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LOW-CYCLE FATIGUE OF STRUCTURAL ALLOYS IN RELATION TO THEIR PLASTICITY

by

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By: R. N. Sizova

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

LOW-CYCLE FATIGUE OF STRUCTURAL ALLOYS IN RELATION TO THEIR PLASTICITY

R. N. Sizova

A study of the repetitive action of high stresses which exceed the yield point of a material is of substantial interest for an evaluation of the supporting power of reusable engine parts (for example, compressor plates), and also engine parts that are used once which are subjected to technological control with high loads in the process of manufacture (for example, inside pressure), the stresses which, especially in their concentration zones, exceed the yield point. Depending on the size of the accompanying load and its number of action cycles failure at such a load is caused either by the monotonic accumulation of plastic deformation and exhaustion of the plasticity resource of the material or by the formation of fatigue cracks [1, 2].

The first type of failure has a tough static character, connected to considerable plastic deformations and, according to [1, 3], it is determined by the size of the monotonically accumulated plastic deformation. The second type of failure connected with variable plastic deformations is determined by amplitude of this deformation and gives a breakdown of the fatigue character [1, 3].

Passage from the first type of failure to the second, depending on the material tested, its hardening ability, the degree of heterogeneity of the stress condition, takes place in the area of numbers of cycles, 10^2-10^5 [3-8].

This work presents the results of tests at small load number of a wide circle of materials, which were used in the design of engines.

Studies of the strength of a number of structural materials were conducted on round samples, smooth, and with notches, at a pulsing tension cycle.

The hydraulic rupture test machine "Amsler" was used for the tests, which was equipped with electric-contact limiters, making it possible to accomplish loading at a frequency of 2 cycles per minute.

The study was made on martensite class steel EI-961F, EI-961, SN3, SN2A and VNS-2, nickel chrome steel EP-696M, EI-835, nickel alloy VZh-101, copper alloy BrKhO-8 and aluminum alloy AK-4. All these materials are used for hull parts, shafts, vane wheels, and other power parts of engines. The basic mechanical features of the tested materials are presented in Table 1. The tests were conducted on round samples, smooth, and with notches 5 mm in diameter. The specimens with a notch had radius vector in the notch of 0.3 mm; the theoretical coefficient of stress concentrations was $\alpha_\sigma = 2.7$. Measurement of the deformations upon removal of diagrams of deformation was accomplished on the smooth samples with the aid of a Martens device.

To evaluate the deformation characteristics and their changes in process of repeated loading over the first three-five cycles measurement of the deformations was accomplished; on the smooth specimens the elongation was measured, and on the samples with the notch - the transverse contraction.

Testing of the smooth specimens at repeated load, accomplished at a constant load amplitude (soft load), did not make it possible to obtain a clear connection between stresses and the number of cycles. The base of tests of all the tested materials, except steels EI-961F and EI-961, was 200-300 cycles. For steels EI-961F and EI-961 - 1000-2000 cycles. At the selected base of the tests a

Table 1.

Material	Heat treatment	σ_B kgf/mm^2	$\sigma_{0.2}$, kgf/mm^2	δ, %	ψ, %	H_{V50}	Notes
EI-961F	Normalization 1070° – 2 h; annealing 715–720° – 2 h; quenching 1070° – 2 h; cooling in oil; tempering 550° – 2 h. Repeated tempering 550° – 2 h	147	127.5	7.2	49.2	438	Group A from a disc (radial)
	Normalization 1070° – 2 h; annealing 715–720° – 2 h; quenching 1070° – 2 h; cooling in oil; tempering 545° – 2 h.	164	–	9.1	42	472	Group C from a disc (radial)
	Normalization 1070°C – 2 h; annealing 715–720° – 2 h; quenching 1070° – 2 h; cooling in oil; tempering 555°C – 2 h	147	123	10.5	43.7	455	Group B from a disc (tangential)
EI-961	Normalization from 1000–1020°C; quenching 1000°C, cooling in air, tempering at 550–600°C	125	107	11.8	6.4	–	From a bar (diameter 80)
SN-3	Heating 930°C – 20 min; treatment by cold –50°C – 4 h; tempering 650° – 1 h	104	71	20	52	–	From a bar (diameter 30)
	Heating 950°C – 20 min; treatment by cold –50°C – 4 h; tempering 450° – 1 h	122	–	7.8	23.5	370	From a turbine housing

