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Investigation for the Parameters of Fatigue Characteristics of Aluminum Casting Alloys: Frequency, Temperature and Loading Parameters

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Abstract **Original Research Article**

In this paper, the fatigue strength of casted aluminum alloys A14 and A17, AK9M2 and AK8M3 was investigated at room elevated temperatures of (20 °C-155^{0}C-270^{0}C-340^{0}C and 20^0-100^0-200^0-250^{0}C) and at different frequencies (0.3KHz,3.0KHz,9KHz and 18KHz) and various loading bases(1.10^6, 5.10^6 and 1.10^7 cycles). Experimental studies were performed at different frequencies on primary aluminum alloys Al4, Al7 and on AK9M2 and AK8M3 as model materials for establishing the influence of high test temperatures on the behavior of endurance limits, and the influence of frequency of alternating bending on the kinetics of micro -hardness, and dislocation density on fatigue characteristics. In addition, the character of the dependencies obtained confirms the possibility of using accelerated fatigue tests by increasing the frequency for aluminum casting alloys made using recycled materials as well. The influence of amplitude-frequency and time parameters on the kinetics of physical-mechanical properties demonstrate that the most intensive changes in structure-sensitive characteristics for the selected levels of variable stresses occur during early stages of cyclic loading. It was confirmed by the results of fatigue tests of the deformable aluminum alloys. The experiments show that the shape of fatigue curves does not change with increasing frequency. Fatigue curves for different frequencies are practically equidistant. All studies materials are characterized by a monotonous increase in the fatigue life with increasing loading frequency, which is observed under alternating bending conditions for various test bases. The analysis of results of experiments demonstrated that the established endurance limits also increase with increasing frequency. The test results demonstrate that the loading frequency significantly influences fatigue life of all studied materials.
Keywords: Aluminum alloys**,** fatigue strength, elevated temperatures, endurance limits, kinetics of microhardness, dislocation density.

INTRODUCTION

Fatigue property is considered as one of the most significant factor for the damage mechanisms in materials particularly at high temperatures and different frequency tests. It has a considerable effect on the properties of material and on the possible running life [1]. The evolution of the environment needs engineering materials with high physical and mechanical properties. Massive strain deformation, crack initiation and development are due to fatigue at high temperature [2]. The structure of material fails in several manners, rupture, damage, fatigue and high deformation. High temperatures and frequencies have serious effect on the properties and fatigue life of the material [3]. The processes of damage initiation and propagations of aluminum alloys structures increase with increasing temperature and increasing load frequency. Some studies are performed on primary aluminum alloys Al4 and AL7 and on AK9M2 and AK8M3 using recycled materials [4].

In this work, a novel technique for the analysis of fatigue at elevated temperature and various loading frequency is suggested. Experiments are performed on caste aluminum alloys A14, A17, AK9M2 and AK8M3 at various loading frequencies (0.3KHz, 3.0KHz, 9KHz and 18KHz) at room temperature (20 °C-155^{0}C-270^{0}C-340^{0}C and 20^0-100^0-200^0-250^{0}C) respectively. The experimental data is further transformed in to an empirical correlation that can predict specimen useful life.

A lot of studies have been conducted on the fatigue behavior of aluminum alloys, other studies investigated the effect of elevated temperature on fatigue characteristics at various loading frequency. As an example, the effect of the loading frequency on the fatigue life of carbon steels, low-alloy steel 1X2M, titanium alloys VT22M, OT4, OT4-1, VT20V, aluminum alloy D16T, stainless steels H18N9 and HN35VT, glass and glass-ceramics determined on the basis of 1×10^7 cycles in the frequency range of 10-10^4 Hz, which are indicated in [5] showed that the values of the high-frequency endurance limit at the same temperature and the testing base, are always higher than the low-frequency limit, because at high deformation speed the rates the fatigue damage of the material decrease (at the same amplitude of cyclic stresses) due to the submission of the sample material to a maximum stresses of the cycle at shorter time. Similarly, another studies showed that the endurance limit of aluminum alloy AMg6N increase with increasing frequency (600, 2000, 2500, 3800, 7500 Hz) [6].

Experimental studies on aluminum, aluminum-magnesium and titanium alloys based on 5×10^7 cycles in the frequency range from 10-20 Hz to 10-30 kHz, show that after monotonous increase in the frequency of the high value of endurance limit led to decrease in endurance limit value, was most likely because of an expansion in the material temperature caused by the loss of hysteresis and a comparing decline in mechanical opposition [7].

