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Titanium alloy fatigue strength and eigenfrequency stability

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Abstract: We conducted a study on fatigue in flat samples of the VT3-1 titanium alloy using “soft” cyclic beam bending tests. For this purpose, we developed an innovative electromagnetic test bench. The test bench's electromechanical system induces mechanical vibrations at a frequency that matches the eigenfrequency of the sample, ensuring that the cyclic load frequency remains constant. The electromagnetic force bends the sample while the elastic force unbends it, producing a quasi-sinusoidal cyclic load. Through our investigation, we determined the impact of this cyclic loading on both cyclic strength and durability. Our findings indicate that the VT3-1 titanium alloy possesses high resistance to fatigue and an endurance limit. Furthermore, we observed a low variability of the experimental fatigue resistance in relation to the approximating fatigue curve, suggesting the alloy has high structural stability. This finding indicates that the VT3-1 titanium alloy possesses high structural stability. To assess eigenfrequency stability, we subjected the alloy samples to cyclic tests, interrupting them at a reference number of 50 million cycles to evaluate changes in eigenfrequencies and stability under loads close to the fatigue limit. The results showed that the titanium alloy has a high level of eigenfrequency stability. Interruptions in cyclic tests resulted in jump-like increases in eigenfrequencies, which was not observed in continuous tests. Nevertheless, the total eigenfrequency deviations from the initial value at the end of the tests were similar in both cases.

Keywords: titanium alloy, fatigue resistance, eigenfrequency stability, cyclic loading frequency, eigenfrequency, endurance limit, durability, cyclic strength

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Усталостная прочность и частотная стабильность титанового сплава

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Аннотация: Исследованы образцы титанового сплава ВТ3-1 на усталость при нагружении по «мягкой» схеме консольного изгиба плоских образцов. Для таких исследований была разработана оригинальная электромагнитная установка. В ней реализована работа на основе электромеханической системы, в которой возбуждение механических колебаний осуществляется исходя из собственной частоты колебания испытуемого образца, т.е. реализуется режим, когда частота возбуждающей силы (частота циклического нагружения) всегда равна частоте собственных колебаний образца. Изгиб образца производится электромагнитной силой, а разгиб происходит под действием сил упругости материала, тем самым обеспечивается циклическое нагружение, близкое к синусоидальному. Изучено влияние реализуемого в данной установке вида циклического нагружения на циклическую прочность и долговечность. Установлено, что исследуемый титановый сплав имеет высокие характеристики показателей сопротивления усталости и предела выносливости. В ходе проведенных исследований отмечен небольшой разброс экспериментальных значений сопротивления усталости образцов относительно аппроксимирующей линии кривой усталости, что свидетельствует о высокой стабильности структурно-чувствительных свойств титанового сплава ВТ3-1. Также исследованы образцы этого сплава на частотную стабильность. За контрольное число наработки было принято 50 млн циклов нагружения, при которых проводилась сравнительная оценка изменения частотных характеристик. Представлены частотные характеристики и выявлена динамика частотной стабильности испытаний образцов при нагрузках, близких к пределу усталости. Установлено, что исследуемый титановый сплав имеет высокие значения частотной стабильности. При этом перерывы в циклических испытаниях приводят к скачкообразному приросту частоты, а при непрерывных испытаниях такого не наблюдалось, однако общее отклонение частоты от первоначальной к концу испытаний примерно одинаковое.

Ключевые слова: титановый сплав, сопротивление усталости, частотная стабильность, частота циклического нагружения (ЧЦН), собственная частота колебаний (СЧК), предел выносливости, долговечность, циклическая прочность

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Introduction

Inelastic materials are commonly utilized for manufacturing spring elements that operate under complex cyclic loading, as well as components that maintain their dimensions under loads [1—7]. Inelastic properties observed under cyclic loading can be referred to as internal friction, imperfect elasticity, damping, mechanical hysteresis, energy dissipation, or cyclic load ductility [8]. Many researchers posit that microplastic deformations arising from cyclic loading are local and sporadic due to the heterogeneity of the material micro-properties. Meanwhile, others utilize dynamic mechanical analysis under temperature variations to determine changes in elastic strength and activation energy of the micro deformations [9—12].

