the result of which was the development of the ATsR2 alloy operating for a long time at temperatures up to 450°C.

APPENDIX 1

Effects of phase composition on the heat resistance of basic aluminum casting alloys

(1) Марка сплава	(2) Химический состав (остальное алюминий)	(3) Наиболее типичный фазовый состав сплавов (кроме α-твердого раствора)	(4) Характеристика α-твердого раствора в закаленном состоянии	(5) Степень взаимодействия вторых фаз с α-твердым раствором при температуре закалки	(6) Характеристика микроструктуры сплава	(7) σ_b при 20° С, кг/мм²	(8) Предел длительной прочности, кг/мм² за 100 час. при температуре, °С: 250	(8) 300
АЛ1	3,75—4,5% Cu, 1,25—1,75% Mg, 1,75—2,25% Ni	S (Al_2MgCu), T_{Ni} (Al_6Cu_3Ni)	(9) Сумма легирующих элементов (4%Cu + 1,5% Mg в отношении 2,61:1) создает устойчивый пересыщенный — α-твердый раствор	(10) Фаза S полностью реагирует с α-твердым раствором, тогда как фаза T_{Ni} лишь частично	(11) Вторые фазы кристаллизуются в виде эвтектических прослоек. Фаза T (Al_6Cu_3Ni) имеет разветвленную форму, препятствуя деформации зерна α-твердого раствора	25	7	5,5
АЛ2	10—13%	Si (Al_4Si_2Fe)**	(12) Малоустойчивый обедненный твердый раствор (с содержанием до 1,5% Si)	(13) Частицы кремния быстро сфероидизируются	(14) Модифицированная структура менее жаропрочна, чем немодифицированная	16—18	3,5—4	2,5—3*
АЛ3	4—5% Si, 1,5—3,5 % Cu 0,35—0,6% Mg, 0,6—0,8% Mn	(15) Si, Mg_2Si W ($Al_xMg_5Cu_4Si_4$) (при содержании Cu на верхнем пределе образуется фаза $CuAl_2$) AlSiMnFe	(16) Медь и магний в отношениях (2,65:1) образования фазы S создают более устойчивый α-твердый раствор	(17) Частицы кремния сфероидизируются, фазы W ($Al_xMg_5Cu_4Si_4$) и AlSiMnFe изменяются мало, тогда как фазы Mg_2Si, $CuAl_2$ реагируют полностью	(18) Структура более многофазна, чем в сплаве АЛ5	20—23*	5—6	3,5—4*

Key: 1--Alloy designation; 2--Chemical composition (remainder aluminum); 3--Most typical phase composition of alloys (besides α solid solution); 4--Characteristic of α solid solution in hardened state; 5--degree of reaction of second phases with α solid solution at hardening temperature; 6--Characteristic of alloy's microstructure; 7--σ_b at 20°C, kg/mm²; 8--rupture strength, kg/mm² for 100 hours at temperature, °C; 9--The sum of the alloying constituents (4% Cu + 1.5% Mg in ratio 2.61 : 1) creates a stable and supersaturated α solid solution; 10--The S phase completely reacts with the α solid solution whereas the T_{Ni} phase reacts only partially; 11--Second phases crystallize in the form of eutectic interlayers. The T(Al_6Cu_3Ni) phase has a branch form

Key to Appendix 1 (continued)

preventing deformation of the grain of the α solid solution; 12--Slightly stable and deficient solid solution (with a content of up to 1.5% Si); 13--Silicon particles sphereodize rapidly; 14--modified structure less heat resistant than the unmodified; 15--Si, Mg_2Si $W(Al_xMg_5Cu_4Si_4)$ (with copper content on upper limit the $CuAl_2$ phase is formed); 16--Copper and magnesium in ratios for formation of S phase (2.65 : 1) create a more stable α solid solution; 17--Silicon particles spherodize, the $W(Al_xMg_5Cu_4Si_4)$ and AlSiMnFe phases change only slightly whereas the Mg_2Si and $CuAl_2$ phases react completely; 18--Structure more multiphase than that in AL5 alloy;

Марка сплава	Химический состав (остальное алюминий)	Наиболее типичный фазовый состав сплавов (кроме α-твердого раствора)	Характеристика α-твердого раствора в закаленном состоянии	Степень взаимодействия вторых фаз с α-твердым раствором при температуре закалки	Характеристика микроструктуры сплава	σ_b при 20° С кг/мм²	Предел длительной прочности, кг/мм² за 100 час. при температуре, °С	
							250	300
АЛ4	8—10,5% Si 0,17— 0,3% Mg, 0,25— 0,5% Mn	Si, Mg_2Si, AlSiMnFe	(19) α-твердый раствор недостаточно устойчив	(20) Частицы кремния сфероидизируются; фаза Mg_2Si реагирует полностью; Фаза AlSiMnFe является весьма устойчивой	(21) Наличие марганцовистой фазы повышает жаропрочность сплава	24	4—5	2,8—3,0*
АЛ5	4,5 —5,5% Si, 1,0 —1,5% Cu, 0,35—0,6% Mg	Si, $CuAl_2$, W ($Al_xMg_5Cu_4Si_4$), AlSiFe	(22) α-твердый раствор легирован больше, чем в сплаве АЛ4	(23) Частицы кремния сфероидизируются, фаза $CuAl_2$ реагирует полностью, фаза W частично,	(24) Устойчивый α-твердый раствор и многофазность обусловливают более высокую жаропрочность сплава, чем у АЛ4	24	5*	3,5—4*
АЛ6	4,0—5,0% Si, 2—3% Cu	Si, $CuAl_2$, Al_7Cu_2Fe	(25) α-твердый раствор устойчивее, чем у сплава АЛ7	(26) Частицы кремния сфероидизируются; фаза $CuAl_2$ реагирует неполностью; фаза Al_7Cu_2Fe практически не изменяется	(27) Кроме двойной эвтектики α + Si содержит еще и тройную α + Si + $CuAl_2$	17	4,0	3,0