Experimental studies conducted on titanium alloys VT18U, VT3-1 and PT-7M at room temperature and expanded temperatures over an extensive variety of frequencies, show that the fatigue characteristics remains unchanged, due to the unimportant level of energy dispersion during the cyclic loading of these materials [8]. In addition, it is recommended to use the obtained results of these alloys tested at high-frequency to accelerate the identification of low-frequency endurance limits. As a result of fatigue tests, the fatigue characteristics under the loading frequency influence of a low-alloy boiler house (10GN2MFA) and chromium heat-resistant (1X2M) steels at high temperatures depend to a large extent on thermally activated processes, vary significantly [9].

Studies conducted at low-frequency cyclic stress on the change in hardness and micro-hardness of materials concluded that an increase in the hardness of annealed materials occurs in the initial loading stage, later it decreases [10]. An increase in the number of cycles causes in changes in hardness and microhardness of the material. The hardening process begins and ends at the early stages in the dangerous loading, in contrast with the softening process.

The study of the change in micro-hardness at high temperatures (873-1223 K) and in the vacuum during the cyclic loading (stretching-compression with a frequency 35 Hz) of deformable super-alloys on the nickel basis EI698VD and EI867 showed [11] that an increase in micro-hardness (~ 20% of the initial value) at the initial stage of fatigue tests. In the future, the hardening of materials was replaced by their softening with a slight increase in micro-hardness, which did not reach the initial value, before the breakdown.

Extensive studies have been conducted on the dislocation structure of aluminums at frequency of 17.7 KHz, whereas the structure of the samples destroyed at a magnitude of stress amplitude 37MPa after 10^6 cycles, and broken at 18MPa after 10^6 cycles [12]**.** The tests under high and normal loading frequency showed that the dislocation structure of samples of copper and aluminum is destroyed, this is due to the fact that at high loading frequency the dislocation formations in the form of loops lead to be smaller than in case of the normal loading frequency. According to the literature review, studying effect of elevated test temperatures on fatigue characteristics of aluminum alloys is so rare especially under various loading frequencies. Therefore, the objective of this work is to investigate the effect of test temperature and loading frequency on the fatigue characteristics and on the behavior of endurance limits of aluminum alloys (A14, A17, AK9M2, AK8M3) with various loading bases and the influence of alternating bending on the kinetics of microhardness on A14 and density dislocation of AK9M2 alloys.

EXPERIMENTATION

The experiments are performed on aluminum alloys A14,A17, AK9M2,AK8M3 at various loading frequencies (0.3KHz,3.0KHz,9KHz and 18KHz) at room temperature (20 °C-155^0C-270^0C-340^0C and 100^0-200^0-250^0C) respectively. The subject-matters of the research are 2-mm thick flat beam specimens from aluminum alloys A14, A17, AK9M2, and AK8M3.

As the previously conducted studies [13, 14] have shown, a very promising method for these purposes is the use of high-frequency oscillations that allow ensuring development of a significant number of load cycles over a short time and identifying the patterns of the effect of deformation frequency on cyclic damageability of the examined metals and alloys.

A complex of magnetostrictive [15] resonance units allowing testing of various construction materials (both metal and non-metal) at large test basis within wide ranges of frequencies (0.3 kHz –3.0KHz- 9KHz-18 kHz) and temperatures (20^0-100^0- 155^0-200^0-270^0 -340^0 C) was developed for implementation of high-frequency. Tests at high frequencies (0.3 KHz, 3.0 KHz, 9 KHz and 18 KHz) were performed using magnetostrictive units operating in auto oscillatory mode. Active element of the fatigue unit is magnetostrictive package in the form of closed loop composed from thin sheets of an active material (nickel, permendure, etc.).

The complex work was performed by an auto-oscillation mode. Since the quality of this auto-oscillation system is largely determined by the quality of the sample, the use of fatigue tests gives a real possibility to study kinetics of accumulation of fatigue damages by monitoring the changes in the system oscillation frequency with the help of an electronic counting frequency meter. Pre-adjustment and calibration of the vibration meter was carried out using a MBC-2 optical microscope. Shape and amplitude of the electrical signals were controlled using the electronic oscilloscope connected to the circuit for the time of testing.

Operational factors having a significant impact on fatigue resistance of construction elements include such environmental parameters as temperature and its composition. The influence of abnormal temperature alters the development of the fatigue processes. In this regard, a test complex was equipped with stationary heating furnaces with measuring equipment in order to account for the influence on fatigue characteristics. The complex will allow modeling various tests within a wide range of frequencies and temperatures, implementing various random loads typical of real operating conditions; various feedbacks will allow real-time monitoring, measurement and analysis of various testing parameters (sample temperature, frequency spectrum, oscillation amplitude, etc). For bending fatigue testing, beam cantilevered samples oscillating at the first, second and (for a frequency of 18 kHz) third forms of their own oscillations.

