

Working capacity of aluminum alloys in structure elements

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Abstract. Mechanical properties of specimens were researched for model analysis of stress-strain behavior in the stress concentration zone for plate structures using aluminum alloys. Traditional and new structure materials including Russian (1915T and 1565ch) and foreign (6082 – Russian analogue AD35) developments with different alloyage systems (Al-Mg, Al-Mg-Si and Al-Zn-Mg accordingly), strengthening methods, corrosive resistances and welding capacities are studied. Strain and fracture resistance is shown for axial and eccentric tension and for impact bending in the temperature range from -70 to +20°C. Acquired results allow us to designate loads reasonably for structure design using aluminum alloys and estimate their durability.

1. Introduction

Working capacity of structure element is its capacity to resist limit states which bounds structure's normal service. Rational choice of material, design and manufacturing technology and permissible defect limits aim to assure strain resistance, crack formation and growth resistance which excludes the possibility for a crack to grow up to critical size during expected service life of structure [1].

The fact that aluminum alloys have higher specific strength and corrosion resistance than carbon and low-alloy steel is stated in Russian design codes (SP) [2]. Design codes have recommendations for choice of aluminum alloy grades both strengthened by heat treatment and not with design resistance from 25 to 195 N/mm². Having equal mass they have three times higher specific stiffness than steel, so aluminum alloys use allow to achieve dramatic decline in structure mass. Comparing structure strength according to SP limited by tension tests results at +20°C (σ_v , σ_{02} , δ) shows that strengthened by heat treatment alloy 1915T (alloyage system Al-Zn-Mg) has the highest design resistance. For alloy grades AVM and AVT1 design strength is 70 and 170 N/mm² depending on supply condition among strengthened by heat treatment alloyage system Al-Mg-Si with good performance properties which are mostly used in building structures. However, alloy 6082 has the highest strength in this alloyage system based on data from [3, 4].

Design resistance level for not strengthened by heat treatment Al-Mg alloys recommended by SP doesn't exceed 140 N/mm². Products from aluminum alloys in addition to high processability (can be processed by cutting and pressure, can be welded

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with any type of weld) have high remaining value and can be easily utilized [2, 4]. Comparison of technical and economical indices for reservoirs from steel and aluminum alloy AMg-6M of the same structure which is done in work [5] showed that aluminum alloys structure have advantages in decreasing of metal consumption by 32%, transportation costs by 8% and service costs for anticorrosion protection and major repairs. Strength and welding capacity of load-bearing structures from light alloys increases with the progress in semi-finished products manufacturing. It is shown in [4] that frame made from pressed profile from aluminum alloys Al-Zn-Mg or Al-Mg-Si and sheeting made from Al-Mg sheets were used for wagons on the starting manufacturing stage. It allowed to lower the mass of wagon by 30%. Labour inputs and mass decreased further when using new series of hollow pressed panels from Al-Mg-Si.

Option for replacement of traditional alloys for new ones in aviation and transport engineering are shown in contemporary reference literature [4]. Not strengthened by heat treatment alloy 1565ch (alloyage system Al-Mg) recently developed and incorporated in Russia by ALCOA is recommended for welded structures [6]. Rolled sheet and plates, pressed and forged semi-finished products made from this alloy can be used as a structure materials for welded structures and composite armor [7].

Thus market presentation of structure material from new alloys and semi-finished products leads to necessity of all-round research of its properties, strain and fracture mechanisms which will allow to transform structures considering acquired characteristics that were design for steel or by recommendation of SNiP 2.03.06.85.

The purpose of this work is to research strength, viscosity and plasticity properties of light aluminum alloys from alloyage systems which can be used as structure materials for building in order to prove loads and conditions of service for designed structures.

2. Methods and materials

Chemical composition of researched manufactured aluminum based alloys is shown in table 1.

Table 1. Element content in researched alloys

Alloy, regulatory document	Element content, % mass								
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr	Al
1565ch, TU1-3210- 2013	0,2	0,3	0,01- 0,20	0,4-1,2	5,1-6,2	0,25	0,45- 1,2	0,2	Rest
6082, DIN EN 573-3: 2009	0.7 - 1.3	<0.5	<0.1	0.4 – 1,0	0.6 – 1,2	<0.25	<0.2	<0,05	Rest
1915T, GOST 4784-97	<0.35	<0.4	<0.1	0.2 - 0.7	1 - 1.8	0.06 - 0.2	4-5	0,08 - 0.2	Rest

Specimen tests for axial tension and properties calculation were done according to GOST 1497-84 [8] with the help of testing equipment Instron 8802 and Instron 1000HDX. Strain diagrams were recorded with the help of extensometer with a base of 20 mm. Specimens in the form of two-sided spatula with a working size part 200x30x9/10/12 (depending on the alloy) were cut from plain half-finished products.

