ISSN 1027-4510, Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques, 2023, Vol. 17, No. 1, pp. 144–149. © Pleiades Publishing, Ltd., 2023.
Russian Text © The Author(s), 2023, published in Poverkhnost', 2023, No. 00000, pp. 00000–00000.

Evolution of the Fracture Surface of Commercially Pure VT1-0 Titanium Subjected to Multicycle Fatigue in a Constant Magnetic Field

V. V. Shlyarov[a, *], K. V. Aksenova[a], D. V. Zaguliaev[a], and A. A. Serebryakova[a]

[a] *Siberian State Industrial University, Novokuznetsk, 654006 Russia*

**e-mail: shlyarov@mail.ru*

Received April 27, 2022; revised May 22, 2022; accepted May 22, 2022

Abstract—High-cycle fatigue tests of commercially pure titanium of VT1-0 grade in the initial state (without the use of a magnetic field) and in a magnetic field of various magnitudes (*in situ*) are carried out. It is established that the use of a constant magnetic field with an induction of 0.3, 0.4, and 0.5 T leads to an increase in the number of cycles until the destruction of titanium samples by 64, 123 and 163%, respectively. Fractographic analysis of the fracture surface of titanium under high-cycle loading conditions allows us to conclude that the destruction of the material proceeds by a mixed mechanism; both quasi-cleavage facets and ductile fracture pits are present on the fracture surface. The fracture structure, regardless of the fatigue conditions, has three characteristic zones: the zone of crack initiation, the zone of stable crack growth, and the breakaway zone. In the zone of stable crack growth, obvious fatigue grooves between ridge formations are observed, the distance between which varies depending on the magnitude of the magnetic field.

Keywords: VT1-0 titanium, high-cycle fatigue, fracture surface, constant magnetic field, induction, fractography, scanning electron microscopy, fatigue grooves, facets

DOI: 10.1134/S1027451023010238

INTRODUCTION

Under modern conditions of the operation of machines and constructions, the problems of increasing the strength, operating life, fault tolerance, and durability of materials are singled out as the main ones. The most important and unique products, machines, and constructions operate in cyclic deformation modes, which determine failure even at low loads [1].

Recent reports [2–4] indicate the complex nature of the fatigue phenomenon associated with the self-organization, accumulation, and/or interaction of lattice defects and a strong dependence on external conditions during fatigue loading. Since titanium alloys are widely used in various fields of technology due to their high fatigue strength, good corrosion resistance, and high heat resistance, study of the behavior of this material under conditions of fatigue failure is an urgent task of modern materials science. Extensive studies of the high-temperature fatigue of titanium alloys are carried out [5–7]. The results of research show that during fatigue loading, oxygen diffuses into the surface layers of the sample, thereby creating an oxygen-enriched layer, which leads to hardening of the material and an increase in fragility. Such behavior of the material at high temperatures reduces the scope of its application in fatigue modes, where the number of cycles is $\geq 10^5$, due to the relatively large amplitude of the asymmetric load [8]. The fatigue failure of parts is a major concern for aircraft-engine companies due to threats to the life of key load-bearing components such as titanium discs and blades. In 1954, a model of crack initiation in titanium alloys under conditions of fatigue exposure was proposed [9]. According to this model, the concentration of stresses near a grain boundary resulting from the accumulation of dislocations causes the nucleation of facets [10]. In the alloy under study, the microstructure is represented by a lamellar γ/α_2 phase, within which the γ phase is located. The γ phase is considered as a “hard” unit, which is located in close proximity to a “soft” unit in the area of crack initiation. Severe plastic deformation can accumulate during the period of stay in the “soft” block, which causes a redistribution of stress to the neighboring “hard” block; this phenomenon is called load shedding [11]. Subsequently, a facet may form in a “hard” block due to an increase in local stress with cycles of fatigue exposure in accordance with the interpretation of dislocation accumulation [9]. The above mechanism has been studied and used to explain fatigue failure by many researchers [12, 13].

