Structural Integrity 24
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Grzegorz Lesiuk · Szymon Duda ·
Jose A. F. O. Correia ·
Abilio M. P. De Jesus *Editors*

Fatigue and Fracture of Materials and Structures

Contributions from ICMFM XX and KKMP2021

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Volume 24

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Editors
Grzegorz Lesiuk
Faculty of Mechanical Engineering
Wrocław University of Science
and Technology
Wrocław, Poland

Szymon Duda
Faculty of Mechanical Engineering
Wrocław University of Science
and Technology
Wrocław, Poland

José A. F. O. Correia
Faculty of Engineering
University of Porto
Porto, Portugal

Abílio M. P. De Jesus
Faculty of Engineering
University of Porto
Porto, Portugal

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Preface

This volume contains forty-two papers presented at the "20th International Colloquium on Mechanical Fatigue of Metals" (ICMFM XX) held in Wroclaw, Poland, September 15–17, 2021, in a virtual mode. The ICMFM XX conference was divided into eight minisymposiums. The symposia are "Fatigue Failure Analysis and Environmentally Assisted Fatigue," "Fatigue and Fracture of Welded Connections and Complex Structures," "Probabilistic Fatigue and Fracture Approaches Applied to Materials and Structures," "Recent Advances on Mixed-Mode Fatigue and Fracture," "Fatigue and Structural Integrity of Metallic Bridges," "Structural Integrity and Fatigue Assessment of Additive Manufactured Metals and Biomaterials," "Structural Integrity And Fatigue Assessment Of Pressurized Metallic Components (Pressure Vessels, Pipes, Hydraulic Components) And Materials," and "Cyclic Deformation Behaviour and Fatigue of Metastable, High Entropy and Smart Materials." Each symposium was led by prominent scientists in the field.

This international colloquium was intended to facilitate and encourage the exchange of knowledge and experiences among the different communities involved in both basic and applied researches in this field, the fatigue of metals, looking at the problem of fatigue from a multiscale perspective, and exploring analytical and numerical simulative approaches, without losing the perspectives of the application.

The attendees of ICMFM XX had an opportunity to interact with the most outstanding world scientists and get acquainted with the latest research in fracture mechanics and fatigue of metals. The eight keynote speaker delivered the latest research updates from the scientific world. This event that lasts for three days will provide a great opportunity to exchange thoughts as well as highlight the latest trends in science.

More than a hundred participants attended ICMFM XX. Considering country affiliation, almost 75% of the scientists were from Europe. People from the Czech Republic and Portugal influence this quantity the most. Secondly, due to the great presents of the Chinese Scientist, Asia is represented by 20% of researchers from the entire participants. The last 5% was represented by scientists from north and south America.

We very sincerely thank the authors who have contributed to this volume, the symposium/sessions organizers for their hard work and dedication and the referees who reviewed the quality of the submitted contributions. The tireless effort of the members of the organizing committee as well as of other numerous individuals and people behind the scenes is appreciated.

Wrocław, Poland — Grzegorz Lesiuk
Wrocław, Poland — Szymon Duda
Porto, Portugal — José A. F. O. Correia
Porto, Portugal — Abílio M. P. De Jesus
December 2021

Chapter 24
On High- and Very High Cycle Fatigue of Metals and Alloys at Axial Loading

E. B. Zavoychinskaya

Abstract There are discussed Mughrabi's diagram and Shanyavskii's bifurcation fatigue curve. Here is shown that the authors represent on one graph the areas of different fatigue curves at different frequencies of uniaxial loading. The well-known mechanisms of micro-fracture initiation are considered. They are ductile and brittle failure mechanisms and they occur at loading with any frequency. The failure stress amplitude is a function of three variables: number of cycles, loading frequency, and temperature. For the nickel alloy EI437B, 9–12% chromium martensitic steel and titanium alloy VT3-1 the fatigue properties of which do not depend on frequency, the areas of brittle micro-, meso- and macro-defect evolution and fatigue curves on defect levels are constructed on the scale-structural fatigue model, they describe the experimental data satisfactorily. The basic characteristics of the model for materials with frequency-dependent fatigue properties are determined as a function of the loading frequency.