Properties of static crack resistance for alloys were acquired at different temperatures (-70, -40, 0, +20°C) with the help of testing equipment Instron 8802. Specimens with a size of

80x80x10 mm with an edge crack were tested for eccentric tension according to GOST 25.506-85 [9].

Tests for impact viscosity were done using specimens with V-shaped and U-shaped cut at different temperatures (-60, -40, 0, +20°C) with the help of impact pendulum according to GOST 9454-78 [10].

3. Results and analysis

Stress-strain diagrams for tension tests at room temperature with constant strain speed for different alloys are shown on fig. 1-4. The diagrams are shown in double coordinates: the upper curve is «Load-strain», the lower curve is «stress-strain».

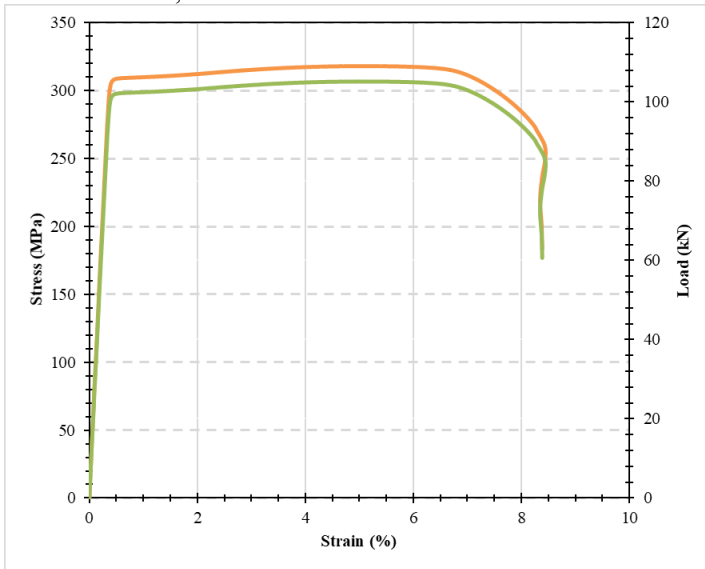


Fig. 1. Tension diagram for alloy 6082

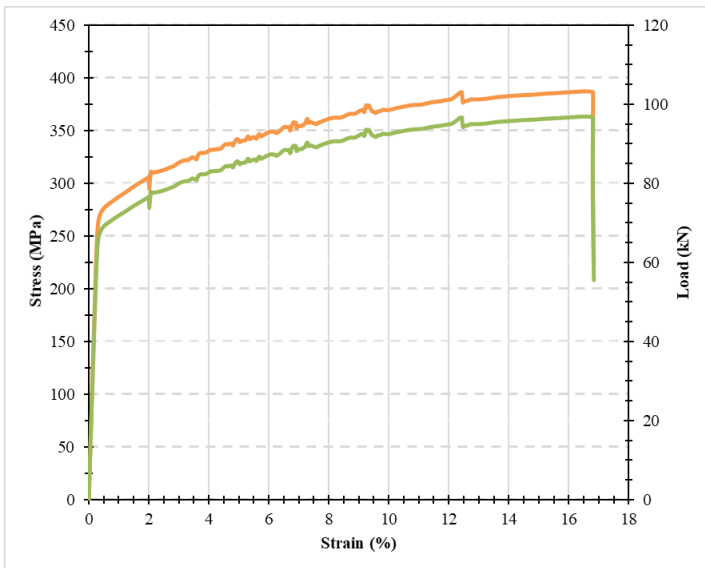


Fig. 2. Tension diagram for alloy 1915T

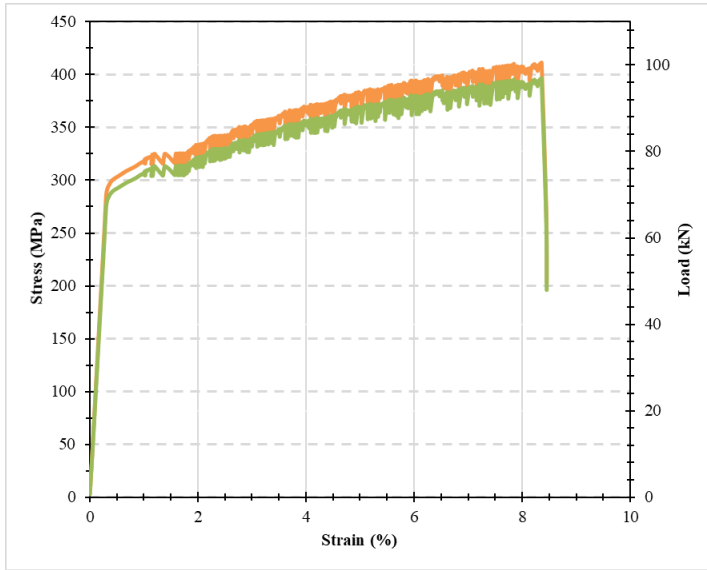


Fig. 3. Tension diagram for alloy 1565ch

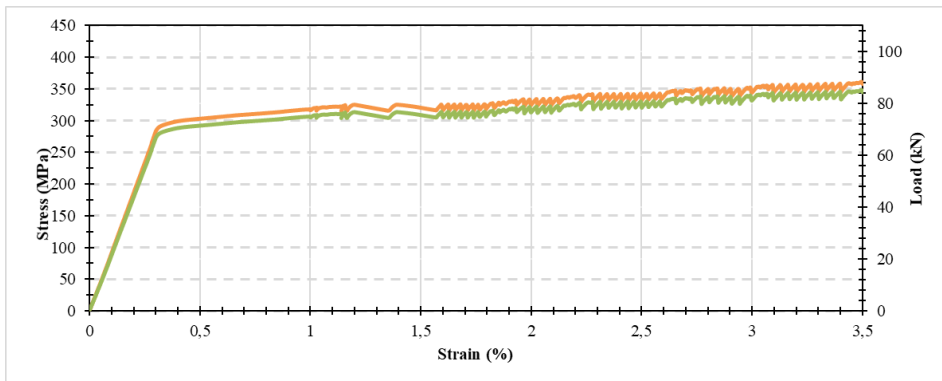


Fig. 4. Tension diagram for alloy 1565ch

Mechanical properties acquired in the axial tension tests according to GOST 1497-84 are shown in table 2.

Table 2. Mechanical properties of aluminum alloys

Alloy	Elastic limit, σ_{pc}	Yield stress, σ_{02}	Tensile strength, σ_v	Modulus of elasticity, E	Elongation at fracture, δ	Reduction of cross-section area, ψ
	MPa				%	
1915T	240	255	360	78 000	10	28
6082	280	293	302	78 000	10	48
1565ch	280	288	397	78 000	11	14

Fast neck growth during tension is indicative for all alloyage systems. It is established that specimens from alloy 6082 strained uniformly (fig. 1). Load spikes («tooth») can be seen on experimental curves for specimens from alloys 1915T and 1565ch. Intermittent strain appeared right after stress reached yield level and was distinguished by low-frequency (fig. 2) and high-frequency (fig. 3-4) jerky flow.