There are two maximum levels for the second form of oscillation: in embedment and on the cross-section part, roughly in the middle of the sample's length. In this case, it is possible to move the sample destruction point to the constant cross-section part. This allows determining the level of stress in the destruction point more precisely and performing studies on influence of various factors on kinetics of fatigue processes and contributes to maintaining the precise given temperature in the dangerous cross-section. The use of the third form of oscillations allows testing of flat beam samples loaded with alternating bending at frequencies of more than 20 kHz. As the oscillation frequency decreases, the resonant length of the sample increases, and it becomes possible to perform direct measurements of the magnitude of present cyclic stresses by strain gauge; due to this fact, it is expedient to perform low-frequency test at the first form.

The first, the second and the third forms of the sample's own oscillations were used for frequencies with high-frequency fatigue testing (0.3 kHz –3.0KHz-9KHz-18 kHz), there is a problem of cooling samples that are heated to high temperatures as a result of hysteresis losses. In order to ensure the same loading conditions for high and low frequencies at room temperature, forced air cooling was used in the latter case, which appeared sufficient for the examined materials to maintain temperature mode within 45°C at a frequency of 18 kHz and maximum cyclic stresses. In this case, compressed air under a pressure of about 0.05 MPa was supplied through the nozzle to the sample in the field of maximum cyclic stresses. Self-heating temperature was controlled with the help of an optical pyrometer SDI-1 by fixing infrared radiation of the smoke-darkened portion of the sample. Calibration of the pyrometer was performed with the help of a thermocouple with an accuracy of up to 1°C.

It is known that when any oscillations of the constant cross-section cantilever beam are excited, absolute value of stresses in the embedment always exceed the stresses acting near anti-nodes of deflections. This circumstance hinders use of the cross section beam samples for fatigue testing. In practice, samples with increased cross-section area near the embedment [16] are used to move the fatigue destruction point from the embedment, which results in a change in rigidity of the root portion of the sample.

When performing fatigue tests, change in the microstructure of the tested material in course of accumulation of fatigue damage leads to loss of resonance by the system, which doesn't allow maintaining an acceptable level of stresses in the dangerous cross-section of the sample, due to which its physical destruction is absent after the endurance limit is reached. To solve this problem, studies were conducted. The aim of these studies was to determine the relationship between the change in the resonant frequency of the system oscillation and the relative number of cycles.

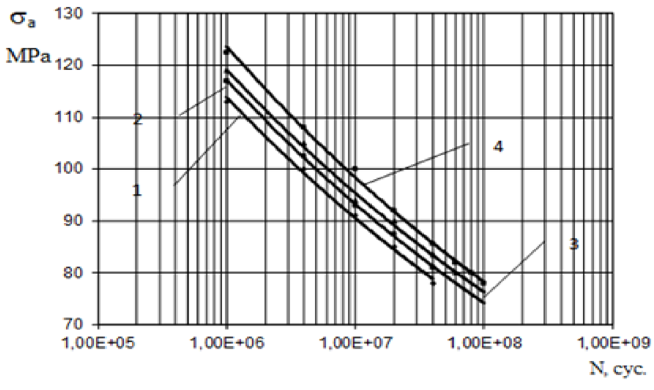
Analysis of the relations shows that the growth of sub-microscopic, microscopic and, eventually, macroscopic cracks results in reduction of rigidity of the tested model and reduction of the system's own oscillation frequency, as its general quality is largely determined by the sample quality.

Bending oscillations of a wide frequency range were used in studying the kinetics of physical and mechanical characteristics of materials during cyclic deformation. Complex studies on the influence of amplitude-frequency and temporal parameters of loading on the course of processes of fatigue damaging of metals and alloys were performed by following the kinetics of such structurally sensitive material properties as micro-hardness, fine structure, specific electrical resistance, magnetic characteristics and micro-structure. The use of bending oscillations not only imitates the mode of operational stresses, but also significantly increases the accuracy of studies of physical and mechanical characteristics due to the presence of cyclic loads of various values, located regularly along the sample axis.