Key: 19--α solid solution insufficiently stable; 20--Silicon particles spheroidize; Mg_2Si phase reacts completely; AlSiMnFe phase is very stable; 21--presence of manganis phase increases alloy's heat resistance; 22--α solid solution is more alloyed than in AL4 alloy; 23--Silicon particles spheroidize; $CuAl_2$ phase reacts completely; W phase only partially; 24--Stable α solid solution and multiphasness promote a higher heat resistance in alloy than in the AL4; 25--α solid solution is more stable than in the AL7 alloy; 26--Silicon particles spheroidize; the $CuAl_2$phase reacts incompletely; Al_7Cu_2Fe phase practically unchanged; 27--in addition to binary eutectic α + Si a third phase α + Si + $CuAl_2$ is contained;

APPENDIX I (continued)

Марка сплава	Химический состав (остальное алюминий)	Наиболее типичный фазовый состав сплавов (кроме α-твердого раствора)	Характеристика α-твердого раствора в закаленном состоянии	Степень взаимодействия вторых фаз с α-твердым раствором при температуре закалки	Характеристика микроструктуры сплава	σ_b при 20° С кг/мм²	Предел длительной прочности, кг/мм² за 100 час. при температуре, °С	
							250	300
АЛ7	4—5% Cu, Si добавляется для литья в кокиль	$CuAl_2$, Si, Al_7Cu_2Fe	(29) α-твердый раствор достаточно легирован медью (до 5%) и устойчивее, чем у сплавов АЛ4 и АЛ5	(30) Фаза $CuAl_2$ полностью переходит в α-твердый раствор; фаза Al_7Cu_2Fe лишь частично, частицы Si сфероидизируются	(31) Границы зерна α-твердого раствора укреплены слабо, что понижает жаропрочность сплава	24	4,2	3,0
АЛ8	9,5—11,5% Mg	β (Al_3Mg_2), Mg_2Si, Al_3Fe	(32) Сильно пересыщенный α-твердый раствор обусловливает низкую жаропрочность сплава	(33) Частицы β (Al_3Mg_2) быстро коагулируют. В этом случае сплав имеет пониженную пластичность	(34) Границы зерна α-твердого раствора укреплены слабо	30—40	2,5	1,5
АЛ9	6—8% Si, 0,2—0,4% Mg	Si, Mg_2Si, Al_4Si_2Fe	(35) α-твердый раствор недостаточно устойчив	(36) Частицы кремния сфероидизируются. Фаза Mg_2Si полностью переходит в α-твердый раствор	(37) Частицы фазы Mg_2Si мелкие, трудно обнаруживаются даже при увеличении в 500 раз	20	4	2,5—3***

Key: 28--4-5% Cu, Si is added for casting in permanent mold; 29--α solid solution sufficiently alloyed with copper (up to 5%) and more stable than in AL4 and AL5 alloys; 30--$CuAl_2$ phase transforms completely into α solid solution; Al_7Cu_2Fe phase only partially; silicon particles spheroidize; 31--grain boundaries of α solid solution are weakly strengthened which lowers alloy's heat resistance; 32--strongly supersaturated α solid solution causes a low heat resistance in alloy; 33--β particles (Al_3Mg_2) coalesce rapidly. In this case alloy has a lowered ductility; 34--Grain boundaries of α solid solution are weakly strengthened; 35--α solid solution insufficiently stable; 36--Silicon particles spheroidized; Mg_2Si phase transforms completely into α solid solution; 37--Particles of Mg_2Si phase are very fine, they are difficult to observe even with a magnification of 500;

APPENDIX I (continued)

Марка сплава	Химический состав (остальное алюминий)	Наиболее типичный фазовый состав сплавов (кроме α-твердого раствора)	Характеристика α-твердого раствора в закаленном состоянии	Степень взаимодействия вторых фаз с α-твердым раствором при температуре закалки	Характеристика микроструктуры сплава	σ_b при 20° C $кг/мм^2$	Предел длительной прочности, $кг/мм^2$ за 100 час. при температуре, °C	
							250	300
АЛ13	4,5—5,5% Mg, 0,8—1,3% Si, 0,1—0,4% Mn	Mg_2Si, β (Al_3Mg_2), AlSiMnFe	(38) α-твердый раствор более устойчив, чем в сплаве АЛ8	(39) Фаза β (Al_3Mg_2) реагирует полностью, а фазы Mg_2Si и AlSiMnFe весьма устойчивы	(40) Структура достаточно гетерогенная	17	4—4,5	3,0
АЛ19	4,5—5,3% Cu, 0,6—1,0% Mn, 0,2—0,4% Ti	$CuAl_2$, T ($Al_{12}Mn_2Cu$)	(41) α-твердый раствор значительно устойчивее, чем в сплаве АЛ7	(42) Фаза $CuAl_2$ реагирует полностью, количество фазы T в закаленном состоянии больше, чем в литом состоянии	(43) Микрогетерогенность внутри зерен выражена сильнее, чем в других сплавах	36	12	6,5—7

