Low-cycle Fatigue of High Processible Aluminum Alloy Flat Products from Alloyage System Al-Mg-Si

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Abstract. Resistance to low-cycle fatigue of hot-rolled plates manufactured from alloyage system Al-Mg-Si alloy 6082 is researched. Cyclic stability of alloy and cyclic proportional elastic limit were defined during tests of specimens without cracks loaded along the rolling direction using curves of cyclic strain and their generalization. Properties used for design of prefabricated structures from thick aluminum plates from alloy 6082 operating in the conditions of low-cycle fatigue are received.

1. Introduction
Alloy 6082 researched in this work relates to alloys strengthened by heat treatment from alloyage system Al-Mg-Si and differs from Russian analogue alloy AD35 (GOST 4784-97) by type of production. Rolled plates specimens 12 mm in thickness were given for the tests while AD35 in Russia is mostly produced in form of pressed section [1].

Aluminum alloys from alloyage system Al-Mg-Si strengthened by heat treatment are materials with medium strength with high corrosion and corrosion cracks resistance according to up-to-date regulatory documents (SP 128.13330.2012 “SNiP 2.03.06-85 Aluminum structures”) [2]. Series 6xxx of alloys from this system have better processability during hot forming [3], higher productivity for products with complicated form than alloys from different systems. Thin-shell structures are formed from parent sheet in annealed condition using deep drawing because of high plasticity [4-7]. Products are capable of colour anodizing that meets requirements for architectural expression and long service of engineering structures in atmospheric conditions [3].

Nowadays registry of aluminum deformed alloys from alloyage system Al-Mg-Si has significantly widened, e.g. in ASTM D221M-13 there are 20 alloys of series 6xxx. However, SP recommendations are limited by alloys AV, AD31, AD33, 6060 and 6063 and gage of pressed sections.

It is known [1, 3] that strength and plasticity of AD35 specimens depend on heat treatment of sections: ultimate stress \( \sigma_u \) and yield stress \( \sigma_y \) after heat treatment and natural ageing are 196 and 108 MPa; after heat treatment and artificial ageing strength properties increase up to 314 and 285 MPa with lowering of relative elongation \( \delta \) from 12 to 8%. Standard properties \( \sigma_u-\sigma_y-\delta \) for section specimens are even higher 270-200-12 and 360-290-11 respectively according to [4].

Alloys from concerned alloyage system are one of the most low-alloyed from alloys strengthened by heat treatment [7]. Mean chemical composition of alloy AD35 – Mg1.1·Si1.0·Mg0.7·Cr0.25, does not include expensive and scarce alloy additives [1, 2, 4]. Similar to AD35, for alloying of aluminum alloy 6082 0.6…1.2% Mg, 0.7…1.3% Si and 0.4…1.0% Mn are used (ASTM D221M-13, DIN EN 573-
Phase composition basis of alloys consists of α-solid solution, chemical compound Mg\textsubscript{2}Si and free silicon disengaged with shown in alloy ratio of Mg/Si. Material resistance to change of forming processing behaviour is explained by higher content of Mn [4].

It is stated in [8-10] that improvement of alloy composition, types, supply conditions and metal forming technologies in the last years allowed to use alloys of alloyage system Al-Mg-Si in aircraft structures of Russian and foreign producers.

Alloy AD35 is recommended for structures of different cisterns, carrier vehicles and small pedestrian bridges [1, 11, 12]. Limitation of structures size is conditioned by supply condition and low material welding capacity for fusion welding. However, contemporary technologies of friction stir welding allows to achieve flawless connections of alloys from alloyage system Al-Mg-Si with strength of 0.8...0.9 from base metal strength [1]. Improvement of welding capacity of alloys from this alloyage system facilitates use of sheet semi-finished product for manufacturing of engineering structures. Additional foundation for materials choice for structure design is acquiring and analysis of resource fatigue strength properties corresponding with service special aspects. Danger of fatigue fracture appears in its abruptness associated with local fracture in small volume of product [13, 14].

The work was done to acquire experimental properties which are necessary for engineering estimation of alloy 6082 (alloyage system Al-Mg-Si) working capacity by limit state parameters in the condition of cyclic loading for rolled plates 12 mm in thickness.

2. Methods and materials

Specimens cut from rolled plates (t = 12 mm) of alloy 6082 with mean chemical composition Mg1.1\cdot Si1.0\cdot Mn0.7\cdot Cr0.25 (ISO 209-1) were researched. Fatigue tests were carried out according to GOST 25.502 using testing machine Instron 8802 at room temperature. Figure 1 shows form and dimensions of the specimens. Flat specimens cut along the rolling direction were centralized before low-cycle fatigue (LCF) tests with the help of strain gage mounted on opposite sides of specimens.