We employed a novel experimental procedure to assess the stability of eigenfrequency in materials utilized for manufacturing elastic elements in high-precision emitters which convert electrical oscillations into mechanical vibrations. Even minor fluctuations in eigenfrequency, resulting from changes in elastic modulus, inelasticity properties, and atom/lattice oscillations, can lead to unsatisfactory oscillation conversion errors and early onset of fatigue failure [13—16].

The aim of this study is to evaluate the cyclic strength and eigenfrequency stability of flat samples made of the VT3-1 titanium alloy under "soft" cyclic beam bending tests.

Materials and methods

We designed and constructed a specialized auto-oscillating electromagnetic bench (see Fig. 1) for conducting cyclic beam transverse bending tests on flat samples [17]. The electromechanical system induces mechanical vibrations at a frequency equivalent to the eigenfrequency of the sample (thus, the cyclic load frequency always matches the sample eigenfrequency). The electromagnetic force bends the sample while the elastic force unbends it, producing a quasi-sinusoidal cyclic load (see Fig. 2).

We produced flat samples following the design depicted in Fig. 3. The stress in the reference cross-section of the sample was determined by analyzing the vibration amplitude. The proposed method involves establishing a correlation between the force applied to the sample and the sample displacement at the point of application and then estimating the stress based on the known force. We identified the analytical force-displacement relationship for the steady mode. It is assumed that under cyclic loads, the forces applied to the sample (inertia, elasticity, and external forces) generate maximum stress and displacement equal to those produced by a static load with a magnitude equivalent to the dynamic resultant force.

We tested the VT3-1 high-strength titanium alloy with the following chemical composition (wt.%): 85.95—91.05 % Ti; 0.2—0.7 % Fe; up to 0.1 % C; 0.15—0.4 % Si; 0.8—2 % Cr; 2—3 % Mo; up to 0.05 % N; 5.5—7 % Al; up to 0.5 % Zr; up to 0.15 % O; up to 0.015 % H; other impurities: 0,3 % (GOST 19807-91).

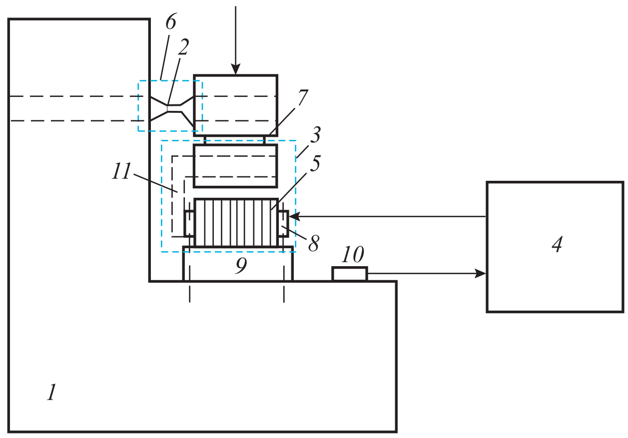
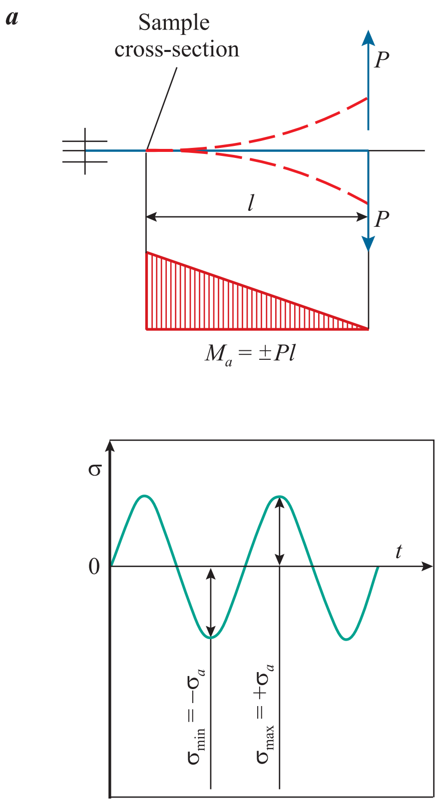