Table 1 (Continued)

Material	Heat treatment	σ_B, kgf/mm^2	$\sigma_{0.2}$, kgf/mm^2	δ, %	ψ, %	HV_{50}	Notes
SN-2A	990°C – 20 min; -50°C – 4 h; tempering 410°C – holding 60 min	132	112	10	51	405	From a bar (diameter 30)
VNS2	Quenching 950°C – 6 h; cooling in air	120	80	12	60	350	From a bar (diameter 45)
EI-696M	Quenching 1170°C – 6 h; cooling in air; tempering 780° – 16 h; cooling in air	102	75	12	18	320	From a bar (diameter 45)
EI-835	Quenching 1150°C – 60 min; cooling in air	80	37	50	66	193	From a bar (diameter 45)
VZh-101	Quenching 1200°C – 60 min; cooling in air	115	83	29	41	352	From a bar (diameter 45)
AK-4	Heating 535°C – 60 min (cooling in water)	43	32	8.8	25	130	From a bar (diameter 45)
BrKhO-8	Quenching 930°C – 2 h – water; tempering 450°C – 5 h; cooling in air	42	27.5	28.0	75	—	From a bar (diameter 45)

majority of the samples from the alloys studied was not destroyed, although the size of the stresses reached a yield point of (0.99-0.9 σ_B). The test data on the smooth samples were used for studying the change in the deformation characteristics in the process of repeated loading.

The plasticity characteristics at failure of δ and ψ are presented in Table 1 (average value of test data for 3-5 samples). The deformation curves at a single load up to failure were also obtained by testing 4-5 samples. An analysis of the accumulation of deformations using the deformation curves for repeated loading showed that for all the investigated materials cyclic hardening is characteristic in the process of repeated loading, which is expressed by the increase in the yield point and the reduction from cycle to cycle of the deformation being accumulated in the cycle.

Smooth specimens of separate alloys were destroyed during repeated loading. Thus, in testing smooth specimens at σ_N = 0.94-0.99 σ_B on a base of 1000 cycles, 25% of the tested specimens of FI-961F steel (from a compressor plate) and 50% of SNZ steel (from a turbine casing) were destroyed.

To study the characteristics of these materials in relation to those not having failures in the smooth samples the characteristics of strength and the plasticity of all investigated materials depending on preliminary cyclic deformation were determined.

The test data before failure after conditioning by different numbers of cycles at σ, close to σ_B, presented in Table 2, attests to the unessential effect of preliminary conditioning on the characteristics of strength. For a majority of the tested materials the limits of strength changed insignificantly; the yield points rose.

For the characteristics of change in the plasticity at repeated loading, the relationship of the sum of accumulated deformations under cyclic loading (conditioning) ϵ_N and single loading to

Table 2.