Currently, there is no universal criterion or standard for determining the crack-initiation period and

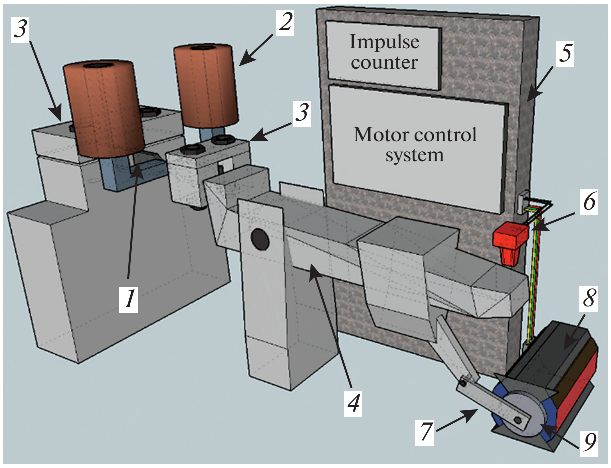

Fig. 1. Installation for fatigue testing in a constant magnetic field: (*1*) is the sample; (*2*) is the electromagnet; (*3*) is the device for fixing the sample; (*4*) is the lever mechanism; (*5*) is the control system including: the engine speed control unit and cycle counter, (*6*) photosensor, (*7*) eccentric cam, (*8*) motor, and (*9*) shaft.

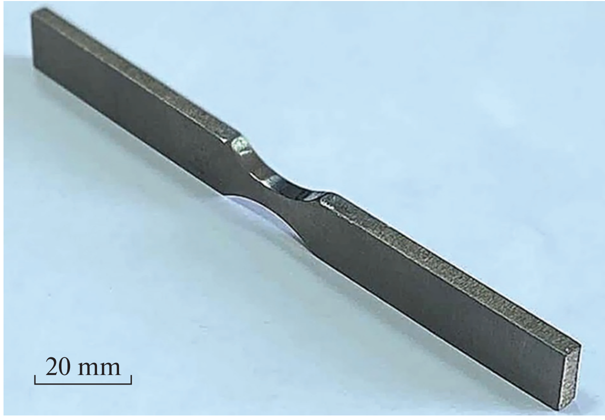

Fig. 2. Appearance of the sample of the VT1-0 titanium for fatigue testing.

predicting fatigue life. Usually, cracks with a length of 0.05–0.1 mm are considered as incipient cracks under fatigue [14]. The duration of the corresponding cycles of crack initiation is determined by the stress levels. At low stresses, the period of fatigue crack initiation can be more than half of the entire service life. The structure of a material and external factors have a great influence on the periods of nucleation and failure under high-cycle fatigue [15–17]. Since the destruction period makes up only a very small part of the high-cycle fatigue life, the study of the influence of structure and external energy effects on fatigue life becomes the most important.

As a result of a review of the current state of research on the fatigue life of titanium alloys, it has been established that in scientific periodicals there are practically no data on the *in situ* influence of external energy effects including magnetic fields on the processes of fatigue failure. In this article, we experimentally study (*in situ*) the effect of a constant magnetic field with an induction from 0.3 to 0.5 T on the fatigue life of commercially pure titanium of VT1-0 grade under asymmetric loads. This study is a logical continuation of the studies of the effect of constant magnetic fields on the microhardness and creep rate of VT1-0 titanium carried out by our research team [18–20].

EXPERIMENTAL

Fatigue tests were carried out on a special installation according to the scheme of cyclic asymmetric-cantilever bending, the appearance of which is shown in Fig. 1.

Sample *1* is fixed with clamps *3*. One end of the sample remains stationary, and an alternating load is applied to the other. Bending is carried out using a lever mechanism *4*, which is connected to the shaft *9*. The amplitude of stresses is changed using the eccentric cam *7*. The shaft is driven by an electric motor *8*. The photosensor *6* is used to record the number of loading cycles. The motor speed can be varied by changing the voltage applied to the motor winding. The source of the magnetic field *2* is located inside the rigid frame; a change in the magnetic-field induction was carried out by adjusting the electric current flowing through the coils.