Fig. 1. Vibration stability test bench

1 – bed, ***2*** – sample, ***3*** – electromagnetic exciter, ***4*** – power supply and control components, ***5*** – solenoid coil, ***6*** – oscillation measuring system, ***7*** – ferromagnetic yoke, ***8*** – stator, ***9*** – dampers, ***10*** – accelerometer, ***11*** – П-shaped tape core

Рис. 1. Схема установки для испытаний на частотную стабильность

1 – станина, ***2*** – образец, ***3*** – электромагнитный возбудитель (ЭМ), ***4*** – блок питания и автоматики, ***5*** – катушка ЭМ, ***6*** – измерительная система параметров процесса колебаний, ***7*** – ферромагнитный якорь электромагнитного возбудителя, ***8*** – статор электромагнитного возбудителя, ***9*** – виброизоляторы, ***10*** – датчик виброускорения, ***11*** – П-образный ленточный сердечник



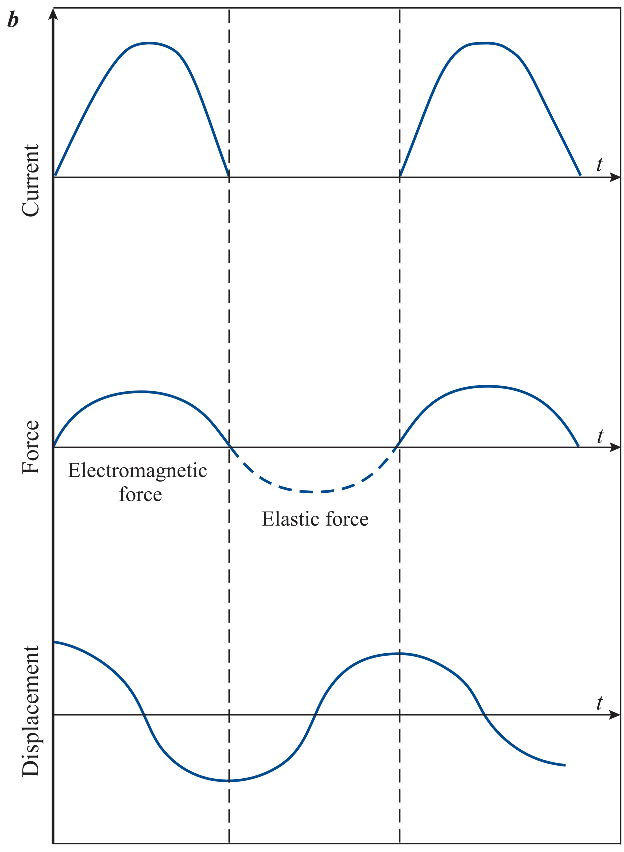
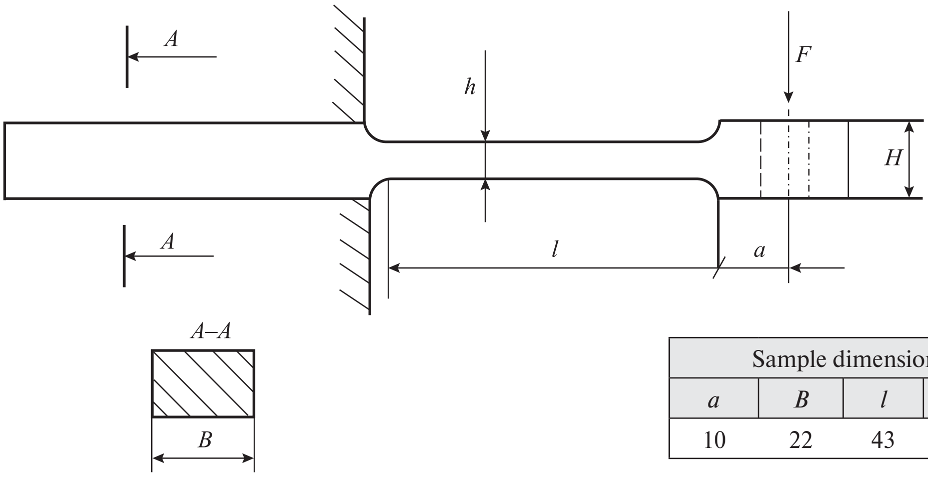


