EFFECT OF STRESS CONCENTRATION ON THE FATIGUE AND CORROSION—FATIGUE PROPERTIES OF CAST ALUMINUM VAL10 AND FORGED ALUMINUM AK6 ALLOYS

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The use of improved cast blanks instead of forgings and stampings of aluminum alloys is one of the main directions of work in reducing labor consumption, amount of material used, and component costs.

In addition, for a positive solution to the question of using in one case or another castings instead of forgings and stampings, it is necessary to have information about the operating capacity of castings under actual conditions and structural factors (corrosive agents and stress concentration).

In the engineering design of components operating with alternating loads, correct evaluation of the combined effect of stress concentration and corrosion is of considerable importance. This evaluation is normally carried out by means of the effective stress-concentration factor, whose basis is determination of fatigue curves plotted from the results of tests in air and in a corrosive medium.

There are insufficient data for the combined effect of stress concentration and corrosive media on the fatigue resistance of aluminum alloys, and they are often contradictory [1-7]. It is noted that similar data for cast aluminum alloys are practically unknown.

In this connection experimental studies were carried out on the effect of a notch (in the form of a circular groove) on the fatigue resistance and corrosion—fatigue failure of cast-alloy-VAL10 specimens with porosity at point 3 of the scale, and alloy AK6 specimens taking account of anisotropy for its mechanical properties.

Selection of the materials is explained by the fact that alloy VAL10 is most promising from the point of view of extensive application of castings instead of forgings and stampings for the manufacture of critical force components, since it is the first of the aluminum cast alloys with mechanical properties competing successfully with wrought alloys.

Of the wrought aluminum alloys used extensively, the mechanical properties of alloy AK6, σ_f and δ, with static loading are closest to similar properties for alloy VAL10. Therefore, it is recommended that cast alloy VAL10 be used to manufacture some forged and stamped blanks made of alloy AK6.

Specimens 10 mm in diameter with a smooth gage length and with a stress concentrator whose shape and size corresponded to GOST 2.5.502—79 were tested in MUI-6000 machines. The concentrator was in the form of a circular groove of radius and depth 1 mm.

In order to carry out corrosion—fatigue tests, the MUI-6000 machine was fitted with a system for supplying corrosive medium to the specimen gage length. The medium was fed dropwise. Consumption of the medium was 20-40 drops per minute. A 3% aqueous NaCl solution was used as the corrosive medium.

Specimens of VAL10 alloy were cut from a specially prepared casting in the form of a plate 14 × 190 × 470 mm in size.

Specimen preparation included the following stages: a) cutting blanks in a milling machine into four-sided blanks; b) turning the four-sided blanks in order to obtain semifinished specimens with a diameter of 12 ± 0.01 mm; c) x-ray sorting of semifinished specimens according to the porosity scale; d) specimen manufacture from semifinished product.

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TABLE 1. Heat-Treatment Schedules and Mechanical Properties of Alloys AK6 and VAL10

Alloy	Heat treatment schedule	Quenching				Aging			Mechanical properties	
		temperature, ℃	soaking time, h	cooling medium	cooling temperature, ℃	temperature, ℃	soaking time, h	cooling agent	σ_f, MPa	δ, %
VAL 10	T5	535±5 then	7	—	—	—	—	—	—	—
		545±3	9	Water	25...35	153±3	5	Air	426,0	8,4
AK6	T1	515±5	4	»	17...18	160± 5	6	»	408,0 (along fibers) 384 (across fibers)	11,8 7,8

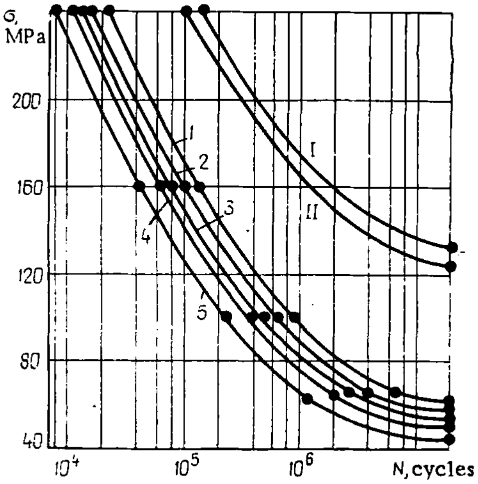

Fig. 1. Fatigue curves for specimens of alloys AK6 along (I) and across (II) fibers and VAL10, tested in air with a failure probability of 50%.

Melting of alloy VAL10 was carried out in a Kolleman type gas-crucible furnace with a 300-kg-capacity cast-iron crucible. Charge material was ingots of previously melted alloy VAL10; and the product recovery was 30% of the charge weight. Molten alloy was treated with potassium fluorozirconate (K_2ZrF_6) in an amount of 0.5% of the alloy weight at 730-740°C.