We used samples of commercially pure titanium of VT1-0 grade, which, in accordance with GOST 19807-91 “Titanium and deformable titanium alloys”, has the following chemical composition: up to 0.25% of Fe, up to 0.07% of C, up to 0.10% of Si, up to 0.04% of N, 99.24–99.70% of Ti, up to 0.20% of O, and up to 0.01% of H. The VT1-0 alloy has the following mechanical properties at room temperature: ultimate tensile strength σ_b = 375 MPa, yield strength $\sigma_{0.2}$ = 295–410 MPa, relative elongation δ_5 = 20–30% and Poisson’s ratio $\upsilon = 0.32$. The samples for investigation had the shape of a parallelepiped with dimensions of 4 × 12 × 130 mm (Fig. 2). A crack was simulated in the central part of the sample by two notches in the form of a semicircle with a radius of 20 mm. Since failure always starts from the surface, the samples prepared in accordance with GOST 25.502-79 were subjected to mechanical grinding with emery papers with a decreasing dispersion of abrasive particles. After grinding with paper, the samples were polished with diamond paste with abrasive particles up to 1 μm in size, since studies show that the quality of product surface preparation affects the fatigue-resistance characteristics [21].

The upper value of the load cycle stress was selected experimentally so that the sample could withstand at least 10^5 loading cycles until failure. The test temperature in all cases was room temperature (~300 K). The frequency of sample loading by bending was ~3.3 Hz.

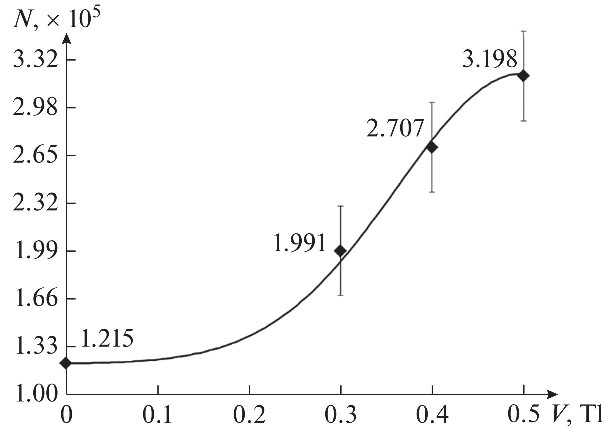

Fig. 3. Dependence of the number of cycles until destruction N on the magnetic-field induction B.

During the tests, the number of cycles that the samples withstood until failure was determined. The samples were tested in the initial state (without the use of a magnetic field) and in a magnetic field of varying induction (*in situ*). At least 10 samples were tested at each value of the magnetic-field induction.

The fracture surface of the samples subjected to high-cycle fatigue tests under normal conditions and in a constant magnetic field was studied by scanning electron microscopy (SEM). The size of the structural elements was determined using the ImageJ specialized software package for image analysis and processing. Analysis of the statistical assessment of the reliability of the obtained experimental results was carried out using the Origin Pro 8.5 mathematical package [22].

RESULTS AND DISCUSSION

As a result of the investigation, it was found that commercially pure titanium of VT1-0 grade subjected to tests under high-cycle fatigue without the use of a magnetic field is destroyed after 121478 cycles after application of an asymmetric load. Turning on a constant magnetic field during testing leads to a multiple increase in the fatigue life. The plot of the dependence of the number of cycles until destruction on the parameters of the external magnetic field is shown in Fig. 3. An analysis of the dependence shows that the use of a constant magnetic field with an induction of 0.3, 0.4, and 0.5 T leads to an increase in the number of cycles until the destruction of VT1-0 titanium samples by 64, 123, and 163%, respectively.

Similar dependences of the influence of a constant magnetic field on the microhardness and creep rate of titanium under the conditions of exposure to a magnetic field were obtained in [18, 19]. It was found that with an increase in the magnetic-field induction, the microhardness linearly decreases, and the creep rate at the steady stage of the process increases linearly.