Fig. 2. Cyclic beam transverse bending of a flat sample (***a***). Synchronization of the current pulses, electromagnetic force, and elasticity force with the sample displacement (***b***)

Рис. 2. Нагружение по схеме консольного циклического поперечного изгиба плоского образца (***a***) и согласование импульсов тока, электромагнитной силы и силы упругости с перемещением консоли исследуемого образца в разработанной установке (***b***)



Sample dimensions, mm				
a	B	l	h	H
10	22	43	5	13

Fig. 3. Dimensional drawing of the test samples

Рис. 3. Эскиз и размеры образцов для испытания

The service life was set to be 50 million cycles, and we halted the fatigue tests each night, with the samples being stored under normal loading conditions.

As the stress approached the fatigue limit, the tests became more prolonged, and we kept the test bench operating overnight. However, we observed that the eigenfrequency of the sample altered after an overnight pause, whereby in the morning, following a 10-hour interruption, it was higher than the previous night when the test was halted.

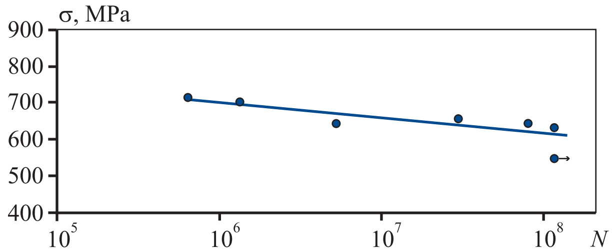


Fig. 4. VT3-1 titanium alloy fatigue curve after annealing at t = 870 °C

Рис. 4. Кривая усталости титанового сплава ВТ3-1 после отжига при t = 870 °C

Fatigue test results and discussion

Fig. 4 illustrates the fatigue curve obtained from the beam transverse self-oscillating bending tests conducted on the flat samples. The fatigue resistance, represented by the slope of the fatigue curve ($\mathrm{tg}\alpha_w = 0.0394$), was found to be low (or very low compared to [18]), while the endurance limit (σ_{-1} = 600 MPa) was high. The fatigue test results displayed in Fig. 4 exhibited low variability when compared to the approximating fatigue curve, indicating the high stability of the alloy's structural properties.

According to papers [19, 20], the number of cycles (N) vs. stress ($\mathrm{tg}\alpha_w$) curve becomes steeper as the damageability under cyclic loading increases. It is worth noting that the opposite triangle leg of $\mathrm{tg}\alpha_w$ represents the stress in the sample, while the adjacent leg represents the number of cycles to failure:

$$\mathrm{tg}\alpha_w = \frac{d\,\lg\sigma}{d\,\lg N}.$$

The physical significance of $\mathrm{tg}\alpha_w$ is related to the propagation rate of local plastic deformation in the surface layer. In the case of beam transverse bending tests, only the surface layer of the sample undergoes plastic deformation, while the rest of the sample experiences elastic deformation. As a result, the propagation rate of plastic deformation in the surface layer is affected by the elastic deformation of the rest of the sample.

The slope angle of $\mathrm{tg}\alpha_w$ indicates the increase in the number of cycles with respect to stress. A smaller $\mathrm{tg}\alpha_w$ value corresponds to a longer time to failure even under high loads. On the other hand, a steeper slope angle of the fatigue curve correspond to a higher $\mathrm{tg}\alpha_w$ value and a lower endurance of the sample. This means the VT3-1 titanium alloy features a low failure rate under cyclic loading.