Key: 38--α solid solution more stable than in AL8 alloy; 39--β phase (AL_3Mg_2) reacts completely and Mg_2Si and AlSiMnFe phases are very stable; 40--Structure sufficiently heterogeneous; 41--α solid solution is much more stable than in AL7 alloy; 42--$CuAl_2$ phase reacts completely, quantity of T phase in hardened state is greater than in cast state; 43--Microheterogeneity within the grains is expressed more intensively than in other alloys;

Марка сплава	Химический состав (остальное алюминий)	Наиболее типичный фазовый состав сплавов (кроме α-твердого раствора)	Характеристика α-твердого раствора в закаленном состоянии	Степень взаимодействия вторых фаз с α-твердым раствором при температуре закалки	Характеристика микроструктуры сплава	σ_b при 20° C кг/мм²	Предел длительной прочности, кг/мм² за 100 час. при температуре, °C	
							250	300
АЛ20	3,6 —4,5% Cu, 0,7 —1,2% Mg, 1,5 —2,0% Si, 1,3 —1,5% Fe, 0,05—0,1% Ti, 0,15—0,25% Cr, 0,15—0,25% Mn	(44) $S(Al_2CuMg)$; Al_3Ti; Mg_2Si $\pi(Al_8Si_6Mg_3Fe)$ или Al_5SiFe и фазы, содержащие Mn и Cr	(45) α-твердый раствор более устойчив, чем в сплавах типа силумин (АЛ2, АЛ3, АЛ4, АЛ5, АЛ9 и др.)	(46) Фазы S (Al_2CuMg) и Mg_2Si реагируют полностью, тогда как другие фазы устойчивы	(47) Зерна α-твердого раствора блокированы устойчивыми железосодержащими и другими фазами	21	8	6
АЛ21	4,5—6,0% Cu, 2,6—3,6% Ni, 0,1—0,25% Cr, 0,2—0,3% Mn	(48) $S(Al_2CuMg)$, $T(Al_6Cu_3Ni)$, $Al_3(CuNi)_2$ и фазы, содержащие Mn и Cr	(49) α-твердый раствор более устойчив, чем у всех остальных литейных алюминиевых сплавов	(50) Фаза $S(Al_2CuMn)$ полностью реагирует, тогда как остальные фазы практически не реагируют	(51) Зерна α-твердого раствора почти полностью блокированы устойчивыми фазами	22	10—12	7—8****

* Железосодержащие фазы образуются, когда сплавы содержат примесь железа: фаза Mg_2Si в сплавах типа АЛ8 образуется в том случае, когда имеется примесь кремния.

** Более низкое значение длительной прочности относится к модифицированным сплавам. При содержании Mn и Cu на верхнем пределе сплав АЛ3 обладает более высокими показателями.

*** Более высокое значение предела длительной прочности относится к сплаву, содержащему молибден.

Key: 44--$S(Al_2CuMg)$; Al_3Ti; Mg_2Si π $(Al_8Si_6Mg_5Fe)$ or Al_5SiFe and phases containing manganese and chromium; 45--α solid solution is more stable than in Silumin type alloys (AL2, AL3, AL4, AL5, AL9 and others); 46--The $S(Al_2CuMg)$ and Mg_2Si phases react completely while the other phases are stable; 47--Grains of α solid solution are blocked by stable iron bearing and other phases; 48--$S(Al_2CuMg)$, $T(Al_6Cu_3Ni)_2$ and phases containing Mn and Cr; 49--α solid solution is more stable than in all other aluminum casting alloys; 50--The $S(Al_2CuMn)$ phase reacts completely whereas the remaining phases practically do not react; 51--Grains of α solid solution are almost completely blocked by stable phases.

Footnotes for APPENDIX I

* Iron bearing phases are formed when the alloys contain an iron addition; the Mg_2Si phase is formed in the case when there is an addition of silicon.

** The lower value for the ultimate strength pertains to the modified alloys. With a maganese and copper content at the upper limit the AL3 alloy has higher indexes.