In order to determine the mechanical properties of the alloy, castings and specimens 12 mm in diameter were prepared by pouring into sand molds by the process current in the factory. Pouring temperature was 710-725°C. The chemical composition of the melt corresponded to technical specifications.

In order to prepare specimens of alloy AK6, forgings 230 × 230 mm in cross section were forged from bars 250 mm in diameter in an MA-417 hammer (during forging, the direction of the blank longitudinal axis was changed twice).

Specimen blanks of alloy AK6, cut from forgings in the longitudinal and transverse directions, were prepared by a schedule similar to that for alloy VAL10, excluding point "c".

Heat-treatment of alloy VAL10 was carried out by schedule T5 in PAP3M (hardening) and PAP4M (aging) furnaces, and for alloy AK6 by schedule T1 in ÉTA-2 (hardening) and PAP4M (aging) furnaces. Heat-treatment schedules and mechanical properties of the test alloys are given in Table 1. Monitoring of the mechanical properties of castings was carried out on individual cast specimens, heat-treated together with the castings. The mechanical properties of forgings were determined in specimens 5 mm in diameter (GOST 1497—73).

Given in Fig. 1 are fatigue curves for alloys VAL10 with different degrees of porosity (from points 1 to 5 on the scale) and AK6 with longitudinal and transverse orientation of the texture. Points on the curve correspond to the mean arithmetic value of endurance

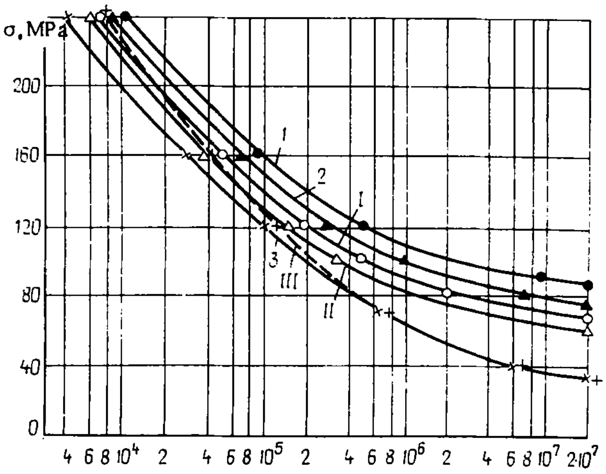

Fig. 2. Fatigue and corrosion—fatigue curves of specimens of alloys AK6, cut along (1, I) and across (2, II) the fibers respectively, and VAL10 with porosity of point 3 on the scale (3, III) with action of stress concentration: 1, 2, 3) testing in air; I, II, III) in 3% aqueous NaCl solution.

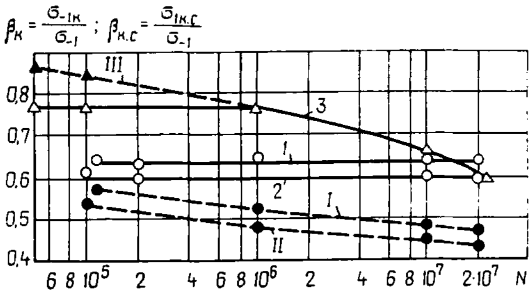

Fig. 3. Change in factors β_k and $\beta_{k.c}$ for the effect of a notch on the fatigue resistance of alloys AK6 and VAL10 in relation to test base in air (1, 2, 3) and in a corrosive medium (I, II, III): 1, I and 2, II) alloy AK6 along and across the fibers, respectively; 3 and III) alloy VAL10 with porosity at point 3 on the scale.

logarithms for a batch of 16-20 specimens tested at a single stress level, i.e., these curves correspond to a failure probability of 50%.

From the nature of the location of the family of curves for alloy VAL10 it can be seen that an increase in porosity leads to a marked reduction in fatigue properties. This may be explained both by stress concentration caused by pores, and by the reduction in the active cross section of the specimen gage length connected with an increase in the size and number of pores. Quantitatively, the reduction in fatigue limit on a 20×10^6 cycle basis for an alloy with a porosity estimated at points 2 to 5 on the scale, compared with that for an alloy with porosity of point 1 on the scale, is 6, 14, 21, and 29%, respectively.

There is a more marked reduction in alloy endurance. At a stress level of 62 MPa, corresponding to the base value of fatigue limit for the alloy with porosity of point 1 on the scale, specimen endurance estimated for porosity of points 2 to 5 on the scale is reduced, respectively, by factors of 5, 6, 8.5, and 15.5.

It also follows from Fig. 1 that the nature of fatigue curves for alloy AK6 is almost the same both for specimens along and across the fibers. In the first case the fatigue limit is about 10 MPa greater than in the second over the whole test-endurance range. This points to comparatively small anisotropy for alloy AK6 fatigue properties.