Such oscillations on metal tension tests diagrams in literature [11, 12] are called Portevin-Le Chatelier effect (PLE) if the strain speed is constant and Savar-Masson effect (SM) if the load increase speed is constant. The appearance of these effects depends on material composition and structure [13, 14]. It is assumed that intermittent strain PLE occurs due to negative speed sensibility of flow stress and strain speed which can be related to dynamic strain dislocation aging [12]. Stability loss in stain behavior during SM effect is connected with elimination of Guignet-Preston zones (GP) and secondary phase particles in aluminum alloys. GP zones dissipation causes the transition from step-type to plain load curves. It was stated during research of alloyage system Al-Mg (AMg6, AMg3) [14] that for alloy AMg3 (Si content is 0,48%) the load curve is plain without macroscopic spikes while with decrease in Si content down to 0,05 – the curve is step-like. Authors assume that factors blocking grain borders (accumulation of Si particle on borders, Mg₂Si and Al₃Mg₂) suppress macroscopic spikes in case of SM effect. Typical plain load curve was acquired for cold-rolled sheet of alloy AMg6 while after heat treatment at 450°C the curve changed to step-like one typical for PLE. Variation in heat treatment regime for alloy AMg6 near the solvus temperature (275°C) leads to dissolving of β-phase (Al₃Mg₂) and causes the change from plain to step-like load curve. It is established that alloys prone to step-like curves have lower corrosion resistance [15].