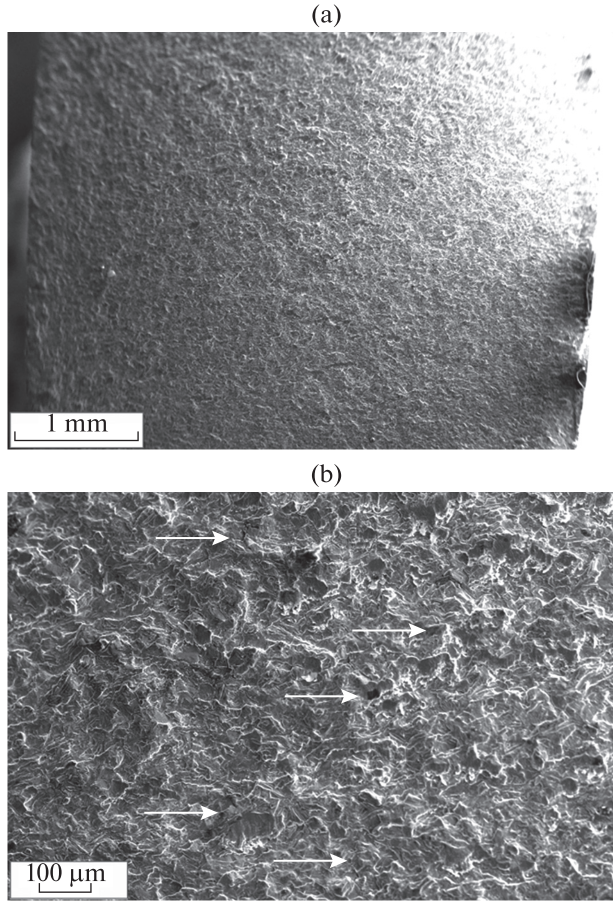

Fig. 4. Structure of the fracture surface of the VT1-0 titanium; arrows indicate pits of separation.

Fatigue destruction, as a rule, is a process that develops over time in local volumes of a deformable material. When the critical state is reached, destruction of the sample as a whole occurs. Figure 4 shows a typical image of the structure of the fracture surface of commercially pure VT1-0 titanium destroyed under fatigue conditions. The structure of the fracture surface contains not only signs of fragile fracture, such as quasi-cleavage facets (Fig. 4b), but also signs of plastic deformation (ridges). It is also worth noting that the structure contains some pits that can be characterized as detachment pits (indicated by arrows in Fig. 4b). Such an element of the structure manifests itself mainly with viscous nature of the fracture. A fractographic analysis of the fracture surface of VT1-0 titanium under high-cycle loading conditions allows us to conclude that material destruction proceeds by a mixed mechanism that coincides with generally accepted ideas about the kinetics of this process in metallic materials [23].

The deformation processes that occur as a result of fatigue tests are mainly developed in the area of fatigue-crack growth and, to a much lesser extent, in the region of fracture. When the direction of the load

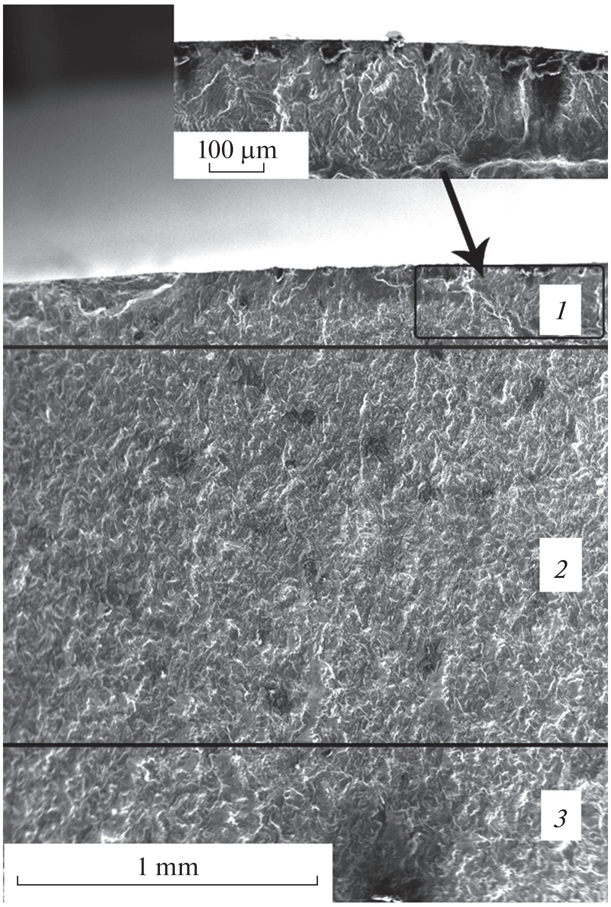

Fig. 5. Characteristic regions of fatigue destruction of commercially pure VT1-0 titanium: (*1*) is the region of crack initiation, (*2*) is the region of cyclic destruction (stable crack growth), and (*3*) is the region of fracture.