Comparison of fatigue limits for alloys VAL10 and AK6 (see Fig. 1) indicates that for alloy AK6 they are much higher. The absolute fatigue limit for alloy AK6 is about 90-100

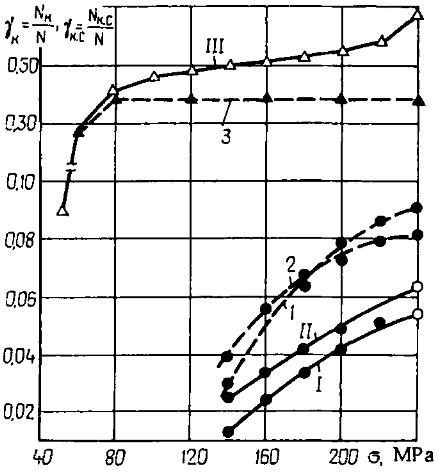

Fig. 4. Change in factors γ_k and $\gamma_{k.c}$ for the effect of a notch on the endurance of alloys AK6 and VAL10 in relation to the cyclic stress level with tests in air (1, 2, 3) and in a corrosive medium (I, II, III): 1, I and 2, II) alloy AK6 along and across the fibers, respectively; 3 and III) alloy VAL10 with porosity at point 3 on the scale.

MPa (respectively for specimens cut across and along the fibers) greater than that for alloy VAL10 with a porosity of point 3 on the scale over the whole test-endurance range.

Of practical interest are the properties (including fatigue) of castings of the lowest quality (with porosity of point 3 on the scale) permissible according to the OST for building into structural components.

Given in Fig. 2 are fatigue curves and the corrosion–fatigue curves for alloys AK6 and VAL10 under the action of stress concentration.

Comparison of fatigue curves for the test alloys obtained in the original condition in air (Fig. 1) with similar curves for alloys under the action of stress concentration and corrosive media (Fig. 2) show that notches and a corrosive medium markedly reduce the fatigue resistance of both alloys.

As criteria for the quantitative evaluation of the effect of a notch and a corrosive medium on fatigue limit and endurance of alloys AK6 and VAL10, factors β (Fig. 3) and γ (Fig. 4) were taken, respectively, as:

$$\beta_к = \frac{\sigma_{-1к}}{\sigma_{-1}}; \qquad \beta_{к.c} = \frac{\sigma_{-1к.c}}{\sigma_{-1}};$$

$$\gamma_к = \frac{N_к}{N}; \qquad \gamma_{к.c} = \frac{N_{к.c}}{N},$$

where β_k and $\beta_{k.c}$ are factors for the effect of stress concentration on fatigue limit for these alloys in air and with the action of a corrosive medium, respectively; σ_{-1}, σ_{-1k}, and $\sigma_{-1k.c}$ are fatigue limits for the test alloys in the original condition in air, with the action of a stress concentrator, and with the combined effect of a stress concentrator and a corrosive medium, respectively, on a base of N cycles; γ_k and $\gamma_{k.c}$ are factors for the effect of stress concentration on the endurance of test alloys in air and with the effect of a corrosive medium, respectively; N, N_k, and $N_{k.c}$ are endurance of the test alloys in the original condition in air, with the action of stress concentration, and a corrosive medium, respectively, at a stress level σ.

As follows from Fig. 3, the reduction in fatigue limit for alloy AK6 with a notch tested in air is 36-40%, and it is almost independent of test base. The reduction in fatigue limit for alloy VAL10 up to a base of 10^6 cycles remains almost constant (24%). With an increase in test base this reduction increases, and with $N = 20 \cdot 10^6$ cycles it is, as for alloy AK6, 40%.

With the combined effect of a notch and a corrosive medium there is a further reduction in the fatigue limit for alloy AK6; this reduction is almost the same both for specimens cut along and across the rolling direction, and it is 45-53% in the test endurance range.

The effect of stress concentration on fatigue limit for alloy VAL10 under the action of a corrosive medium in the load range 32-70 MPa hardly develops. With an increase in cyclic stress the fatigue limit for alloy VAL10 under similar conditions increases a little. As a result of this, with endurances less than $70 \cdot 10^6$ cycles the corrosion-fatigue limit for specimens of alloy VAL10 under the action of stress concentration is greater than the corrosion-fatigue limit for specimens of alloy AK6 cut across the fibers.

This is evidently connected with the mechanism of fatigue crack initiation and the effect of adsorption [8]. With high overloads (in the zone of limited endurance), when crack initiation is caused by local hardening, the action of adsorption develops in facilitating emergence of dislocations at the surface and resorption of local hardening, which leads to an increase in fatigue resistance.

The effect of stress concentration and a corrosive medium has a more marked effect on endurance of the test alloys. A quantitative estimate of this effect is given in Fig. 4, and it is expressed by means of factors γ_k and $\gamma_{k.c}$.