Eigenfrequency test results and discussion

The key point is to investigate the eigenfrequency stability under loads close to the fatigue limit. To achieve this, individual samples were tested for eigenfrequency stability under the specified load. The samples used for the eigenfrequency tests had been subjected to different numbers of loading cycles. In order to make comparisons between the samples, the maximum eigenfrequency deviation (Δω) is assumed to be the eigenfrequency change from the initial value after $50 \cdot 10^6$ cycles. A positive Δω deviation represents an increase in the eigenfrequency, while a negative deviation represents a decrease.

Fig. 5 and 6 depict the eigenfrequencies of two VT3-1 titanium alloy samples under loads close to the fatigue limit.

Fig. 5, *a* displays two envelope curves, with the upper curve indicating the initial eigenfrequency and the lower curve representing the final eigenfrequency as the test bench was stopped after a daily run. The daily eigenfrequency changes during the cycle testing are contained within the area between the two curves.

In Fig. 5, *b* the eigenfrequencies are presented as a single polyline. The vertical steps signify the eigenfrequency changes following overnight breaks, while the sloped lines indicate the daily eigenfrequency variations as the number of load cycles increases.

The sample in Fig. 5, operated at 550 MPa stress, exhibited a total eigenfrequency deviation of 0.27 Hz. This deviation corresponds to the eigenfrequency deviation observed during the reference number of cycles (50 mln cycles). However, the largest eigenfrequency deviation of 0.36 Hz was observed approximately in the middle of the sample's service life, with the highest deviation occurring after the first 10 million cycles.

The total eigenfrequency deviation observed in the sample operated at 630 MPa stress in Fig. 6 was 0.34 Hz, which decreased to 0.32 Hz after the reference number of cycles (50 mln). No other significant eigenfrequency changes were detected. The largest eigenfrequency variation occurred after the first 10 million cycles, similar to the previous case.

It is worth noting that the observed eigenfrequency deviation was small (0.36 Hz), and its change during the overnight break was only 0.1 Hz.

Other researchers [21—25] have reported that fatigue test interruptions have little to no effect on the fatigue limit but may result in increased cycles to failure. However, in the case of eigenfrequency tests, our results indicate that interruptions do affect the eigenfrequency of

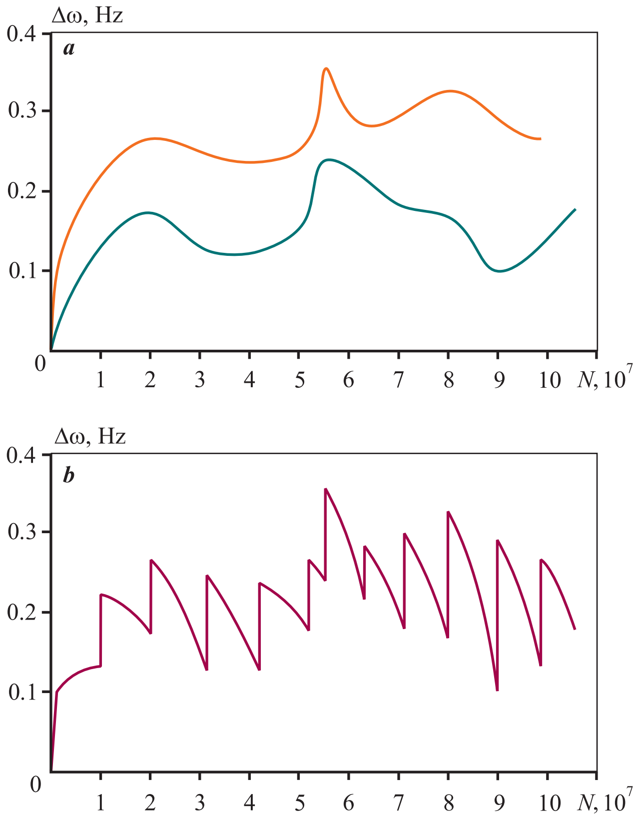


Fig. 5. Sample eigenfrequency variations (***a***) and deviations (***b***) vs. the number of load cycles
Initial eigenfrequency ω_0 = 231.28 Hz, load σ = 550 MPa

Рис. 5. Графические изображения изменения (***а***) и отклонения (***b***) частоты колебаний образца в зависимости от количества циклов нагружения
Начальная частота ω_0 = 231,28 Гц, нагрузка σ = 550 МПа

the samples. Specifically, we observed a 0.1 Hz increase in eigenfrequency when the test bench was turned on in the morning compared to when it was turned off the night before.