Properties of researched aluminum alloys compared to properties stated in regulatory documents are shown in table 3. Having the same modulus of elasticity specimens differed by engineering characteristics: specimens from alloy 6082 showed higher resistance to plastic deformation, all 8 specimens from alloy 1565ch showed higher tensile strength but reduction of cross-section area for them was 2-3 times lower than for other specimens.

Table 3. Comparison of acquired properties (numerator) and properties stated in regulatory documents (denominator)

Alloy, regulatory document	Alloyage system	Supply conditions	Thickness, mm	Mechanical properties			
				σ_v , MPa	$\sigma_{0.2}$, MPa	$\sigma_v/\sigma_{0.2}$	δ , %
1565ch, TU 1-2-466-2014	Al-Mg	Sheet	10	335/397	175/288	0,52/0,72	15/11
1565ch, TU1-3210-2013, TU1-2-668-2016		Plate without heat treatment	11	335/397	175/288	0,52/0,72	15/11
1915T, GOST 21631-76	Al-Zn-Mg	Sheet, hardening, natural aging for 30 days	10	315/360	195/255	0,62/0,70	10/10
1915T, GOST 21631-76		Sheet, hardening, natural aging for 3 days	10	315/360	195/255	0,62/0,70	10/10
6082 T1, DIN EN 573-3: 2009	Al-Mg-Si	Plate, hardening, artificial aging for 30 days	12	290-310/302	250-260/293	0,86-0,84/0,72	10/10

Comparing the test and reference data (table 3) shows that all tested half-finished products fractured at higher stress. Plasticity corresponds with regulatory documents for strengthened by heat treatment alloys 6082 T1 and 1915T and did not exceed regulative indexes for alloy 1565ch not strengthened by heat treatment.

Working capacity of half-finished products in the temperature range from -70°C to +20°C was estimated by fracture mechanics criteria on specimens type III with a cut and crack according to GOST 25.506-85 [9]. Calculation of strain and fracture resistance criteria was

done based on acquired diagrams «load-displacement» which are shown on figure 4 and formulae for type III specimens according to [9].

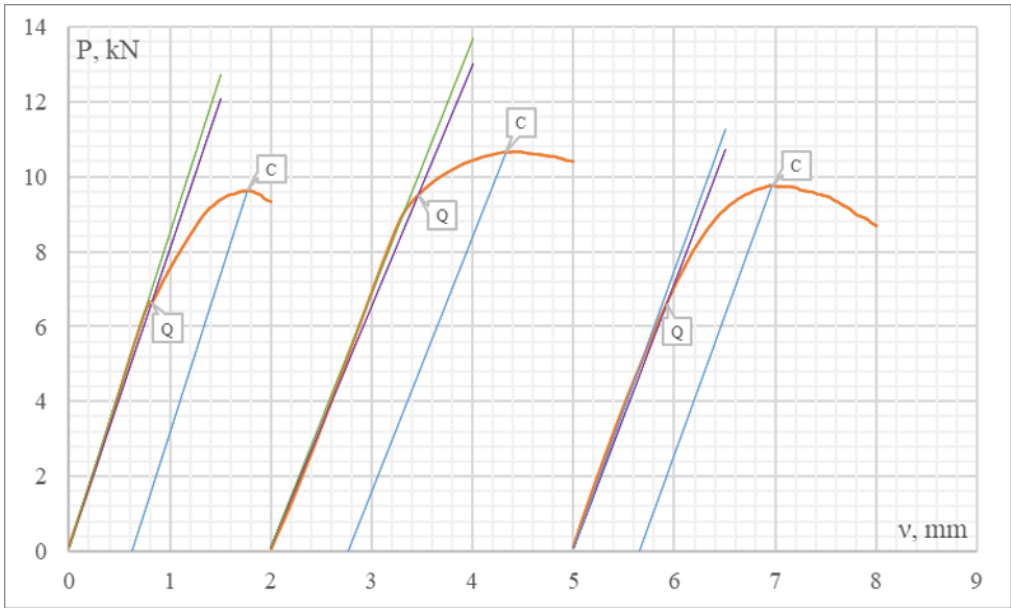


Fig. 4. Diagrams «Load-displacement» at -70°C for aluminum alloys: 1 – 6082; 2 – 1915T; 3 – 1565ch.