As can be seen, the reduction in endurance of alloy AK6 specimens with a notch cut both along and across the fibers is almost the same; in the cyclic stress range 140-240 MPa the amount of this reduction is 91-97%, respectively.

The nature of the effect of a notch on endurance of alloy VAL10 is somewhat different. In the cyclic stress range 52-80 MPa the reduction in endurance of this alloy is 91-64%. With an increase in stress to 240 MPa this reduction is almost constant (64%).

Attention should be drawn to the markedly small effect of stress concentration on the endurance of alloy VAL10 compared with alloy AK6. This is explained by the presence in cast VAL10 alloy of specimens with a large number of pores which, as additional stress concentrators themselves, relieve the main concentrator.

The combined effect of a notch and a corrosive medium reduces the endurance of alloy AK6 specimens cut in both texture directions to an even greater extent at all cyclic stress levels. The greatest reduction in endurance (99%) is observed for specimens cut along the fibers at a stress level of 140 MPa (curve 1 in Fig. 4).

A corrosive medium does not affect the endurance of VAL10 alloy specimens with a notch in the cyclic stress range 32-70 MPa (in this loading range curves 2 and III in Fig. 4 are identical). In the cyclic stress range 70-240 MPa a corrosive medium promotes an increase in the endurance of specimens with a stress concentrator, and correspondingly the value of factor $\gamma_{k.c}$ will be higher than the value of factor γ_k (with $\sigma_{max} = 80...240$ MPa $\gamma_k = 0.36$; $\gamma_{k.c} = 0.4...0.67$, curves 3 and III in Fig. 4).

It is noted that with a reduction in cyclic loading level the effect of a notch on endurance of the test alloys increases both with testing in air and in a corrosive medium.

It is of practical interest to compare the level of the effect of stress concentration on the endurance of alloy VAL10 with a varying degree of porosity.

Tests were carried out on batches of 12-15 specimens for each point on the porosity scale at the level of maximum stress 65 MPa. Given in Table 2 are values of endurance for specimens corresponding to the mean arithmetic logarithm of endurance for the test batches of smooth specimens and specimens with stress concentrators, and also values of a factor for the effect of stress concentration on endurance.

As can be seen, with an increase in specimen porosity from point 1 to point 5 on the scale factor γ_k increases from 0.128 to 0.5, which indicates a reduction in the effect of stress concentration on the endurance of alloy VAL10 with an increase in casting porosity. It is noted that the absolute value of notched specimen endurance falls from $0.77 \cdot 10^6$ to $0.53 \cdot 10^6$ cycles with an increase in their porosity from point 1 to point 5 on the scale.

This confirms the assumption about the effect of pores on the effectiveness of stress concentrators in castings, i.e., pores are additional concentrators relieving the main concentrator, and to a greater degree with increasing pore size and number.

TABLE 2. Fatigue Endurance of Alloy VAL10 Specimens

Porosity scale	$N \cdot 10^{-6}$, cycles	$\gamma_{\text{к}} = \frac{Nk}{N}$
1	$\frac{6}{0{,}77}$	0,128
2	$\frac{2{,}97}{0{,}7}$	0,236
3	$\frac{2{,}14}{0{,}6}$	0,280
4	$\frac{1{,}91}{0{,}56}$	0,293
5	$\frac{1{,}06}{0{,}53}$	0,500

Note. Data given beneath the line are for a smooth specimen, and above the line for a notched specimen.

CONCLUSIONS

1. The fatigue resistance of cast aluminum alloy VAL10 depends on the degree of casting porosity. There is no marked anisotropy in the fatigue properties of alloy AK6 in relation to texture direction.

2. Under the action of stress concentration (notch r = 1 mm) the fatigue limit of alloy AK6 is reduced by 36-40% and it is almost independent of test base. For alloy VAL10 this reduction in fatigue limit depends on test base, and it is 24% with $N = 5 \cdot 10^4 - 10^6$ cycles and 24-40% with $N = 10-20 \cdot 10^6$ cycles.

3. The reduction in alloy AK6 endurance with presence of a notch is almost identical for specimens with longitudinal and transverse orientation of the texture.

4. With an increase in alloy VAL10 specimen porosity the degree of the effect of stress concentration on endurance is reduced, which may be explained by an increase in the relieving effect connected with an increase in pore number and size.

5. Under conditions of simultaneous operation of stress concentration and corrosion medium the reduction in fatigue limit for alloy AK6 is 45-53% in the test endurance range, both for specimens of longitudinal and transverse orientation of the texture.

6. It was established that a corrosive medium has practically no effect on the endurance of notched alloy VAL10 specimens in the cyclic loading range 32-70 MPa. With endurances less than $70 \cdot 10^6$ cycles, the corrosion—fatigue resistance of alloy VAL10 under the action of stress concentration is greater than for alloy AK6 (across the fibers).

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