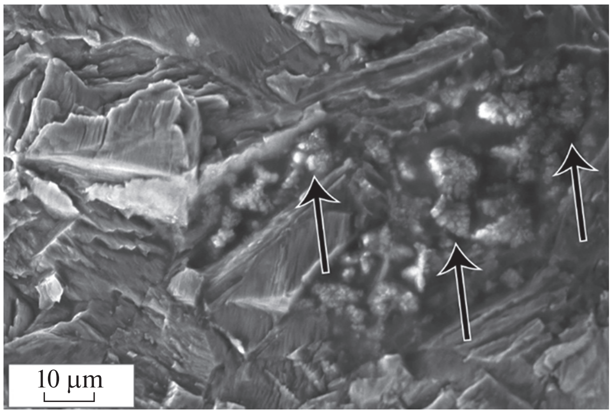

Fig. 6. Fractographic image of the fracture surface of VT1-0 titanium destroyed under fatigue conditions in a magnetic field of 0.3 T.

changes, a rather significant localized plastic deformation occurs at the crack mouth. Since the material under study is a polycrystalline aggregate, the crack front propagates in a kind of web (branching). In the general case, the structure of the sample destroyed under fatigue-testing conditions has three characteristic zones (Fig. 5a): *1* is the crack-initiation zone, *2* is the zone of cyclic destruction (stable crack growth), and *3* is the fracture region of single quasi-static destruction (when $\sigma_{acting} > \sigma_{destructive}$).

In the case of the fatigue failure of commercially pure VT1-0 titanium, the region of stable crack growth is characterized by various structural elements inherent in ductile destruction, among which elements of pulling and separation pits can be noted. Figure 6 shows the shape of these elements (indicated by arrows) to be a conglomerate of columnar morphology elongated in the shooting direction. The size of these regions may depend on the number of micropore nucleation sites and the relative plasticity of the material matrix [24].

One of the most important signs of the fatigue failure of materials that determine its nature is the presence of fatigue grooves in the fracture structure. Figure 7 shows images of the surface of fractures with fatigue grooves of samples of commercially pure titanium destroyed under fatigue conditions in a constant magnetic field and without it. At the initial stage of initiation and propagation of a fatigue crack, the fracture surface is characterized by an ordered relief with poorly visible short fatigue grooves. At the second stage of destruction, the stage of stable crack growth, typical viscous fatigue grooves are already clearly visible; the grooved relief is located between the comb formations (Fig. 7).

Analysis of the structures showed that the distance between the fatigue grooves varied depending on the test conditions. During fatigue tests without the use of a constant magnetic field, the distance between the grooves in the destroyed titanium samples is 0.683 ± 0.002 μm. The use of a constant magnetic field in the process of fatigue leads to ambiguous results. It was established that at field inductions of 0.4 and 0.5 T, the distance between regular fatigue grooves decreases by 36% (0.643 ± 0.003 μm) and 47% (0.535 ± 0.002 μm), respectively. At a constant magnetic-field induction of 0.3 T, the distance between the grooves decreases by ≈65% and amounts to 0.3510 ± 0.0014 μm.