RESULTS AND DISCUSSIONS

Influence of the frequency of tests on fatigue characteristics of aluminum casting alloys

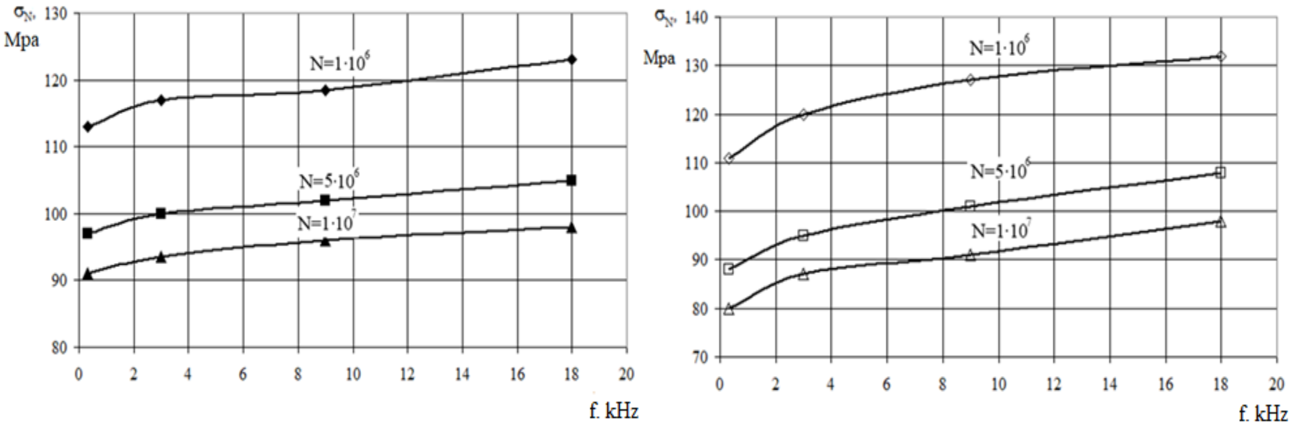
Results of the experiments (figures 1) demonstrate that the shape of fatigue curves does not change with increasing frequency. The analysis of results of experiments demonstrated (figures 2) that the established endurance limits also increase with increasing frequency. For example, increase in the frequency from 0.3 to 18.0 kHz during tests under conditions of alternating bending of the Al4 alloy based on 10^6 cycles led to an increase in the endurance limits from 112 to 125 MPa.



a) b)

Fig-1: Fatigue curves under alternating bending at 1) 0.3 kHz;2) 3.0 kHz; 3) 9.0 kHz; 4) 18.0 kHz for a) Al4 and b) Al7 alloy

With an increase in the number of test cycles, the difference in the values of limited endurance limits gradually decreases. For the alloy Al4, the difference based on 10^7 cycles amounted to just 7 MPa. For the stronger Al7 alloy, the frequency dependencies obtained were generally similar, but the value σ_N increased significantly. The test results demonstrate that the loading frequency significantly influences fatigue life of all studied materials. An increase in frequency from 0.3 to 18.0 kHz increases the number of cycles before the destruction of the Al4 alloy more than three times.



a) b)

Fig-2: Endurance limits at various loading frequencies for a) Al4 alloy b) Al7 alloy

For the AK9M2 casting alloy (figure 3) produced using recycled materials, the endurance limits for the same number of cycles are significantly (1.4-2.5) times lower than for the primary alloy Al4 (figure 2a); however, dependencies of σ_N from the testing frequency are almost equivalent to the ones obtained for Al4. Therefore, fatigue characteristics of the studied materials within the frequency range of 0.3-18.0 kHz under alternating bending tend to increase monotonously with increasing frequency. However, a further increase in frequency (above 18.0 kHz) can lead to a reduction in the endurance limits at high levels of cyclic loads.