To provide a comparison, we conducted continuous tests on two samples of VT3-1 titanium alloy and found that the maximum eigenfrequency variation for sample *1* was +0.45 Hz, while for sample *2*, it was —0.09 Hz. This means that the eigenfrequency of sample *1* continuously increased, while that of sample *2* slightly decreased.

We also compared the eigenfrequencies recorded in the continuous and intermittent tests. The continuous tests did not result in any eigenfrequency jumps typical of the tests interrupted at night, but the overall eigenfrequency deviations from the initial value by the end of the tests were approximately the same. These findings further support the high stability of the titanium alloy eigenfrequency.

Continuous tests of the VT3-1 titanium alloy samples*

Результаты непрерывных испытаний образцов* из титанового сплава ВТ3-1

Sample *1*		Sample *2*	
Number of cycles, mln.	Frequency change, Hz	Number of cycles, mln.	Frequency change, Hz
1.9	0.13	2.0	0.01
5.4	0.15	4.5	–0.03
9.5	0.12	5.4	–0.07
12.8	0.22	10.5	–0.06
14.5	0.27	14.8	–0.04
20.3	0.31	19.0	–0.04
23.1	0.38	23.3	–0.05
24.7	0.37	24.2	–0.07
26.3	0.37	25.9	–0.08
27.2	0.43	26.1	–0.11
29.8	0.42	27.6	–0.10
32.3	0.45	28.6	–0.09
33.5	Failure	29.4	Failure

* Sample *1*. Stress U = 550 MPa, initial eigenfrequency ω_0 = 231.28 Hz; sample *2*: U = 580 MPa, ω_0 = 238.8 Hz.

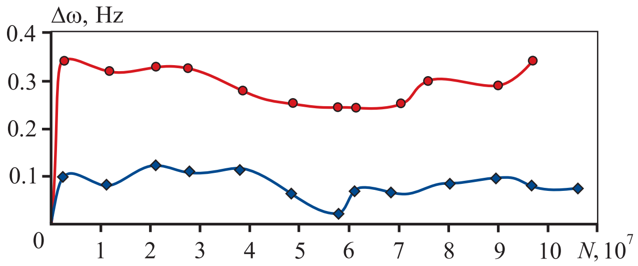


Fig. 6. Sample eigenfrequency deviations vs. the number of load cycles

Initial eigenfrequency ω_0 = 236.9 Hz, load σ = 630 MPa

Рис. 6. Графическое изображение отклонений частоты колебаний образца в зависимости от количества циклов нагружения

Начальная частота ω_0 = 236,9 Гц, нагрузка σ = 630 МПа

Conclusion

The fatigue behavior of VT3-1 titanium alloy flat samples was assessed using a “soft” self-oscillating cyclic beam bending test. The results indicated high fatigue resistance, with tgα_w value of 0.0394 and an endurance limit of σ_{-1} = 600 MPa. The fatigue test results also showed low variability relative to the approximating fatigue curve, suggesting high stability of the VT3-1 alloy eigenfrequency. The maximum eigenfrequency deviation observed was 0.36 Hz. However, cyclic test interruptions resulted in a jump in eigenfrequency of 0.1 Hz. Comparing the results of continuous and intermittent tests showed that both tests resulted in a similar total eigenfrequency deviation.

Overall, the VT3-1 alloy is well-suited for the manufacture of dimensionally stable components with low inelastic properties.