*** The higher values for the rupture strength pertain to an alloy containing molybdenum.

Typical mechanical properties of aluminum casting alloys as a function of heat treatment conditions at room and elevated temperatures

(1) Марка сплава	(2) Режим термической обработки	(3) Механические свойства при 20° С				(4) σ_b при кратковременном разрыве, кг/мм² при температуре, °С			(5) σ_{100° кг/мм², при температуре, °С			(6) Остаточная деформация 0.2% за 100 (час.) при температуре 300 °С $\sigma^{300^\circ}_{02/100^\circ}$ кг/мм²
		σ_b кг/мм²	$\sigma_{0,2}$ кг/мм²	δ, %	HB кг/мм²	200	250	300	200	250	300	
AL1	T5 T7	25,0 22,0	20,0 18,0	0,6 1,2	100 90	18,0 —	16,0 —	14,0 —	13,0 —	7,0 —	5,5 —	3,7 —
AL2	T2	16,0	9,0	5,0	50	15,0	13,0	8,0	7,0	4,0	2,8	1,2
AL3	T1 T2 T5 T7	20,0 18,0 24,0 21,0	17,0 14,0 18,0 —	1,0 1,5 0,8 1,0	70 65 75 70	— — 18,0 —	— — 15,0 —	— — 11,0 —	— — 9,0 —	— — 6,0 —	— — 3,75 —	— — 2,5 —
AL4	T1 T5 T6	18,0 22,0 24,0	14,0 17,0 18,0	2,0 4,0 3,6	65 70 75	— — 16,0	— — 14,0	— — 10,0	— — 8,0	— — 5,0	— — 2,8	— — 1,25
AL5	T1 T6 T7	18,0 24,0 20,0	15,0 18,0 —	— 0,8 1,5	65 75 70	— 18,0 —	— 15,0 —	— 10,0 —	— 9,0 —	— 5,5 —	— 3,5 —	— 2,4 —
AL6	T2	17,0	11,0	2,0	55	—	—	—	—	—	—	—
Al7	T4 T5	24,0 26,0	16,0 20,0	7,0 3,0	65 85	18,0 —	14,0 —	10,0 —	10,0 —	6,0 —	3,0 —	— —

Key: 1--Alloy designation; 2--Heat treatment conditions; 3--Mechanical properties at 20°C; 4--σ_b at temporary rupture, kg/mm² at temperature, °C; 5--σ_{100° kg/mm², at temperature, °C; 6--Permanent set 0.2% for 100 hours at temperature of 300°C, $\sigma^{300^\circ}_{02/100^\circ}$ kg/mm²; 7--[illegible], kg/mm²;

Марка сплава	Режим термической обработки	Механические свойства при 20° C				σ_b при кратковременном разрыве, $кг/мм^2$ при температуре, °C			$\sigma_{100°}$, $кг/мм^2$, при температуре °C			Остаточная деформация 0,2% за 100 (час.) при температуре 300°
		σ_b $кг/мм^2$	$\sigma_{0,2}$ $кг/мм^2$	δ, %	HB $кг/мм^2$	200	250	300	200	250	300	300° C $\sigma_{0,2/100°}^{300°}$ $кг/мм^2$
АЛ8	Т4	30,0	17,0	10,0	90	22,0	15,0	9,0	8,0	4,0	1,5	1,0
АЛ9	Т4 Т5	19,0 22,0	14,0 16,0	5,0 3,0	50 75	— 14,0	— 11,0	— 9,0	— 6,0	— 4,5	— 2,8	— 1,2
АЛ11	Т2	22,0	15,0	2,0	80	—	—	—	—	—	—	—
АЛ12	Т2	18,0	13,0	1,5	75	15,0	13,0	10,0	—	—	—	—
АЛ13	Т2	17,0	11,0	3,0	65	—	—	—	—	—	—	—
АЛ19	Т4 Т5	32,0 36,0	18,0 25,0	8,0 4,0	70 100	26,0 26,0	19,0 19,0	14,0 14,0	16,0 16,0	12,0 12,0	6,5 6,5	— 4,0
АЛ22	Т4	26,0	18,0	4,0	90	20,0	18,0	14,0	9,0	5,0	2,0	—
АЛ20	Т6 Т7	30,0 21,0	23,0 19,0	0,8 0,8	80 65	— 20,0	— 16,0	— 13,0	— 14,0	— 9,0	— 5,5	— 4,0
АЛ21	Т2 Т6 Т7	21,0 30,0 22,0	— 25,0 20,0	1,2 0,7 1,5	65 80 75	— — 21,0	— — 20,0	— — 16,0	— — 18,0	— — 12,0	— — 7,0—8,0	— — 5,0

APPENDIX 2 (continued)

Марка сплава	Режим термической обработки	Механические свойства при 20° C				σ_b при кратковременном разрыве. кг/мм² при температуре. °C			$\sigma_{100°}$, кг/мм² при температуре °C			Остаточная деформация 0.2% за 100 (час.) при температуре 300° C $\sigma^{300°}_{02/100°}$ кг/мм²
		σ_b кг/мм²	$\sigma_{0,2}$ кг/мм²	δ, %	HB кг/мм²	200	250	300	200	250	300	
8)ВАЛ-1	Т5	28,0	22,0	2,0	100	25,0	20,0	15,0	18,0	15,0	10,0	6,0
9)АЦР-1	Т1	22,0	16,0	1,5	75	19,0	18,0	17,0	17,0	15,0	11,0	6,0

(10)Примечания:

Key: 8--VAL-1; 9--ATsP-1; 10--Notes: 1) The presented data concerning the mechanical properties of aluminum casting alloys to attain to a nominal chemical composition of the above indicated alloys. An increase or decrease in the content of the basic alloying constituents participating in the phase transformations during heat treatment will cause a sharp change in the mechanical properties. For instance with a magnesium content at the upper limit in the AL3, AL4, AL5, and AL9 alloys it is possible to obtain the maximum values for the tensile strengths, the yield point and h limit at a minimum value for the relative elongation. When the magnesium content is at the lower limit maximum ductility at minimum strength is assured in the above indicated alloys. A change in strength can attain 30% and a change in ductility can attain 100% in comparison with the data for a nominal composition. 2) In the modified state all alloys of the Silumin type (AL2, AL4 and AL9) have a rupture strength of 10-20% lower than in the unmodified. 3) If the AL21 alloy contains molybdenum it will then have a rupture strength of not less than 8 kg/mm² and a temperature of 300°C for 100 hours. 4) When it is necessary to obtain the strength characteristics of the alloys which are different from those indicated in Appendix 2 the cooling rate during the hardening should be changed by the application of various media (water, oil, salt solution and others) or various artificial aging regimes or by varying the heating temperature and duration of holding. 5) The testings at elevated temperatures were carried out by the generally accepted methods, viz: a) short time tensile tests were carried out on test specimens of 12 mm diameter after heating for 30 minutes at the test temperature; b) the ultimate strength was determined on 10 mm diameter test specimens by tension under fixed temperatures for 100 hours without failure; c) the creep limit was determined on individually cast test specimens at a 300°C temperature with a 0.2% plastic permanent set for 100 hours. The data for the creep limit pertain to permanent set. 6) Isothermal hardening is recommended for increasing the AL21 alloy's plasticity (the temperature for heating to below hardening is the same) in saltpeter heated to 250°C with holding of the castings for 5 hours.

Engineering properties and areas of application of heat resistant aluminum casting alloys

(1) Сплавы	(2) Температура, °С: (3) плавления	(4) литья	(5) Линейная усадка, %	(6) Жидкотекучесть при 700° С (прутковая проба), мм	(7) Склонность к образованию горячих трещин (ширина кольца) мм	(8) Герметичность	(9) Свариваемость	(10) Обрабатываемость резанием	(11) Склонность к газонасыщению	(12) Коррозионная стойкость и защита деталей от коррозии	(13) Рекомендуемые области длительного применения сплавов
AL1	535	740	1,35	260	27,5	(14a) Пониженная	(22a) Удовлетворительная	(29) Хорошая	(40) Средняя	(48) Пониженная	(55) Поршни
AL3	530	750	1,15	340	13	Средняя (14b)	То же (22b)	(30) Удовлетворительная	»	(49) Выше, чем у сплава АЛ1	(56) Головки цилиндров и другие детали, от которых требуется повышенная герметичность и достаточная прочность до 275° С
AL4	570	730	1,0	359	Не имеет	(15) Хорошая	(23) Хорошая	(31) Пониженная	(41) Высокая	(50) Повышенная	То же. для работы деталей до температуры 225° С (57)
AL5	535	730	1,1	344	10	(16) Средняя	(24) Удовлетворительная	(32) Удовлетворительная	(42) Средняя	Выше, чем у сплава АЛ1 (51)	То же. для работы деталей до температуры 250° С (58)
AL10V	525	700	1,15	355	12	»	То же (25)	Повышенная (33)	(43) Высокая	Пониженная (52)	Поршни для двигателей мощностью ниже 100 л. с. (59)
ZhLS1	540	700	1,1	360	5	(17) Высокая	Хорошая (26)	Пониженная (34)	»	(53) Повышенная	Поршни и головки цилиндров, работающих до температуры 275° С (60)
VKZhLS	660	800	1,1	350	7,5	» 18	»	Низкая 35	» (44)	»	То же (61)
AL19	548	750	1,25	205	32	Пониженная	»	Хорошая 36	Пониженная	Пониженная (54)	Высоконагруженные детали (62)
AL20	525	730	1,1	320	17	Средняя (19)	(27) Удовлетворительная	Удовлетворительная 37	Средняя (45)	»	Для деталей, работающих до температуры 275° С, от которых требуется повышенная герметичность (63)
AL21	540	750	1,2	300	22	(20) Повышенная	Хорошая (28)	Хорошая (38)	(46) Пониженная	»	Поршни и детали, работающие при температурах до 325° С (64)
VAL1	540	750	1,25	330	30	(21) Высокая	»	»	Малая (47)	»	Поршни и детали, работающие при температурах до 350° С (65)
AT3R1	603	750	1,2	360	Не имеет	»	»	(39) Удовлетворительная	Средняя	»	Для герметичных деталей, работающих при температурах до 400° С (66)

(67) Примечание. При литье трубообразных крупных деталей линейная усадка может быть 2—2.5%.