Keywords High- and very high fatigue · Frequency · Brittle and viscous fracture · Scale-structural fatigue model

24.1 H. Mugrabi Fatigue Curve [1] and Bifurcation Fatigue Curve [2–4]

A large number of works in recent years are devoted to the problem of safety operation of structures with long service life. For economic reasons, design and operating companies are making efforts to extend the element life. Studies on high- and very high cycle fatigue are carried out in the Institute of Applied Mechanics named after Ishlinsky [5], MAI, MATI named after Tsiolkovsky, VIAM [2–4], IMET named after Baykov [6, 7], IMASH named after Blagonravov [8, 9], SPBPU [10], in the institutes

E. B. Zavoychinskaya (✉)
Department of Theory of Elasticity, Faculty of Mechanics and Mathematics, Moscow State University named after M. V. Lomonosov, Leninskie Gori, GSP-1, Moscow 119991, Russia
e-mail: elen@velesgroup.com

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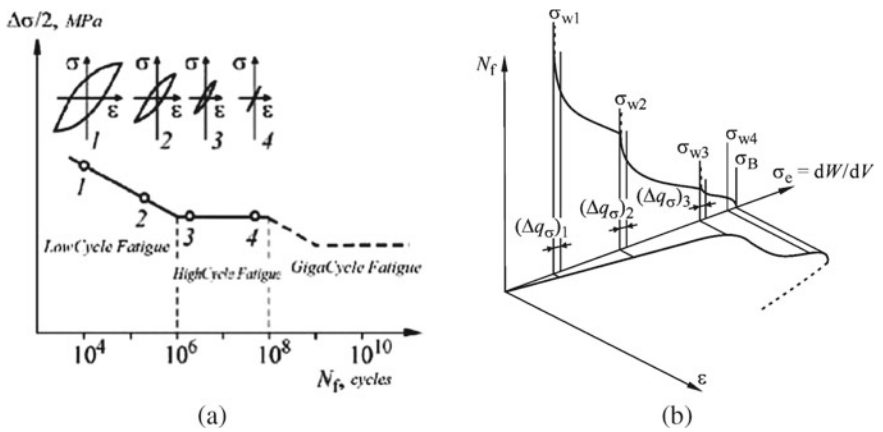


Fig. 24.1 **a** Mughrabi's chart [1], **b** Shanyavskii's chart [2–4]

and universities of Germany and Austria [11–13], France and Italy [2, 3, 14, 15], Japan [16, 17], in the institutes of South Korea [18], and other scientific organization.

In the most works the theoretical high- and very high cycle fatigue curve at symmetric uniaxial loading is based on the multistage model of Mughrabi [1] (Fig. 24.1a) with the identification of two mechanisms of fatigue initiation: from microfailure on the sample surface (stable slip bands are observed) and from the geometric concentrators of the structure in the body volume (microfacets are observed inside and at the grain boundaries, in the area of inclusions with the formation of fine-grained structure area "fish eye") with or not the endurance. This behavior is observed in Cr–Mo steels, bearing steels, titanium alloys. For example, in the VT3-1 two-phase titanium alloy, the micro failure nucleation sites are the phase boundaries, the micro failure occurs by the second mechanism and an optically dark zone near the inclusion is formed. In the area of high cycle fatigue, both mechanisms of micro failure initiation are observed.

In [2–4] the bifurcation fatigue curve (Fig. 24.1b) is considered with the area in which these mechanisms are realized with different probabilities, determined by the energy absorption, it is discussed possible a break of the fatigue curve and several endurance limits. Different branches of fatigue curve are described by different power functions of the failure amplitude from the cycle number. If it is accepted that the fatigue curves have bifurcation regions, possible discontinuities, the presence of several endurance, then there is a problem to describe such fatigue processes (for example on the hypotheses of the scale-structural fatigue theory [19–23]) with transition to the next level to reach the failure state at the previous level. And the problem of determination of basic characteristics for failure probability at each level exists.

24.2 Influence of Frequency on Fatigue Characteristics of Metals and Alloys

The numerous number of experimental works are devoted to the study of high and very high cycle fatigue at various loading frequencies (for example in the works [10, 11, 18, 24–26]). At changing of the modes of high-speed units vibrations can occur in various areas of the sound range (up to 20 kHz), up to the range of ultrasonic frequencies (up to 100 MHz and above). For example, the supporting structures of modern aircraft could be subjected to high-frequency loading due to aerodynamic interaction with the environment and the action of intense acoustic fields generated by jet engines. High-frequency cyclic loads take place in parts of various technological ultrasonic equipment, in hydroacoustic transducers. The Wehler curve in the areas of high- and especially very high cycle fatigue is plotted on the high-frequency test data. For the study of high- and, especially, very high cycle fatigue, as a rule, high-frequency test methods could be applied (as methods of accelerated tests).