Under conditions of asymmetric loading cycles, fatigue grooves and tears are formed perpendicular or almost perpendicular to the direction of crack propagation. It was reported in [25] that the distance between fatigue grooves indirectly indicates the ability of the material to resist crack propagation: the smaller the distance between the grooves, the greater resistance of the material to crack propagation. The obtained experimental results show that the application of a constant magnetic field with an induction of 0.5 T during the fatigue process leads to a maximum increase in the number of cycles until destruction (Fig. 3). The

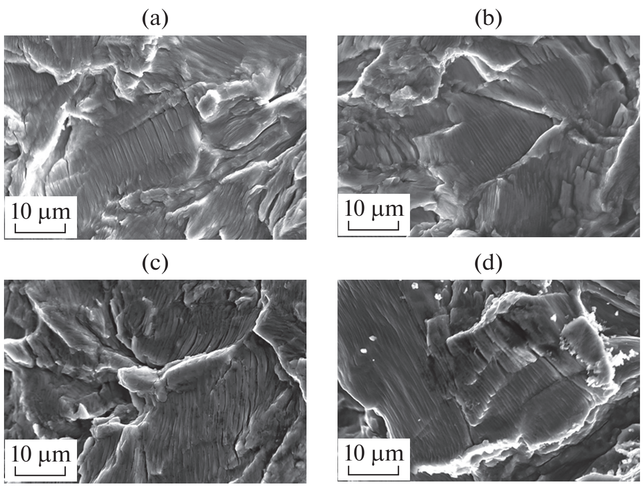

Fig. 7. Fatigue grooves formed in titanium as a result of fatigue destruction in a constant magnetic field at B equal to (a) 0, (b) 0.3, (c) 0.4, and (d) 0.5 T.

reduction in the distance between fatigue grooves in this mode is 47%. However, the shortest distance between the fatigue grooves is characteristic of the samples destroyed in a field of 0.3 T, which, as a consequence, theoretically should have the highest resistance to crack propagation. Obviously, the identified location and size of the structural elements do not allow us to make an unambiguous conclusion about the reasons for the increase in fatigue life under the influence of a magnetic field of different magnitudes.

CONCLUSIONS

As a result of the research, it was found that the use of a constant magnetic field in the process of fatigue testing of commercially pure titanium of VT1-0 grade leads to a multiple increase in the number of cycles until destruction. It was shown that with an increase in the field induction, the number of cycles until destruction increases significantly: at $B = 0.3$ T, the number of cycles until destruction increases by 64%, and at 0.4 and 0.5 T, it increases by 123 and 163%, respectively.

Fractographic analysis of the fracture surface indicates a mixed destruction character. The structure contains signs of both fragile and ductile fractures. In the region of stable crack growth, obvious fatigue grooves are visible, which are located between the comb formations. The distances between the grooves vary depending on the test conditions.

The results obtained are qualitatively similar to those obtained in the study of the creep process and measurement of the microhardness of the VT1-0 titanium. Thus, it can be concluded that a constant magnetic field at the qualitative and quantitative level can affect the processes of plastic deformation of commercially pure titanium.

FUNDING

The study was supported by a grant from the Russian Science Foundation (project no. 21-79-00118).

CONFLICT OF INTEREST

We declare that we have no conflict of interest.