Unstable crack growth at -70°C during the test of strengthened by heat treatment alloy 1915T (alloyage system Al-Zn-Mg) started at load $P_Q=9,6$ kN which is one third higher than for alloyage systems Al-Mg-Si and Al-Mg specimens ($P_Q=6,5-6,6$ kN). Critical loads P_C and displacement of crack edges v_C had the same alloy dependency. Strain criterion for material crack resistance δ_C which showed the value of crack proceeding in the direction of specimen thickness increased with the increase in v_C (table 3).

Table 3. Strain and energy properties of aluminum alloys during eccentric tension tests

Alloy	a, mm	Crack resistance criteria at T, °C				Temperature of minimal criterion T, °C
		+20	0	-40	-70	
		Energy criterion J_C , kJ/m ²				
1915T	10	-	17,73	-	30,16	0
6082T1	12	19,11	13,86	21,59	19,8	0
1565ch	9	28,27	23,17	23,68	26,52	0
Strain criterion δ_C , m · 10 ⁴						
1915T	10	-	1,50	-	1,25	0
6082T1	12	0,75	0,93	0,73	0,79	-40
1565ch	9	1,64	1,48	1,39	0,9	-70

The deformation criterion decreased for all alloys with the decrease in temperature but in a greater degree for alloy 1565ch. Blunting of crack peak according to values of plastic constituent of edge opening δ_0 is higher for alloy 1915T than for alloys 1565ch and 6082. Calculated edge opening (10^{-12} m) are lower than parameter of elementary lattice for aluminum. Areas of transition from viscous condition to fragile are not identified in this temperature range. All alloys show stable level of fracture viscosity J_C with the decrease in temperature with the minimum fracture viscosity showing at 0°C .

Working capacity of researched alloys in the condition of dynamic loading with impact bending was found out by the results of series of tests for specimens with a cut. Figure 5 shows experimental dependencies for impact viscosity KCV (J/cm^2) from test temperature ($-60, -40, 0$ and $+20^\circ\text{C}$) for steel and aluminium alloys. The higher values of viscosity were received for specimens with U-shaped cut. At the lowest temperature (-60°C) KCU was 48,3 and $30,0 \text{ J}/\text{cm}^2$ for alloys 1915T and 1565ch accordingly.

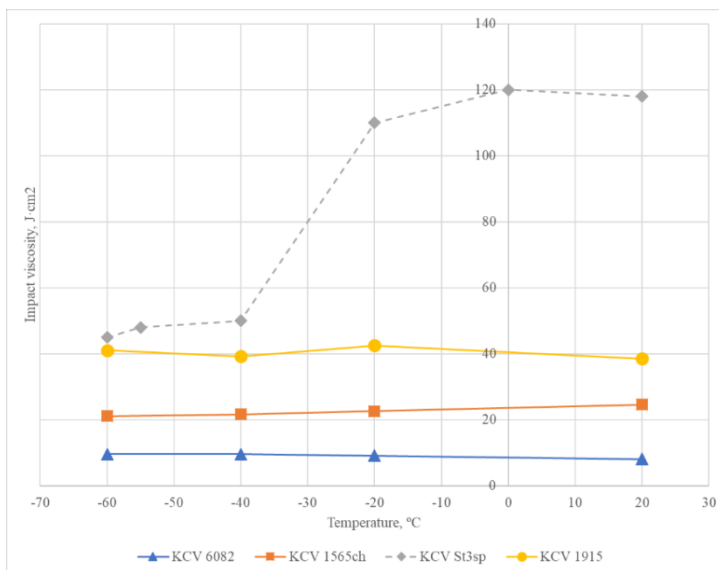


Fig. 5. Effect of temperature on impact viscosity for steel and aluminum alloys

Acquired temperature dependencies show that impact viscosity for all aluminum alloys is stable in the researched temperature range. Specimens from half-finished products of new alloy 1565ch have 2 times lower KCV than specimens of alloy 1915T. KCU viscosity for new alloy increased with increase of the radius on the concentrator peak.

4 Conclusions

Dependencies for strength, plasticity and viscosity from temperature were acquired based on the experimental research of aluminum alloys half-finished products with the highest design resistances which are recommended to use as structure materials for welded structures by SP.

It is established that:

- half-finished products of new alloy 1565ch (alloyage system Al-Mg) have high strength and reduced plasticity;
- there is no drastic decline in viscosity and plasticity with the decreasing temperature for all tested alloys;

- there is intermittent strain during axial tension tests at room temperature for specimens from alloys 1915T (alloyage system Al-Zn-Mg) and 1565ch (alloyage system Al-Mg); the strain during similar tests for specimens from alloy 6082 (alloyage system Al-Si-Mg) is uniform.

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