Alloy	Mode of conditioning: σ_N	Mode of conditioning: N	ε_N, %	Tests after conditioning: σ_B kgf/mm²	δ, %	ψ, %	$\frac{\delta+\varepsilon_N}{\delta_0}$	$\sigma_{n.q.}$ kgf/mm²
EI-961	—	—	—	125	11,8 (δ_0)	6,4	1	107
	113—117	1000	0,55—2,04	125—131	9—12,6	6,5—6,8	0,88—1,16	107—129
EI-961F	—	—	—	147	7,2 (δ_0)	49,2	1	127
	138—149	500—2000	1—5,8	147—163	2,5—4	30—48	0,5—1,17	146—160
	—	—	—	120	10 (δ_0)	60	1	80
VNS2	113—116	109—400	1,1—1,4	121—124	74—90	57—61	0,86—1,08	—
	—	—	—	132	10 (δ_0)	51	1	112
SN2A	100—115	200	0,3—1,3	129—134	10,1—11	50,6—51,7	1,07—1,12	—
	—	—	—	104	20 (δ_0)	52	1	71
SN3 (bar)	90	200	4—6	109—117	12,6—13,8	48—54	0,8—0,93	—
SN3 (from a turbine)	—	—	—	112	7,8 (δ_0)	23,5	1	—
	110	200	0,3—3,2	127—131	2,0—4,9	8,3—19,3	0,3—0,9	—
EI-835	—	—	—	80	50 (δ_0)	68	1	37
	70	200	19,1—25,6	82—104	20—27	57—68	0,82—0,9[illegible]	—
EI-696M	—	—	—	103	16 (δ_0)	20	1	75
	86	10	1,6—6	99—10[illegible]	7,7—13	8,3—17	0,8—0,98	—
VZh-101	—	—	—	115	32 (δ_0)	40	1	83
	90	10	1,2—2,5	109—118	23,4—30	35—42	0,8—0,96	—
BrKhO-8	—	—	—	41	30 (δ_0)	75	1	27,5
	36	5—250	8,5	36—42	20—23,0	75—81	0,9—1,1	

breakage after conditioning δ to the value of relative elongation in specimens without conditioning - δ_0 was determined.

The size of this ratio $a_\delta = (\varepsilon_N + \delta)/\delta_0$, given in penultimate column of Table 2, makes it possible to evaluate the loss of plasticity in the material (its embrittlement) as a result of preliminary cyclic deformation. In this case it was considered that if $a_\delta \geq 1$, embrittlement of the material does not occur and the summary accumulated deformation up to failure under cyclic and single loading does not differ substantially; if $a_\delta < 1$, the material becomes brittle.

As follows from the data presented in Table 2, the values of a_δ for the majority of tested materials are sufficiently stable from sample to sample and are insignificantly distinguished from a unit: for steels VNS2, SN-3 (from a bar), EI-961, EI-696M, EI-835, and alloy VZh-101 a_δ = 0.8-0.9, for steel SN2A a_δ > 1.

For steels EI-961F and SN3 (from a turbine casing) considerable scattering of the value of a_δ is characteristic, being from 0.3 to 1.1. For these materials, the separate specimens of which exhibited large-scale embrittlement, one should also expect instability of the test data on low-cyclic failure.

Actually, steels SN3 (from a turbine casing) and EI-961F exhibited the greatest instability of all the tested materials during testing of the smooth samples at repeated loading.

Tests to failure of smooth samples, which underwent preliminary cyclic deformation, make it possible to evaluate according to the degree of embrittlement of the material its sensitivity to repeated low-cyclic loading.

Test data from specimens with a notch are presented in the charts given below in the form of curves of the dependence of the number of cycles to failure from stress. The curves are built in logarithmic coordinates. Along the ordinate axis of these charts the logarithms of nominal stresses are plotted which are determined as load P, relating to the cross-sectional area of the specimen along the bottom of the notch; the abscissa axis - the logarithms of the numbers of cycles. On these charts the curves of change in the relative lateral contraction ψ, measured in the specimens, which were destroyed after a corresponding number of cycles, are plotted.

As follows from the presented charts, repeated loading by a pulsing tension cycle exerts a substantially greater effect on the strength of the notched specimens than on the smooth ones. If smooth specimens of all the tested materials, except EI-961F and SN3 (from a turbine casing), are not destroyed in the range of number of cycles of up to 500-1000 cycles, then for notched specimens from a majority of tested materials the expressed dependence between stress and the number of cycles before failure is obtained.