References

1. Terent’ev V.F., Korableva S.A. Fatigue of metals. Moscow: Nauka, 2015. 479 p. (In Russ).
   Терентьев В.Ф., Кораблева С.А. Усталость металлов. М.: Наука. 2015. 479 с.
2. Mughrabi H., Christ H.-J. Cyclic deformation and fatigue of selected ferritic and austenitic steels; specific aspects. *ISIJ International*. 1997;37(12):1154—1169.
3. Gromov V.E., Ivanov Yu.F., Vorobiev S.V., Konovalov S.V. Fatigue of steels modified by high intensity electron beams. Cambridge, 2015. 272 p.

4. Shkol'nik L.M. Fatigue testing methodology: Guide. Moscow: Metallurgiya, 1978. 304 p. (In Russ).
Школьник Л.М. Методика усталостных испытаний: Справочник. М.: Металлургия, 1978. 304 с.
5. Gadolina I.V., Makhutov N.A., Erpalov A.V. Varied approaches to loading assessment in fatigue studies. *International Journal of Fatigue*. 2021;144:106035.
https://doi.org/10.1016/j.ijfatigue.2020.106035
6. Suresh S. Fatigue of metals. Cambridge University Press, 2006. 701 p.
7. Myl'nikov V.V., Kondrashkin O.B., Shetulov D.I., Chernyshov E.A., Pronin A.I. Fatigue resistance changes of structural steels at different load spectra. *Steel in Translation*. 2019;49(10):678—682.
https://doi.org/10.3103/S0967091219100097
Мыльников В.В., Шетулов Д.И., Кондрашкин О.Б., Чернышов Е.А., Пронин А.И. Изменение показателей сопротивления усталости конструкционных сталей при различных спектрах нагружения. *Известия высших учебных заведений. Черная металлургия*. 2019; 62(10): 796—802.
https://doi.org/10.17073/0368-0797-2019-10-796-802
8. Troshchenko V.T., Khamaza L.A., Pokrovsky V.V. Cyclic deformation and fatigue of metals (Ed. M. Bily). Amsterdam: Elsevier, 1993. 500 p.
9. Golovin S.A., Tikhonova I.V. Temperature dependence of internal friction and properties of deformed low-carbon iron alloys. *Deformatsiya i razrushenie materialov*. 2013;(7):16—21. (In Russ.).
Головин С.А., Тихонова И.В. Температурная зависимость внутреннего трения и свойства деформированных малоуглеродистых сплавов железа. *Деформация и разрушение материалов*. 2013;(7): 16—21.
10. Golovin S.A., Petrushina A.G. Temperature spectrum of internal friction of cast iron. *Izvestiya vysshikh uchebnykh zavedenii. Chernaya metallurgiya*. 2009; (9):51—54. (In Russ.).
Головин С.А., Петрушина А.Г. Температурный спектр внутреннего трения чугунов. *Известия высших учебных заведений. Черная металлургия*. 2009;(9):51—54.
11. McClaflin D., Fatemi A. Torsional deformation and fatigue of hardened steel including mean stress and stress gradient effects. *International Journal of Fatigue*. 2004;26(7):773—784.
https://doi.org/10.1016/j.ijfatigue.2003.10.019
12. Golovin I.S., Bychkov A.S., Mikhailovskaya A.V., Dobatkin S.V. Contributions of phase and structural transformations in multicomponent Al—Mg alloys to the linear and nonlinear mechanisms of anelasticity. *The Physics of Metals and Metallography*. 2014;115(2):192—201.
https://doi.org/10.1134/S0031918X14020082
Головин И.С., Бычков А.С., Михайловская А.В., Добаткин С.В. Вклад фазовых и структурных превращений в многокомпонентных Al—Mg сплавах в линейные и нелинейные механизмы неупругости. *Физика металлов и металловедение*. 2014;115(2):204.
https://doi.org/10.7868/ S0015323014020089
13. Kardashev B.K., Sapozhnikov K.V., Betekhtin V.I., Kadomtsev A.G., Narykova M.V. Internal friction, young's modulus, and electrical resistivity of submicrocrystalline titanium. *Physics of the Solid State*. 2017;59(12):2381—2386.
https://doi.org/10.1134/S1063783417120204
Кардашев Б.К., Сапожников К.В., Бетехтин В.И., КадомцевА.Г., Нарыкова М.В. Внутреннее трение, модуль Юнга и электросопротивление субмикрокристаллического титана. *Физика твердого тела*. 2017;59(12):2358—2362.
https://doi.org/10.21883/FTT.2017.12.45231.131
14. Blanter M.S., Golovin I.S., Neuhäuser H., Sinning H.R. Internal friction in metallic materials. *Springer Series in Materials Science*. 2007;90:1—535.
https://doi.org/10.1007/978-3-540-68758-0
15. Stolyarov V.V. Inelasticity of ultrafine-grained metals. *Izvestiya vysshikh uchebnykh zavedenii. Chernaya metallurgiya*. 2010;(11):51—54. (In Russ.).
Столяров В.В. Неупругость ультрамелкозернистых металлов. *Известия высших учебных заведений. Черная металлургия*. 2010;(11):51—54.
16. Romaniv O.N., Laz'ko L.P., Krys'kiv A.S. Relationship of internal friction to the fatigue life of patented steel wire. *Materials Science*. 1984;19:522—527.
https://doi.org/10.1007/BF00722120
Романив О.Н., Лазько Л.П., Крыськив А.С. Зависимость внутреннего трения от усталостной долговечности запатентованной стальной проволоки. *Физико-химическая механика материалов*. 1984;19(6):44—50.
17. Myl'nikov V.V., Shetulov D.I. Fatigue testing facility. Patent 2781466 (RF). 2022. (In Russ.).
Мыльников В.В., Шетулов Д.И. Установка для испытаний на усталость: Патент 2781466 (РФ). 2022.
18. Myl'nikov V.V., Shetulov D.I., Chernyshov E.A. Variation in factors of fatigue resistance for some pure metals as a function of the frequency of loading cycles. *Russian Journal of Non-Ferrous Metals*. 2010;51(3):237—242.
https://doi.org/10.3103/S1067821210030089
Мыльников В.В., Чернышов Е.А., Шетулов Д.И.