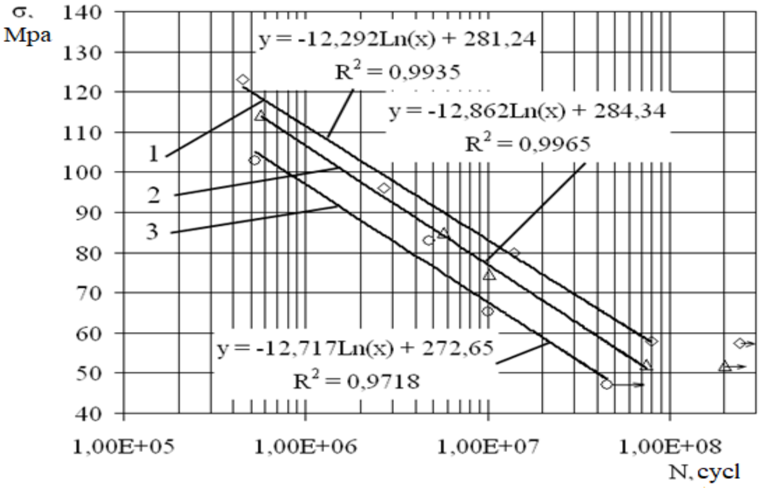
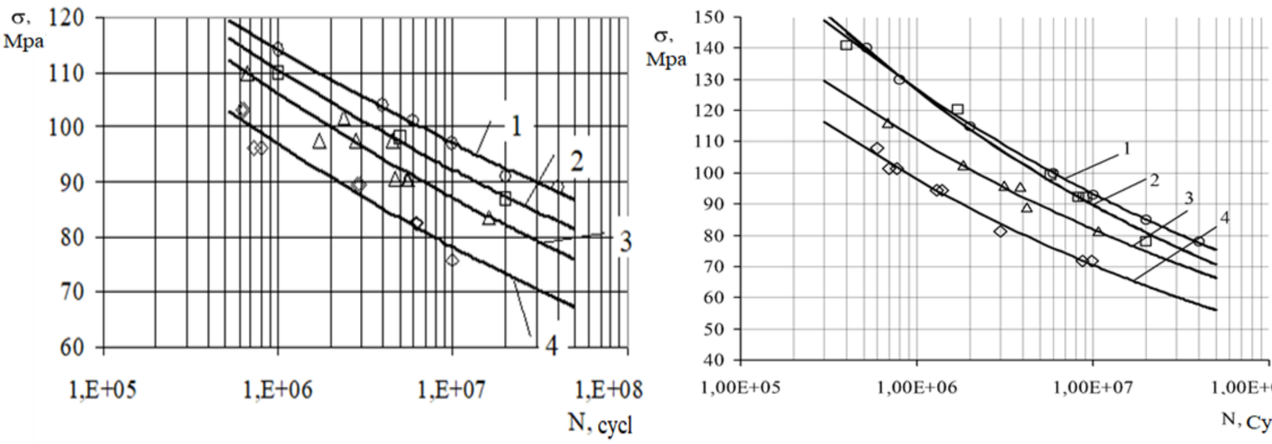


Fig-3: Fatigue curves of the AK9M2 alloy (testing frequency 18 kHz)

Influence of the temperature of tests on fatigue characteristics of aluminum casting alloys

The results of tests of deformable aluminum obtained for cast alloys Al4 and Al7 (figures 4) demonstrate that an increase in temperature monotonously reduces the fatigue characteristics at all studied bases. Determination of the endurance limits σ_N (figure 5) indicates that the temperature increase influences this parameter more than the number of cycles.



a) b)

Fig-4: Fatigue curves at different temperatures and at various frequencies (testing frequency – 9 kHz) for a) Al4 alloy and b) Al7 alloy (1- 20°C; 2- 155°C; 3- 270°C; 4- 340°C)

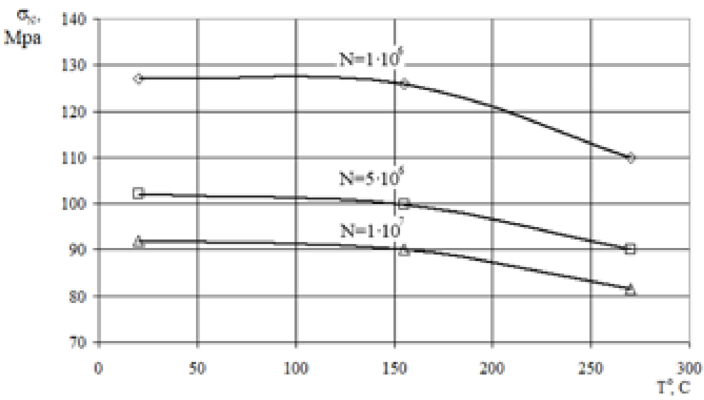


Fig-5: Influence of the test temperature on the behavior of endurance limits for the Al7 alloy

With an increase in temperature, the influence of the test bases on the values of σ_N decreases. For example, if for the Al7 alloy an increase in temperature from 20°C to 155°C leads to a decrease in the endurance limit value on the base of 10^7 cycles by 3 MPa, then a temperature increase from 155°C to 270°C on the same base leads to a decrease in σ_N by 8Mpa. This dependency is manifested more prominently in smaller test bases with higher stress levels. For example, for the base of 10^6 cycles the difference in values of σ_N at 155 and 270°C increases two times and reaches 16 MPa. However, the character of fatigue curves does not change significantly with increasing temperature, which shows the possibility of using high loading frequencies for testing of aluminum alloys at elevated temperatures as well. This conclusion is also confirmed by tests of the alloys AK9M2 and AK8M3 made using recycled materials (Figures 3 & 6).