For martensite class steels, which were studied in the range of numbers of cycles from 0.5 to 0.5-1 × 10^3, curves, characterizing the dependence of stresses on the number of cycles are presented in Figs. 1 and 2 as an example. It was possible to approximate them in two sections. The initial section of the curve up to the number of cycles, close to 10^2, goes slantingly with a very small slope toward the axis of abscissa. The second section of the curves, studied more specifically, can be expressed in selected coordinates by a straight line.

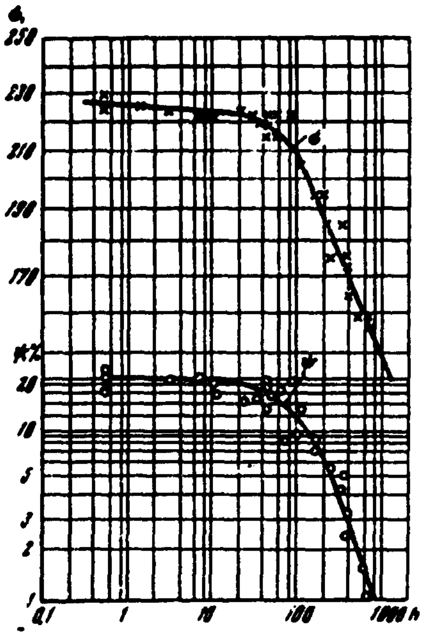

Fig. 1.

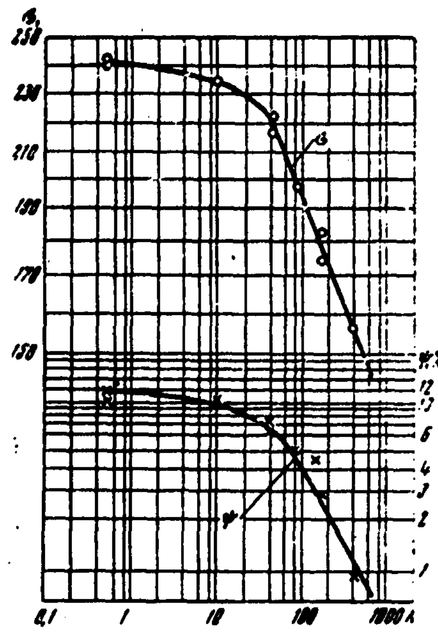

Fig. 2.

Fig. 1. Curves of low-cycle fatigue and the changes in plasticity of notched specimens of steel EI-961.

Fig. 2. Curves of low-cyclic fatigue and the changes in plasticity of notched specimens of steel SN2A.

Analysis of the character of failure of the specimens, which broke under stresses, corresponding to the first section of the obtained curves, shows that failure in this range, as a rule, has a tenacious character and is accompanied by considerable plastic deformation, which almost does not change in proportion to the increase in the number of cycles.

In proportion to the increase in the number of cycles to failure, test data are stabilized; the sharp drops of destructive stresses characteristic for the first cycles of loading when N > 10-20 are not observed.

An indirect index of sensitivity to defects was obtained during testing of the smooth specimens of the steels EI-961F and SN3 (from a turbine casing) in the form of unstable and small values for the sum of the relationships of deformations a_{σ}. But the sensitivity to such defects, which is expressed directly in the drop of the strength characteristics, appeared most clearly in the notched specimens.

The most substantial defects appear already during single load testing; for detection of smaller defects repeated loading over the course of several cycles is necessary.

An analysis of the deformation characteristics at failure of the notched specimens (see curves ψ in Fig. 2) made it possible to connect the behavior of the examined steels to these characteristics, expressed in this case by the size of the relative lateral contraction ψ. As follows from the obtained data, the upper value of lateral contraction of the notched specimens of steel SN-3 comprises on the whole 2-2.5%, of specimens of steel EI-961F 6-7%. For samples of steels EI-961, SN2A, VNS2 and SN3 (from a bar with high tempering) these values are 20, 11, 26, and 16% respectively.