Corset specimens were used to determine endurance limit in zero-to-tension and symmetric cycles of compression-tension loading with constant load amplitude. Load frequency was 10 Hz. Endurance limit with \( r = 0 \) and \( r = -1 \) equals \( \sigma_0 = 87.5 \) MPa and \( \sigma_1 = 62.5 \) MPa. Behaviour of material during elastoplastic strain in symmetric cycles was studied on the same specimens. Change of loads in LCF was performed with a frequency of 3 cycles per minute. Strain in LCF were registered by strain gages (base of 3.0 mm) using strain-gage type device from National Instruments. Influence of stress concentrator on fatigue resistance was researched on specimens with holes.

![Figure 1](image1.png)

**Figure 1.** Flat specimens for LCF tests: a) flat corset specimen without crack, b) fracture behaviour of corset specimen, c) specimen with centred circular hole \( \varnothing 24 \) mm, d) specimen with centred elliptic hove with axis ratio of 1,5
Rectangular specimens for eccentrical tension with edge cut and previously propagated crack until ratio of $l/b = 0.4$ were used for estimating of fatigue crack propagation speed according to GOST 25.506 (figure 2).

![Sketch of specimen with a cut for estimation of fatigue crack propagation speed: a) plan view; b) detail](image)

**Figure 2.** Sketch of specimen with a cut for estimation of fatigue crack propagation speed: a) plan view; b) detail

Structure of lateral and cross section of specimens was controlled on optic microscope Olympus BX-51 at 50x magnifying. Analysis has shown that metal structure along the specimens’ axis corresponded with lateral rolling direction of plate.

Fracture surfaces was studied on stereomicroscope (Nikon SMZ800N) and scanning electric microscope (Phenom ProX) with built-in system for energy-dispersive stereoscopy.

3. **Results and discussions**

Diagram of cyclic strain (figure 3a) and generalized diagram of cyclic strain (figure 3b) show test results of rolled plates specimens from alloy 6082 (figure 1a) for cyclic strength.

![Diagram of cyclic strain](image)

**Figure 3.** Test results: a) in “stress-strain” coordinates; b) in “cyclic stress-strain” coordinates
It was established that after one-time straining up to $\varepsilon<2.2\%$ alloy showed properties of cyclically stable material. Width of mechanical hysteresis loop which defines residual strain inside each cycle stabilized after 10 cycles during the test of flat specimens’ series with controlled load level (figure 3a). Value of unloading modulus during the series of tests almost corresponded with normal modulus of elasticity and did not depend on initial strain value and number of cycles.

Generalized diagram of cyclic strain in “cyclic stress-strain” coordinates was plotted to estimate stress behaviour in researched areas of specimens and stress concentration (figure 3b). Strain curves on each loading cycle almost match together in symmetric cycle conditions ($r = -1$) according to generalized diagram. Acquired value of cyclic proportional elastic limit (460 MPa) does not depend on number of cycles and initial value of plastic strain [15-17]. Ratio between cyclic proportional elastic limit and static yield stress was 1.57 (460/293). Exceeding of cyclic proportional elastic limit critical value above yield stress of zero-to-tension cycle equals 1.69 times for alloy AMg6M; 1.62 times for alloy V95C; 1.78 times for alloy D20 according to [17].

Cyclic loading of specimens with concentrator (figure 2c, d) with indented load level was done until initiation of crack 1.0-1.5 mm in length in stress concentration area.

Figure 4 shows example of distribution diagram for strain intensity, cycle stress and residual strell for different load levels: $F = 45$ kN – 0.23·$\sigma_{0.2}$; $F = 80$ kN – 0.40·$\sigma_{0.2}$; $F = 98$ kN – 0.50·$\sigma_{0.2}$.

![Figure 4. Strain and stress intensity distribution around elliptic hole: a) strain intensity; b) cycle and residual stress intensity](image-url)

Stress-strain behaviour of material around holes with stress concentration factors in elastic area $\alpha_s = 2.35; 3.25$ was found out in a range of 1…100 loading cycles. Strain intensity on specimens’ surface for elliptic hole was higher at $\alpha_e = 3.2$ than for circular hole and comes to values of 5.20, 4.10 and 0.82 at load levels 0.50, 0.40 and 0.23 respectively. Strain $\varepsilon_n$ at load level $\sigma_n/\sigma_{0.2} = 0.4…0.6$ stabilize after 10 loading cycles in case of repeated loading for all tested specimens. Similar stress and strain distributions were acquired on specimens with circular holes.