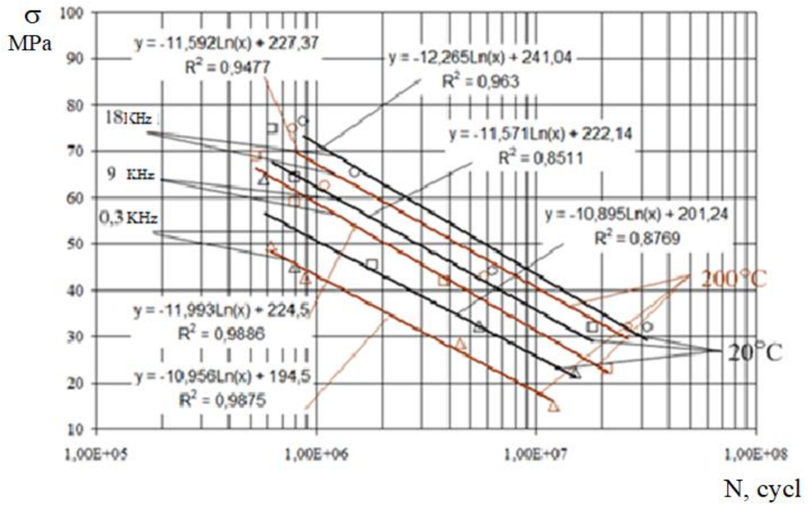


Fig-6: Influence of Loading frequency and temperature on fatigue characteristics of AK8M3 alloy (cast state)

Values of σ_N for such alloy are lower for primary alloys Al4 and Al7, and an increase in temperature leads to a more significant decrease in the endurance limits by 1.1-1.6 times (figure 6). It can be noted that the character of fatigue curves is similar to behavior of endurance limits both at normal and at elevated temperatures (increase by 1.5-2.5 times) for various loading frequencies (figure 7), which confirms the expediency of using high loading frequencies for determining fatigue characteristics of secondary aluminum.

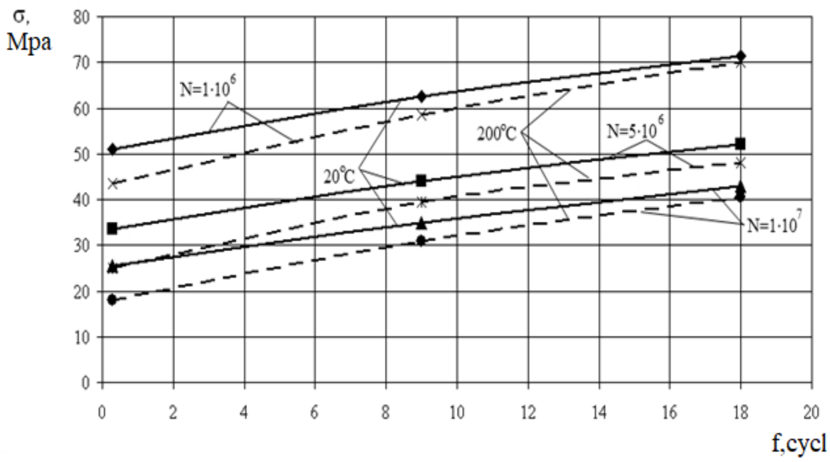
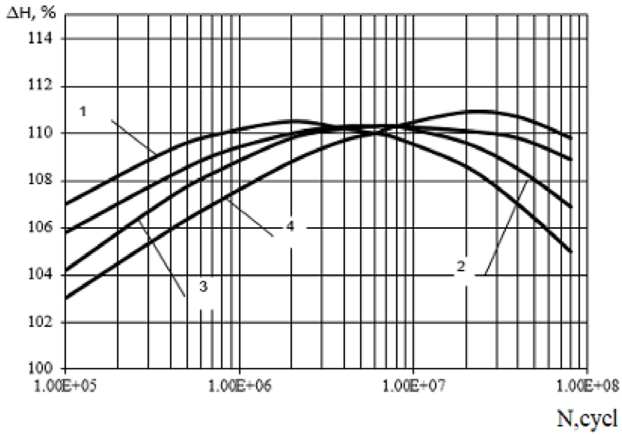


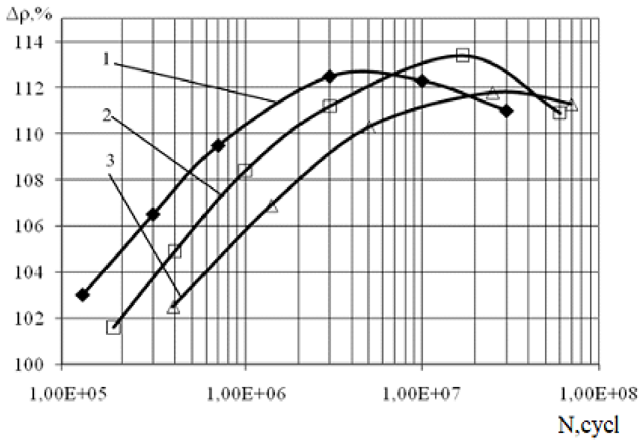
Fig-7: Endurance limits of the AK8M3 limits at various frequencies and with various loading bases