Изменение показателей сопротивления усталости некоторых чистых металлов в зависимости от влияния частоты циклов нагружения. *Известия вузов. Цветная металлургия*. 2010;(3):40—45.

19. Mylnikov V.V., Shetulov D.I., Chernyshov E.A. Investigation into the surface damage of pure metals allowing for the cyclic loading frequency. *Russian Journal of Non-Ferrous Metals.* 2013;54(3):229—233. https://doi.org/10.3103/S1067821213030103
Мыльников В.В., Шетулов Д.И., Чернышов Е.А. Исследование повреждаемости поверхности чистых металлов с учетом частоты циклического нагружения. *Известия вузов. Цветная металлургия*. 2013;(2):55—60.
20. Shetulov D.I On the estimation of the metals endurance fatigue by the damage of the surface anomalous layers. *Soviet Materials Science.* 1984;(6):117—120.
Шетулов Д.И. К оценке сопротивления усталости материалов по повреждению поверхностных аномальных слоев. *Физико-химическая механика материалов.* 1984. No. 6. C. 117—120.
21. Stephens R.I., Fatemi A., Stephens R., Fuchs H.O. Metal fatigue in engineering. New York: John Wiley & Sons, 2000. 472 p.
22. ASM Metals: HandBook. Vol. 19. Fatigue and fracture. ASM International, 2002. 2592 p.
23. Schijve J. Fatigue of structures and materials. Springer Science & Business Media, 2001.
24. Campbell F.C. Fatigue and fracture: Understanding the basics. ASM International, 2012. 525 p.
25. Lee Y-L., Barkey M.E., Kang H-T. Metal fatigue analysis handbook: Practical problem-solving techniques for computer-aided engineering. Butterworth-Heinemann: Elsevier Inc., 2011. 632 p.

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