Figure 6b shows stabilized stress ($\sigma_i$ and $\sigma_{ires}$) intensity distribution diagram for specimens with elliptic holes. Stress $\sigma_i$ intensity achieve maximum on the hole outline and diminishes with distance.
from hole until nominal stress on all load levels. Area of plastic strain widens with increase in load but increase in stress $\sigma_{\text{max}}$ is insignificant which confirms small degree of researched alloy strengthening [13-15]. Residual compression stresses $\sigma_{\text{res}}$ achieve maximum on the hole outline, diminishes with distance from hole and reverses sign on the plastic area border. Residual stress almost equals zero when distance from hole is 10…15 mm. Stress value increase with growth in initial strain level and its area of action widens.

Fatigue crack appeared near the hole at stress concentration factor $\alpha_\sigma = 2.35$ after $(3.4…95.5)\cdot10^4$ cycles of loading and with factor increase until $\alpha_\sigma = 3.25$ – after $(1.1…17.0)\cdot10^4$ cycles. Design and experimental values of cycles number until crack initiation in specimens with circular and elliptic holes almost correspond.

![Figure 5.](image)

**Figure 5.** a) Design and experimental values for number of cycles until crack initiation in specimens with circular and elliptic holes; b) Linear section of fatigue fracture diagram for specimens from alloy 6082

Test results for eccentric tension (figure 2) in LCF including diagrams for “crack length-number of loading cycles” allows to plot diagram of fatigue fracture in “$\frac{dL}{dN}$-$\Delta K$” coordinated (figure 5b). Crack propagation speed in LCF was $5\cdot10^{-2}$ mm/cycle with stress intensity span in specimen approaching maximum values (37 MPa).

Initiation of fatigue crack started on free surface of sheet close to the edge with additional stress concentration on non-metallic additives (figures 9, 10) in tested specimens. Non-metallic additives can lead to decrease in crack resistance on initial stage of strain and change fatigue mechanism at cyclic loading conditions [13, 14].
Figure 6. Fracture surface on responding halves of corset specimens a) fatigue source (stereomicroscope x20 magnifying) b) fatigue grooves (fracture pattern x750 magnifying)

| Point 1 | Element Symbol | Atomic Conc. | Weight Conc. |
|---------|----------------|--------------|--------------|
| Al      | 88.43          | 80.95        |
| Fe      | 4.45           | 8.43         |
| Mn      | 3.85           | 7.17         |
| Si      | 3.20           | 3.05         |

| Point 3 | Element Symbol | Atomic Conc. | Weight Conc. |
|---------|----------------|--------------|--------------|
| O       | 52.99          | 40.63        |
| Al      | 34.62          | 44.76        |
| C       | 6.55           | 3.77         |
| Ca      | 4.51           | 8.66         |
| Si      | 1.27           | 1.71         |

Figure 7. Microstructure and additives composition on fracture surface

Research of responding halves of fracture showed that white non-metallic additive was fatigue source (figure 6a). Crack propagation occurred perpendicular to load action and was accompanied by fatigue grooves initiation. After the end of test relief was changed by round burrows of viscous rupture (figure 7). White non-metallic additives composition includes compounds of aluminum with iron, manganese and silicon on the burrows bottom of fracture surface (point 1) and includes aluminum and calcium oxide in the area of fatigue grooves (point 3).

Correspondence of design and experiment results in LCF allows to use dependency shown in [15, 16] for determining number of cycles until crack initiation.

4. Conclusions

The possibility of gage expansion for high processible aluminum alloys from alloyage system Al-Mg-Si recommended by SP 128.13330.2012 for engineering structures manufacturing with sheet half-manufactured products from alloy 6082. Earlier in article [18] we showed the research results for static strength and crack resistance of specimens from alloy 6082. Complex of tests was supplemented by series of long-term tests for substantiation of material choice. Research results given in this publication show resistance of half-manufactured sheet product to cyclic tests in the area of LCF. Cyclic stability of alloy 6082 and values of endurance limit ($\sigma_0 = 87.5$ MPa and $\sigma_{-1} = 62.5$ MPa) were found out during
tests of specimens without cracks loaded along the rolling direction. It was identified that cyclic proportional elastic limit is higher that static by 1.57 times. Areas of flaw initiation and change in crack propagation direction was studied for series of specimens in the conditions of LCF limited by crack initiation. Dependency for fatigue crack propagation speed in plate (12 mm in thickness) from span of stress intensity factor and numerical values for Paris factors used in design \( C = 2.29 \times 10^{-12} \text{m/cycle/(MPa·m}^{1/2}\text{)} \), \( n = 4.59 \) were established.

Increase in level of stress and strain intensity on the surface of elliptic hole, a steep decline in stabilized span of strain intensity and smoother decrease of stress intensity with distance from the hole edge compared to circular hole were detected. Difference in concentration of residual stress near holes of different form and size was found out.

Acquired properties are necessary for substantiation of material and supply condition choice for prefabricated structures from sheet aluminum half-manufactured products design used in the conditions of LCF. Complex of determined mechanical properties of hot-rolled plates from alloy 6082 will allow to widen its application domain for sheet structures.

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