Influence of the loading parameters on the kinetics of physical-mechanical properties of the studied materials

Test studies show that, an increase in microhardness of the Al4 alloy ($\Delta H_{0.50}$ – 62.5 MPa) under alternating bending at a frequency of 0.3 kHz for the cycle base of 10^5 cycles amounted to 1.07 %, while the following 10^5 cycles increased microhardness only by 1% as compared to the initial condition (figure 8a). The nature of the change in the density of dislocations (figure 8b) is generally similar to the kinetics of microhardness.



a)



b)

Fig-8: Influence of the frequency of alternating bending on the kinetics on the Al4 alloy for: a) microhardness 1) 0.3 kHz, 2) 3.0 kHz, 3) 9 kHz, 4) 18 kHz and b) dislocation density1) 0.3 kHz, 2) 9 kHz, 3) 18 kHz

An increase in the level of stresses of σ_a from 62.5 MPa to 87.5 MPa at each frequency monotonously increases the magnitude of the relative changes, the more significantly the lower the loading frequency is (figure 9). Similar results were also obtained for secondary aluminum alloys AK9M2 (figures 10-12).

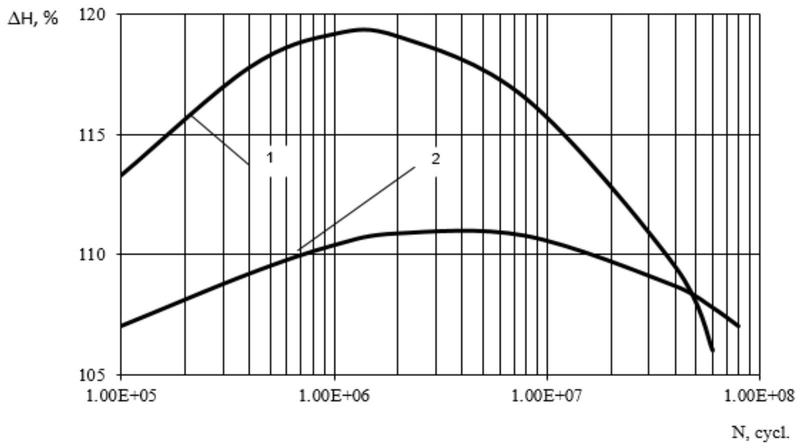


Fig-9: Influence of the magnitude of alternating bending on the kinetics of microhardness of the Al4 alloy (0.3 kHz). 1) 87.5 MPa; 2) 62.5 MPa

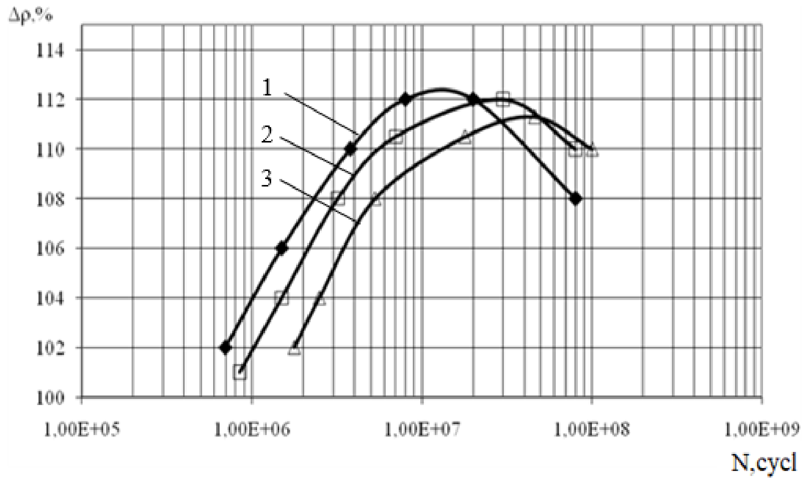


Fig-10: Influence of the frequency of alternating bending on the kinetics of density of dislocations of the AK9M2 alloy. 1) 0.3 kHz, 2) 9 kHz, 3) 18 kHz