Thus the instability of the values of destructive stresses of specimens from steel EI-961F and SN3 (from a turbine casing with low tempering) is connected both with the possible presence of small defects in the metal or on the surface of the notch, and also with the great sensitivity of the material to these defects, caused by the small plasticity of the material.

The results of tests of notched specimens, which fail in the range of small numbers, form a gently sloping curve. Failure in this range bears a quasi-static character, accompanied by a narrowing of the cross section, whose dependent on the number of cycles does not bear an expressed character. The transition to the second section of the curves of low-cyclic fatigue, investigated more specifically for steels EI-961F, EI-961, VNS2, SN2A, and SN3 (from a bar) begins at the number of cycles close to 10^2. This second section can be approximated in selected logarithmic coordinates by a straight line equation of the type $\sigma^m N$ = const. A study of the character of failure shows that a majority of fractures in this range bear traces of fatigue failure. For a number of specimens they are exhibited in the form of clearly expressed circular zone, evenly spread on the circumference of the specimen; in some specimens there are only insignificant one-sided sections with traces of fatigue failure.

The curve, characterizing the size of the limit, which fades after failure of the fatigue cracks depending on the number of cycles to the failure of notched samples of steel EI-961, is presented in Fig. 3.

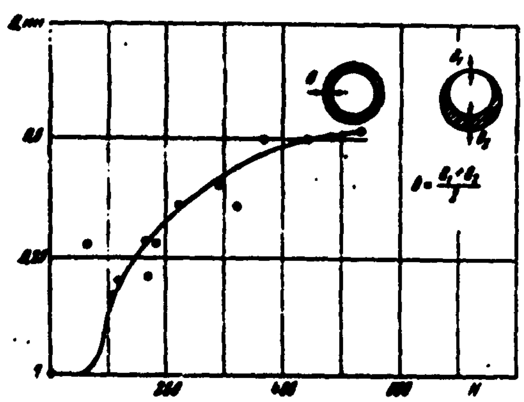

Fig. 3. Change in the width of maximum fatigue cracks, measured on notched specimens after failure, depending on the number of cycles (steel EI-961).

The transfer from one form of failure to another, characterized by the change in the passage of the low-cyclic fatigue curves, is also accompanied by a change in the deformation characteristics ψ. The values of the lateral contraction during the transition to fatigue failure of steels EI-961, VNS2, SN2A and SN-3 (from a bar) fall sharply. For steels EI-961F and SN3 (from a turbine casing) with little plasticity under single loading this drop is expressed less sharply.

For some tested materials of the selected base of tests, this was insufficient for detection of the transition to the second type of failure. Thus, during the tests of steel SN3 (from a turbine casing) only on the fractures of three samples, which failed after 500-700 cycles, were insignificant traces of fatigue failure found. During tests of steel EI-696M based on 100 cycles all fractures bore a static character and were accompanied by considerable plastic deformation and the formation of a large number of static cracks after 80-100 cycles.

The results of tests of alloys - nickel VZh101 to 500 cycles, aluminum AK-4 to 200 cycles and highly-alloyed chrome-nickel-manganese steel EI-835 to 2000 cycles - just as the steels examined above, can be presented in the form of two sections of fatigue curves with different (in the number of cycles) arrangements of the fracture points on the curves.

The results of tests of specimens of the alloy BrKhO-8 (Fig. 4) were different from the majority of investigated materials. For this alloy the failures were accompanied by a large plastic deformation ψ = 45-55%, which diminishes slightly with an increase in the number of cycles up to 1000 in a majority of the tested specimens. The failures of these specimens bore a statical character, accompanied by the formation of a large number of cracks (visible with an increase ×30 after 100-200 cycles); presence of these cracks did not lead to retardation of the deformation process. However in separate specimens a substantial decrease in plastic deformation at failure has been detected (up to 15-25%). Namely, the fractures of these specimens had clearly expressed focuses of fatigue failure.