For some materials fatigue characteristics are weakly dependent on the loading frequency, for example, for pure metals (aluminum, copper), most nickel alloys, as for alloy EI437B [24, 25] on Fig. 24.2a (the experimental data at a frequency of 10 kHz are marked solid circles, hollow circles correspond to a frequency of 16 Hz). Figure 24.2b is presented a calculation on the model [19–23] for nickel alloy EI437B, fatigue properties not depending on frequency, the I–III areas correspond to

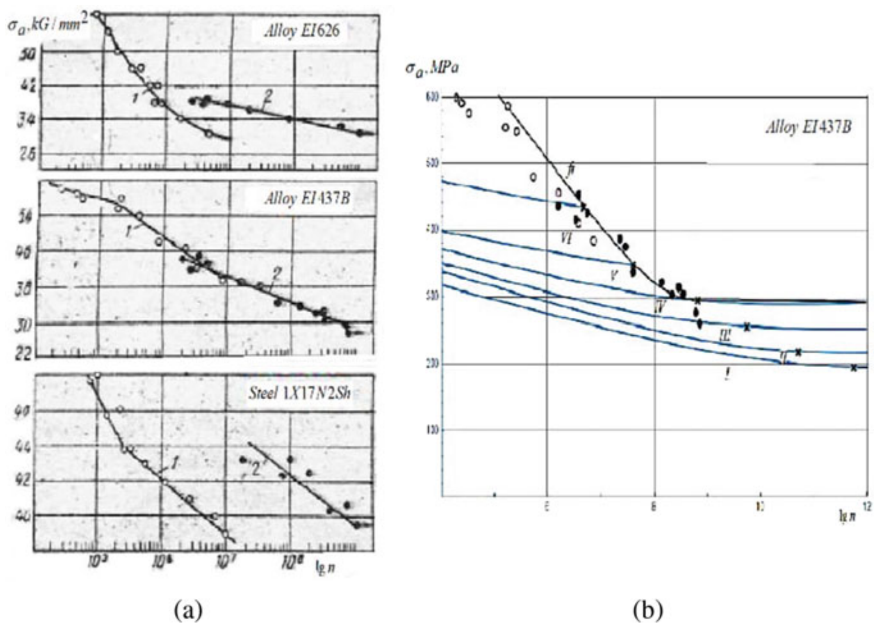
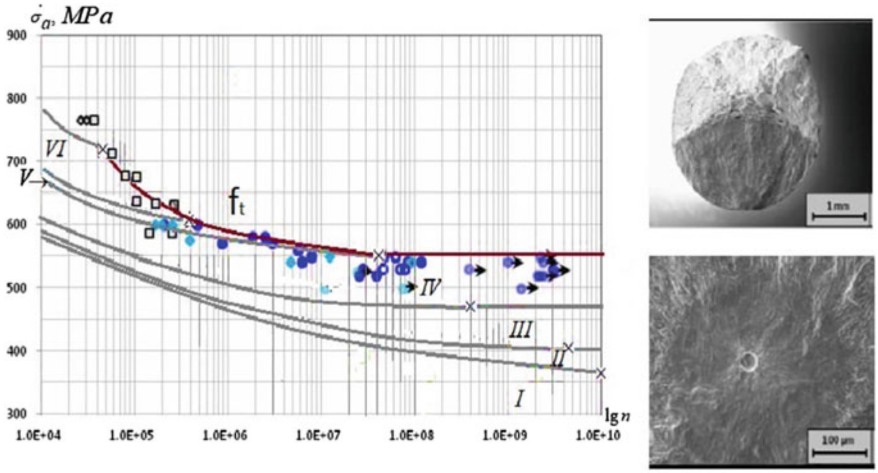


Fig. 24.2 **a** Experimental data [27], **b** calculation data for nickel alloy EI437B