Key to APPENDIX 5

1--Alloys; 2--Temperature °C; 3--Melting; 4--Casting; 5--Shrinkage, %; 6--Flowability at 700°C (bar test) mm; 7--hot crack formation tendency (band width) mm.
10--Machineability; 11--Gas saturation tendency; 12--Corrosion resistence and protection of part against corrosion; 13--Recommended areas of prolonged use of alloys; 14a--Reduced; 14b--average; 15--Good; 16--Average; 17--High; 18--Reduced; 19--Average; 20--Increased; 21--High; 22a--Satisfactory; 22b--The same; 23--Good; 24--Satisfactory; 25--Satisfactory; 26--Good; 27--Satisfactory; 28--Good; 29--Good; 30--Satisfactory; 31--Reduced; 32--Satisfactory; 33--Raised; 34--Reduced; 35--Low; 36--Good; 37--Satisfactory; 38--Good; 39--Satisfactory; 40--Average; 41--High; 42--Average; 43--High; 44--Reduced; 45--Average; 46--Very low; 47--Average; 48--Reduced; 49--Higher than in AL1 alloy; 50--Increased; 51--Higher than in AL1 alloy; 52--Reduced; 53--Raised; 54--Reduced; 55--Pistons; 56--Cylinder heads and other components from which an augmented airtightness and sufficient strength up to 275°C is required; 57--The same for the operation of the parts up to a temperature of 225°C; 58--The same for the operation of the parts to a temperature of 250°C; 59--Pistons for engines with a horsepower below 100; 60--Pistons and cylinder heads operating up to temperatures of 275°C; 61--The same; 62--Heavily loaded parts; 63--For parts operating up to 275°C requiring an augmented airtightness; 64--Pistons and parts operating at temperatures up to 325°C; 65--Pistons and parts operating at temperatures up to 350°C; 66--For airtight components operating at temperatures up to 400°C; 67--Note. The shrinkage can be 2-2.5% during the casting of tubular shaped big parts.

APPENDIX 6

Physical properties of aluminum casting alloys

(1) Сплавы	(2) Плотность $г/см^3$	(3) Коэффициент термического расширения, α	(4) Теплопроводность λ кал/см·сек, °C	(5) Электросопротивление, ρ, $см \cdot мм^2/м$
AL1	2,75	$22{,}3 \cdot 10^{-6}$ (20—100° C) $24 \cdot 4 \cdot 10^{-6}$ (20—300° C)	0,31 (25° C) 0,37 (300° C)	0,0528 (20° C)
AL3	2,7	$22 \cdot 10^{-6}$ (20—100° C) $24 \cdot 10^{-6}$ (20—300° C)	0,39 (25° C) 0,38 (300° C)	0,0449 (20° C)
AL5	2,68	$23{,}1 \cdot 10^{-6}$ (20—100° C) $24 \cdot 10^{-6}$ (20—300° C)	0,38 (25° C) 0,42 (300° C)	0,0462 (20° C)
AL9	2,78	$19{,}5 \cdot 10^{-6}$ (20—100° C) $25{,}6 \cdot 10^{-6}$ (20—300° C)	0,25 (25° C) 0,34 (300° C)	0,0595 (20° C)
AL20	2,74	$18{,}1 \cdot 10^{-6}$ (20—100° C) $23{,}6 \cdot 10^{-6}$ (20—300° C)	0,31 (30° C) 0,35 (300° C)	0,0518 (20° C)
AL21	2,83	$22{,}9 \cdot 10^{-6}$ (20—100° C) $27{,}8 \cdot 10^{-6}$ (20—300° C)	0,27 (30° C) 0,3 (300° C)	0,0572 (20° C)
VAL1	2,89	$23{,}8 \cdot 10^{-6}$ (20—100° C) $28{,}7 \cdot 10^{-6}$ (20—300° C)	0,32 (100° C) 0,37 (300° C)	0,0545 (20° C)
ATsR1	2,8	$23{,}6 \cdot 10^{-6}$ (20—100° C) $26{,}7 \cdot 10^{-6}$ (20—300° C)	0,23 (25° C) 0,27 (300° C)	0,053 (20° C)
AL10V	2,78	$22{,}3 \cdot 10^{-6}$ (20—100° C) $24{,}4 \cdot 10^{-6}$ (20—300° C)	0,40 (25° C) 0,42 (300° C)	0,046 (25° C)
AL21	2,72	$19 \cdot 10^{-6}$ (20—100° C) $20{,}5 \cdot 10^{-6}$ (20—300° C)	0,38 (25° C) 0,38 (300° C)	0,050 (25° C)
AL26	2,68	$17{,}0 \cdot 10^{-6}$ (20—100° C) $19{,}0 \cdot 10^{-6}$ (20—300° C)	0,40 (25° C) 0,42 (300° C)	0,058 (025° C)

(6) Примечание. В скобках дана температура или интервал температур, в котором определено это свойство.

Key: 1--Alloys; 2--Density g/cm^2; 3--Coefficient of thermal expansion; α; 4--Thermal conductivity λ cal/cm·sec, °C; 5--Electrical resistance, ρ, $cm \cdot mm^2/m$; 6--Note. The parentheses contain temperature or the temperature interval in which this property was determined.