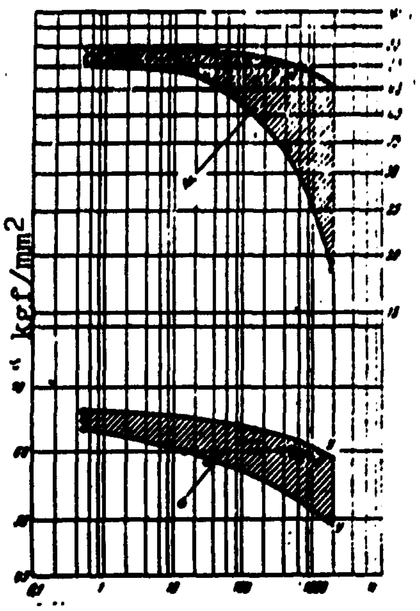

Fig. 4. Curves of low-cyclic fatigue and changes in the plasticity of notched specimens of alloy BrKhO-8.

Thus at the selected base of tests (1000-2000 cycles) the alloy BrKhO-8 was located in a transitional stretched range, in which both statical and fatigue failure are possible. Displacement of the region of transition to fatigue failure to the side of a large number of cycles is connected to the high plasticity of alloy BrKhO-8. At approximately these numbers of cycles the break in the fatigue curve was detected also for steel EI-835 with plasticity ψ = 35-40%.

Thus despite the differences revealed during the study of different materials, their behavior under repeated loading is characterized by general regularities.

Conclusions

1. Tests of smooth samples from materials of different classes under repeated pulsing loading to stresses which reach 0.99 σ_B, did not make it possible to reveal a clear connection between the acting stresses and number of cycles up to failure in the range of up to 1000-2000 cycles.

2. Tests up to failure of the smooth samples after conditioning with repeated loading and comparing the size of the sum of the

deformation relationships, accumulated during conditioning and the failure of a_{δ} with a unit, made it possible to evaluate the sensitivity of the material to repeated loading and to connect it to the amount of monotonically accumulated deformation, which decreases with the presence of defects in the material.

3. The results of tests of notched specimens at a selected base of testing (to 1000-2000 cycles) may be presented in the coordinates lg σ-lg N by the rectilinear dependence with fracture at 100-1000 cycles. The presence of the fracture on the curves of low-cyclic fatigue is connected to the transition of failure from the quasi-static to the fatigue.

4. Static failures under stresses, corresponding to the first section of the low-cyclic fatigue curve, are determined by the processes of the monotonic accumulation of plastic deformation at cyclic loading and take place during one-sided accumulated deformations, differing little from that obtained under single loading.

5. Sharp deviations in test data from the low-cyclic fatigue curve in the range of static failure are connected to the premature failure of microdefects present in the material. Such failures have a brittle character and take place during the first one-ten cycles.

6. The failures of notched specimens under stresses, corresponding to the second section of low-cyclic fatigue, are determined by the processes of cyclic accumulation of plastic deformations before formation of fatigue cracks and by the characteristics of development of a fatigue crack.

In specimens which were destroyed as a result of the development of fatigue cracks, a substantial drop in the accumulated deformation, measured after failure, is observed.

7. The dependence of ψ on the number of cycles, just as the curve of low-cyclic fatigue, can be presented by the coordinates

lg ψ-lg N of the curve with a break at the point of transition from the quasi-static to fatigue failure (in the area of 100-1000 cycles).

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13. ABSTRACT

A Study was made of the low-cycle fatigue life of martensitic steel EI-961F, EI-961, SN3, SN2A, VNS-2, chromium-nickle steels EI-696M, EI-835, nickel alloy VKh-101, copper alloy BrKhO-8, and aluminum AK-4. The fatigue tests were made with smooth and notched samples. For notched samples, relations between stress and number of cycles are presented. No such relations for unnotched samples could be found. The mechanism of the low cycle fatigue rupture is discussed. [AT0033226]

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Mechanical Fatigue Cyclic Load Test Fatigue Test Alloy Structure Plasticity						