REFERENCES

1. Yu. F. Ivanov, S. V. Vorob'ev, S. V. Konovalov, V. E. Gromov, and N. N. Koval', *Physical Basis for Increasing the Fatigue Life of Stainless Steels* (Inter-Kuzbass, Novokuznetsk, 2011).
2. G. Li and C. Sun, J. Mater. Sci. Technol. **122**, 128 (2022). https://www.doi.org/10.1016/j.jmst.2022.01.010
3. F. Liu, Y. Chen, C. He, C. Wang, L. Li, Y. Liu, and Q. Wang, Int. J. Fatigue **152**, 106446 (2021). https://www.doi.org/10.1016/j.ijfatigue.2021.106446
4. Z. Zheng, P. Zhao, M. Zhan, S. Shen, Y. Wang, and M. W. Fu, Int. J. Plast. **149**, 103161 (2022). https://www.doi.org/10.1016/j.ijplas.2021.103161
5. K. Tokaji, Scr. Mater. **54**, 2143 (2006). https://www.doi.org/10.1016/j.scriptamat.2006.02.043
6. H. Shi, D. Liu, Y. Pan, W. Zhao, X. Zhang, A. Ma, B. Liu, Y. Hu, and W. Wang, Int. J. Fatigue **151**, 106391 (2021). https://www.doi.org/10.1016/j.ijfatigue.2021.106391
7. F. Liu, Y. Chen, C. He, L. Li, C. Wang, H. Li, H. Zhang, Q. Wang, and Y. Liu, Mater. Sci. Eng., A **811**, 141049 (2021). https://www.doi.org/10.1016/j.msea.2021.141049
8. D. P. Satko, J. B. Shaffer, J. S. Tiley, S. L. Semiatin, A. L. Pilchak, S. R. Kalidindi, Y. Kosaka, M. G. Glavicic, and A. A. Salem, Acta Mater. **107**, 377 (2016). https://www.doi.org/10.1016/j.actamat.2016.01.058
9. A. N. Stroh, Proc. R. Soc. London, Ser. A **223**, 404 (1954). https://www.doi.org/10.1098/rspa.1954.0124
10. W. J. Evans and M. R. Bache, Int. J. Fatigue **16**, 443 (1994). https://www.doi.org/10.1016/0142-1123(94)90194-5
11. V. Hasija, S. Ghosh, M. J. Mills, and D. S. Joseph, Acta Mater. **51**, 4533 (2003). https://www.doi.org/10.1016/S1359-6454(03)00289-1
12. Y. Xu, K. Fox, D. Rugg, and F. P. E. Dunne, Int. J. Plast. **134**, 102753 (2020). https://www.doi.org/10.1016/j.ijplas.2020.102753
13. M. A. Cuddihy, A. Stapleton, S. Williams, and F. P. E. Dunne, Int. J. Fatigue **97**, 177 (2017). https://www.doi.org/10.1016/J.IJFATIGUE.2016.11.034
14. L. P. Pook, Eng. Fract. Mech. **187**, 115 (2018). https://www.doi.org/10.1016/j.engfracmech.2017.10.028
15. X. Nie, W. He, Z. Cao, J. Song, X. Li, Z. Pang, and X. Yan, Mater. Sci. Eng., A **822**, 141658 (2021). https://www.doi.org/10.1016/j.msea.2021.141658
16. D. Sharma, V. B. Pandey, I. V. Singh, S. Natarajan, J. Kumar, and S. Ahmad, Mech. Mater. **163**, 104071 (2021). https://www.doi.org/10.1016/j.mechmat.2021.104071

17. X. Luo, N. Dang, and X. Wang, Int. J. Fatigue **153**, 106465 (2021). https://www.doi.org/10.1016/j.ijfatigue.2021.106465
18. V. V. Shlyarov, D. V. Zagulyaev, V. E. Gromov, A. M. Glezer, and A. A. Serebryakova, Russ. Metall. **2022**, 1169 (2022). https://www.doi.org/10.31044/1814-4632-2022-0-3-25-31
19. V. V. Shlyarov, D. V. Zagulyaev, and A. A. Serebryakova, Front. Mater. Technol., No. 1, 91 (2022). https://www.doi.org/10.18323/2782-4039-2022-1-91-100
20. D. Zagulyaev, S. Konovalov, S. Shlyarov, and X. Chen, Mater. Res. Express **6**, 096523 (2019). https://www.doi.org/10.1088/2053-1591/ab2c8a.
21. *Fatigue and Fracture* (A.S.M.H. Committee, 1996). https://www.doi.org/10.31399/asm.hb.v19.9781627081931
22. S. N. Ahmed, in *Physics and Engineering of Radiation Detection*, 2nd ed. (Elsevier, Amsterdam, 2015), p. 595. https://doi.org/10.1016/B978-0-12-801363-2.00010-3
23. V. F. Terentiev and S. A. Korableva, *Metal Fatigue* (Nauka, Moscow, 2015) [in Russian].
24. G. V. Klevtsov, L. R. Botvina, N. A. Klevtsova, and L. V. Limar', *Fractodiagnostics of Destruction of Metallic Materials and Structures* (MISiS, Moscow, 2007) [in Russian].
25. L. P. Shestopalova and T. E. Likhacheva, *Methods to Study Materials and Machine Parts during Autotechnical Expertise* (Mosk. Avtomob.-Dorozhn. Inst., 2017) [in Russian].

Translated by S. Rostovtseva

SPELL: 1. OK