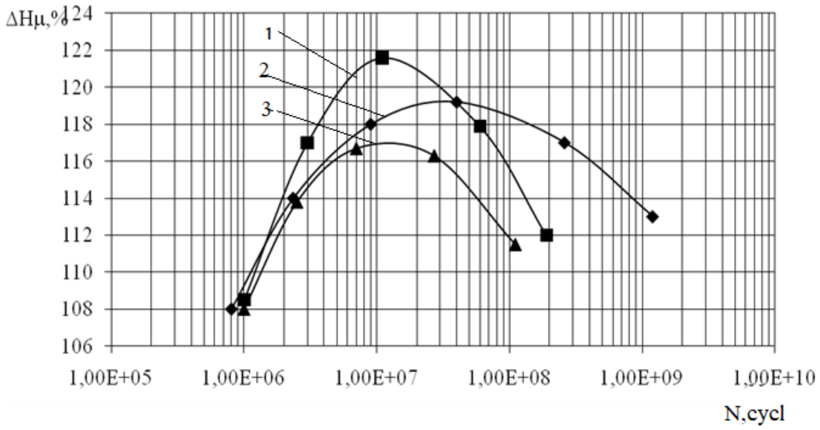


Fig-11: Influence of temperature on the microhardness kinetics of AK9M2 alloy. 1) 20°C; 2) 100°C; 3)250°C

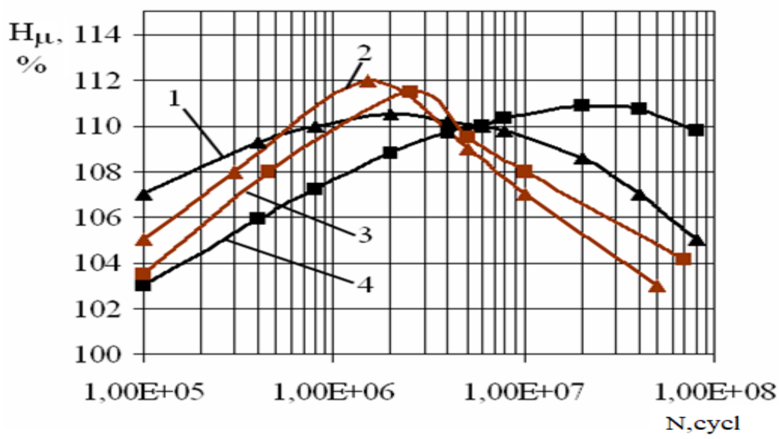


Fig-12: Change in microhardness of the AK9M2 alloy at various test temperatures and frequencies. 1) 0.3 kHz (20°C); 2) 0.3 kHz (200°C); 3)18.0 kHz (200°C); 4) 18.0 kHz (20°C)

Curves of the kinetics of the studied physical-mechanical characteristics in the examined range of frequencies and temperatures do not change significantly for the AK9M2 alloy as well (figures 10-12), which confirms the conclusion on the possibility of use of high test frequencies for secondary aluminum casting alloys.

CONCLUSION

In this study the analysis of fatigue property performed on aluminum alloys A14,A17, AK9M2 and AK8M3 respectively, is conducted at various loading frequencies (0.3KHz,3.0KHz,9KHz and 18KHz) and temperatures (20 °C-155^{0}C-270^{0}C-340^{0}C and 100^0-200^0-250^{0}C). The influence of amplitude-frequency and time parameters on the kinetics of physical-mechanical properties demonstrate that the most intensive changes in structure-sensitive characteristics for the selected levels of variable stresses occur during early stages of cyclic loading. It was confirmed by the results of fatigue tests of the deformable aluminum alloys. The experiments show that the shape of fatigue curves does not change with increasing frequency. Fatigue curves for different frequencies are practically equidistant. All studied materials are characterized by a monotonous increase in the fatigue life with increasing loading frequency, which is observed under alternating bending conditions for various test bases.

The analysis of results of experiments demonstrated that the established endurance limits also increase with increasing frequency. The test results demonstrate that the loading frequency significantly influences fatigue life of all studied materials. With an increase in temperature, the influence of the test bases on the values of σ_N decreases. Also the studies of physical- mechanical character conclude that the possibility of use of high test frequency for secondary casted aluminum. However, the character of fatigue curves does not change significantly with increasing temperature, which shows the possibility of using high loading frequencies for testing of aluminum alloys at elevated temperatures as well.

It is noticed that the fatigue strength for aluminum alloys A14, A17, AK9M2 and AK8M3 demonstrated that the monotonic increase in temperature reduces the fatigue performance on all tested data. Also a study for the kinetics of the microhardness is carried out and demonstrated that the nature of its changes are conserved with increasing frequency under both regular and elevated temperatures. However, more experiments on fatigue strength response at various frequencies are required for better evaluation of fatigue performance. It is also required to derive mathematical models that correlate fatigue strength with temperature and frequencies variation.

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