Hardness of binary aluminum alloys at temperature of 300°C as a function of their composition, state (load of 100 kg, ball diameter 10 mm) and heat treatment condition

(1) Система сплавов	(2) Состояние сплавов	(3) Выдержка	(4) Твердость, *HB*, $кг/мм^2$ при содержании второго компонента, %												
			0,5	1	2	3	4	5	6	7	8	9	10	11	12
Al—Cu	(5) Литой	30 сек. 60 мин.	— —	8,5 6,7	— —	13,6 8,77	— —	27,1 19,9	— —	30,0 20,5	31,2 21,5	— —	32,1 22,3	— —	— —
	(6) Литой после стабилизации (300—100 час.)	30 сек. 60 мин.	— —	3,2 2,5	6,99 5,95	8,5 6,7	9,66 7,9	13,0 7,2	12,1 7,9	— —	13,5 8,65	— —	15,9 10,9	— —	— —
	(7) Закаленный и естественно состаренный (10 дней)	30 сек. 60 мин.	— —	7,71 3,77	8,63 6,09	10,0 8,4	11,9 9,0	24,8 13,7	24,1 14,4	— —	23,3 14,0	— —	22,0 14,1	— —	— —
	(8) Закаленный отпущенный (300°C—5 час.)	30 сек. 60 мин.	— —	8,3 5,1	— —	20,5 14,5	25,5 16,2	33,2 18,4	32,0 19,5	31,8 21,6	31,5 20,7	— —	31,3 21,1	— —	— —
	(9) Закаленный и стабилизированный (300° C, 100 час.)	30 сек. 60 мин.	— —	6,62 3,56	8,44 6,62	— —	9,44 6,75	13,2 7,02	13,6 8,68	— —	14,4 8,87	— —	15,7 8,97	— —	— —
	Литой (10)	30 сек. 60 мин.	— —	— —	— —	24,2 11,5	— —	37,7 15,7	— —	39,0 16,0	— —	— —	42,6 14,2	— —	41,0 13,6
	(11) Литой и стабилизированный (300° C, 100 час.)	30 сек. 60 мин.	— —	— —	— —	— —	15,9 7,8	— —	19,2 7,9	— —	23,8 8,0	— —	2,4 7,9	— —	24,4 7,79
	(12) Закаленный и естественно состаренный (10 дней)	30 сек. 60 мин.	— —	— —	— —	— —	17,4 7,39	— —	22,9 8,53	— —	28,0 8,81	— —	30 8,3	— —	25,7 8,21
	(13) Закаленный и отпущенный (300° C, 5 час.)	30 сек. 60 мин.	— —	— —	— —	24,6 14,7	— —	32,8 10,7	— —	— —	— —	— —	40,8 13,5	— —	36,1 12,9

Key: 1--Alloy system; 2--State of alloys; 3--Holding time; 4--Brinnell, kg/mm^2 at content of second component, %; 5--Cast; 6--Cast after stabilization (300-100 hours); 7--Hardened and naturally aged (10 days); 8--Hardened and annealed (300°C - 5 hours); 9--Hardened and stabilized (300°C, 100 hours); 10--Cast; 11--Cast and stabilized (300°C, 100 hours); 12--Hardened and naturally aged (10 days); 13--Hardened and annealed (300°C, 5 hours)

Система сплавов	Состояние сплавов	Выдержка	Твердость, *HB*, *кг/мм²* 0,5	1	2	3	4	5	6	7	8	9	10	11	12
Al—Mg	(14) Закаленный и стабилизированный (300° C, 100 час.)	30 сек. 60 мин.	— —	— —	— —	— —	15,7 7,75	— —	20,0 8,53	— —	23,0 8,53	— —	2,4 9,5	— —	26,0 8,63
Al—Zn	Литой (15)	30 сек. 60 мин.	— —	— —	— —	9,23 4,92	— —	— —	9,27 6,71	— —	— —	9,33 6,80	— —	— —	9,77 6,92
	(16) Литой и стабилизированный (300° C, 100 час.)	30 сек. 60 мин.	— —	— —	— —	4,7 2,0	5,05 2,0	— —	— —	— —	5,28 2,37	— —	— —	— —	5,9 2,0
	(17) Закаленный и естественно состаренный (160 дней)	30 сек. 60 мин.	— —	— —	— —	1,2 2,8	15,5 2,96	— —	— —	— —	15,27 3,32	— —	— —	— —	16,37 3,43
	(18) Закаленный и отпущенный (300° C, 5 час.)	30 сек. 60 мин.	— —	— —	— —	9,95 7,43	— —	— —	8,0 4,88	— —	— —	10,6 4,65	— —	— —	11,9 —
	(19) Закаленный и стабилизированный (300° C 100 час.)	30 сек. 60 мин.	— —	— —	— —	— —	5,0 2,0	— —	— —	— —	5,2 2,4	— —	— —	— —	5,5 2,6
Al—Si	(20) Литой и стабилизированный (300° C, 100 час.)	30 сек. 60 мин.	— —	7,36 5,05	9,07 7,58	— —	10,0 7,3	— —	10,2 8,4	— —	10,5 9,8	— —	10,9 9,55	— —	11,4 10,5
	(21) Закаленный и естественно состаренный (10 дней)	30 сек. 60 мин.	 —	9,39 6,24	9,39 6,92	— —	10,1 7,5	 —	10,3 8,2	 —	10,6 10,4	 —	11,0 10,4	 —	12,5 10,5
	(22) Закаленный и естественно состаренный (10 дней)	30 сек. 60 мин.	— —	9,39 6,24	9,39 6,92	— —	10,1 7,5	— —	— —	— —	11,2 10,4	— —	10,4 9,7	— —	— —
	(23) Закаленный и отпущенный (300° C, 5 час.)	30 сек. 60 мин.	— —	8,2 5,1	9,5 6,0	— —	10,0 7,8	— —	10,5 8,0	— —	11 10	— —	10,1 9,7	— —	10 9,8