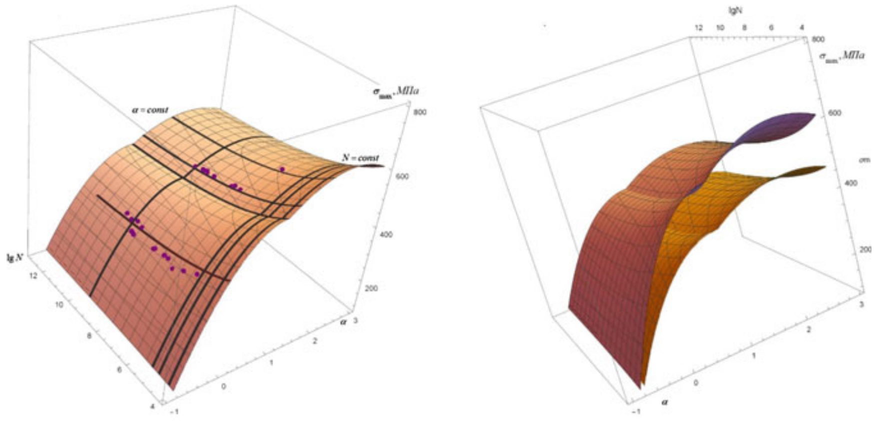
(a) (b)

Fig. 24.3 **a** Calculation data for nickel alloy and 9–12% martensitic-chromium steel correspondingly, **b** macro-failure surface with initiation over inclusion, $\sigma_{-1} = 550\,\text{MPa}$, $N_{-1} = 4.66 * 10^7$cycles [11].

micro level defect nucleation and growing, the IV is the growth of mesodefects (on average, by grain size), the V–VI areas are brittle macro crack growing. Curve ft is the theoretical fatigue curve on the model. It can be seen that the model is satisfactorily described the experimental data at different frequencies. The Wöhler curve of 9–12% martensitic-chromium steel [11] is also independent of frequency. For this steel the experimental [11] and calculation data [21–23] are presents in Fig. 24.3a (solid circles are first mechanism failure, hollow circles are second failure mechanism at frequencies 100 Hz and 20 kHz, black hollow squares are the first mechanism at 25 Hz).

There is observed the same situation for titanium alloy VT3-1 [5, 10, 26]. It was conducted the analysis of fatigue at uniaxial asymmetric loading (at different values of the parameter $\alpha = (\sigma_{\max} + \sigma_{\min})/(\sigma_{\max} - \sigma_{\min})$) at sound frequencies up to 100 Hz and an ultrasonic frequency of 20 kHz, the basic characteristics of the scale-structural fatigue model were found. The areas of defect growing are obtained. It is shown that the fatigue curves for IV level defects at sound and ultrasonic vibrations practically coincide, the fatigue is practically independent of the frequency. The macro-failure and micro-failure (on the α—phase splitting and the β—phase mesodefect initiation) are shown in Fig. 24.4.

On the other hand, for example, as for the nickel alloy EI826 and steel 1X17N2Sh on Fig. 24.2a, we can see that the fatigue curves are different for different frequencies. An analysis of exploration on fatigue of steels, nickel, aluminum and titanium alloys at different loading frequencies allows us to conclude that for materials, fatigue properties depending on frequency, different sections on Fig. 24 1 a) describe different failure processes, namely, with subsonic frequency as usually in the region of low



(a) (b)

Fig. 24.4 **a** Macro-failure surface of VT3-1 in coordinates ($\sigma_{\max}\alpha N$) and experimental data [2, 3, 5, 10, 26], **b** micro- and macro-failure surface of VT3-1

and high cycle fatigue and with ultrasonic loading frequency at the very high cycle fatigue. This can also explain the break of the fatigue curve mentioned in some works. The diagram of Mughrabi (Fig. 24.1a) and Shanyavskii's chart (Fig. 24.1b) show two different Wehler curves at different frequencies for a material depending on frequency fatigue characteristics. The right section after point 4 can be continued to the left into the region of low- and high cycle fatigue, while it will be located the Sects. 24.1–24.4, which indicates the material hardening with an increase of SSfrequency, as is observed in most experiments at high cycle fatigue. This is explained by the fact that at subsonic frequencies the material is under a stress of the same sign for a sufficiently long time, and microdefects have time to develop in many microregions, only single microdefects have time to develop at ultrasonic frequencies and a small half-period. The left part 1–4 on Fig. 24.1a can be continued to the right in the area of very high cycle region and it will probably be a different curve than the one plotted on the basis of ultrasonic loading.