Key: 14--Hardened and stabilized (300°C, 100 hours); 15--Cast; 16--Cast and stabilized (300°C, 100 hours); 17--Hardened and naturally aged (160 days); 18--Hardened and annealed (300°C, 5 hours); 19--Hardened and stabilized (300°C, 100 hours); 20--Cast and stabilized (300°C, 100 hours); 21--Hardened and naturally aged (10 days); 22--Hardened and naturally aged (10 days); 23--Hardened and annealed (300°C, 5 hours);

Система сплавов	Состояние сплавов	Выдержка	Твердость, *HB*, кг/мм²												
			0,5	1	2	3	4	5	6	7	8	9	10	11	12
	(24) Закаленный и стабилизированный (300° С, 100 час.)	30 сек.	6,3	7,0	9,61	—	10	—	10	—	10	—	10,2	—	10
		60 мин.	4,8	5,2	6,58	—	7	—	7,4	—	8,7	—	9,6	—	9,5
Al—Ni	(25) Литой	30 сек.	—	12,0	13,2	14,4	13,9	—	—	17,5	—	—	—	—	—
		60 мин.	—	8,1	8,5	9,17	9,77	—	—	10,7	—	—	—	—	—
	(26) Литой и стабилизированный (300° С, 100 час.)	30 сек.	—	11,46	11,5	—	—	—	—	—	—	—	—	—	—
		60 мин.	—	9,08	10,48	—	—	—	—	—	—	—	—	—	—
	(27) Закаленный и естественно состаренный (10 дней)	30 сек.	9,0	10	10,4	—	—	—	—	—	—	—	—	—	—
		60 мин.	5,83	8	8,26	—	—	—	—	—	—	—	—	—	—
	(28) Закаленный и состаренный (300° С, 100 час.)	30 сек.	—	9,71	8,80	—	—	—	—	—	—	—	—	—	—
		60 мин.	—	6,83	6,28	—	—	—	—	—	—	—	—	—	—
Al—Mn	(29) Литой	30 сек.	—	13,3	20,2	21,5	—	—	—	—	—	—	—	—	—
		60 мин.	—	12,2	17,0	18,4	—	—	—	—	—	—	—	—	—
	(30) Литой и стабилизированный (300° С, 100 час.)	30 сек.	13,1	14,5	16	—	—	—	—	—	—	—	—	—	—
		60 мин.	9,7	10,5	12	—	—	—	—	—	—	—	—	—	—

Key: 24--Hardened and stabilized (300°C, 100 hours); 25--Cast; 26--Cast and stabilized (300°C, 100 hours); 27--Hardened and naturally aged (10 days); 28--Hardened and aged (300°C, 100 hours); 29--Cast; 30--Cast and stabilized (300°C, 100 hours)

Система сплавов	Состояние сплавов	Выдержка	Твердость, *HB*, *кг/мм²*												
			0,5	1	2	3	4	5	6	7	8	9	10	11	12
Al—Mn	(31) Закаленный и естественно состаренный (10 дней)	30 сек. 60 мин.	13,9 9,04	12,53 10,7	15,9 11,56	— —	— —	— —	— —	— —	— —	— —	— —	— —	— —
	(32) Закаленный и отпущенный (300° C, 5 час.)	30 сек. 60 мин.	— —	13,5 12,4	16,2 13,5	18,4 14,2	— —	— —	— —	— —	— —	— —	— —	— —	— —
Al—Fe	(33) Закаленный и стабилизированный (300° C, 100 час.)	30 сек. 60 мин.	12,8 9,98	13 10,4	15,55 12,25	— —	— —	— —	— —	— —	— —	— —	— —	— —	— —
	(34) Литой и стабилизированный (300° C, 100 час.)	30 сек. 60 мин.	9,98 6,11	10,24 8,5	10,9 8,05	— —	— —	— —	— —	— —	— —	— —	— —	— —	— —
	(35) Закаленный и естественно состаренный (10 дней)	30 сек. 60 мин.	9,11 6,65	10,5 8,40	11,9 8,33	— —	— —	— —	— —	— —	— —	— —	— —	—	— —
	(36) Закаленный и состаренный (300° 5 100 час.)	30 сек. 60 мин.	9,41 6,11	10,24 8,55	11,9 8,65	— —	— —	— —	— —	— —	— —	— —	— —	— —	— —

Key: 31--Hardened and naturally aged (10 days); 32--Hardened and annealed (300°C, 5 hours); 33--Hardened and stabilized (300°C, 100 hours); 34--Cast and stabilized (300°C, 100 hours); 35--Hardened and naturally aged (10 days); 36--Hardened and aged (300°C, 100 hours).

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