So different Wöhler curves as a function of two variables: the number of cycles and the loading frequency, namely, in the area of high cycle fatigue—with one, as a rule, sonic frequency, in the area of gigacycle fatigue—with another, as a rule, ultrasonic frequency, are represented in Fig. 24.1. In this case, both, namely, the first mechanism of viscous fracture, and the second of the brittle failure take place at loading with any frequency, depending on the number of cycles. In the area of endurance of the investigated ductile materials, the viscous mechanism was basic. The temperature is the third independent variable. In using air and water cooling of sample experiments, a dependence on the loading frequency was also observed [11, 24, 25]. In the area of gigacycle fatigue, significant heating of samples (due to irreversible transformations of mechanical energy into thermal energy) leads to softening of the material with increasing frequency. The basic characteristics of the fatigue model [19–23] should be the functions of loading frequency and temperature.

24.3 On the Mechanisms of Viscous and Brittle Failure

Both described above failure mechanisms take place at loading at any frequency. The first mechanism is the mechanism of viscous failure. In the low cycle region (at $N \in \left(10^4, 10^6\right)$ cycles) of plastic materials, inelastic deformation and viscous failure processes are possible, at the nanoscale level there are characterized by the appearance of plastic distortion at the critical curvature of the crystal lattice with the generation and evolution of dislocations by twinning and sliding mechanisms and the cellular substructure formation, which leads to the movement of grain ensembles and the appearance of microshear bands at the microlevel, to the formation of mesoscale slip bands and structural-phase decomposition of the deformable material with the generation and growth of porosity, ending by the initiation of a viscous macrocrack. At the macroscale level, intense sliding of grain ensembles occurs. In this area, the magnitude of inelastic deformations does not exceed elastic strains and inelastic straining inhibits the brittle crack growing.

The second mechanism is the brittle failure mechanism, which is the main in the areas of high- and very high cycle fatigue. A focus of brittle micro-fracture from the structure geometric concentrators is likely both in the volume of the body and on the surface in the case when the surface is ahead of the internal volumes in the accumulation of microdefects. In the area of low cycle fatigue of plastic materials, the process of viscous failure by the first mechanism and the growing of brittle micro- and macro-cracks by the second one take place simultaneously. On the fractographs it is possible to distinguish both a zone of shear fracture, namely, the region of evolution of inelastic straining and viscous cracks with pits, and a zone of brittle fracture by separation. For plastic materials, in many cases, the process of viscous failure is decisive in the macrocrack nucleation.

24.4 Conclusion

Thus, the fatigue analysis in metals and alloys at uniaxial loading, including asymmetric cycles, allows to formulate the following conclusions.

In general, fatigue curves on defect levels are functions of frequency and temperature. So the diagram of H. Mughrabi and Shanyavskii's chart shows two different Wehler curves at different frequencies for a material depending on frequency fatigue characteristics.

Here are presented the areas of micro-, meso- and macro-defect growing and uniform fatigue curves on defect levels and brittle fracture for nickel alloy EI437B, two-phase titanium alloy VT3-1, and 9–12% martensitic-chromium steel, fatigue properties are independent on the loading frequency, at asymmetric uniaxial loading. The model is satisfactorily described the experimental data at different frequencies.

For materials (for example, nickel alloys, highly alloyed stainless steels, and others), fatigue properties are dependent on the loading frequency, fatigue curves are different for different frequencies.

There are known two mechanisms of fatigue initiation. The first one is from microfailure on the sample surface (stable slip bands are observed). This mechanism is of the viscous failure. And the second one is from the geometric concentrators of the structure in the volume or on the surface of the body with or not the endurance. This is the mechanism of brittle failure.

In the low cycle region of plastic materials, inelastic deformation and viscous failure processes take place. Wherein brittle fracture processes from surface microdefects develop also. In this area the magnitude of inelastic deformations does not exceed elastic strains and inelastic straining inhibits the brittle crack growing.

In the high cycle region, the brittle micro-fracture from the structure geometric concentrators take place in the volume or on the surface of the body.

In the very high cycle region, the brittle micro-fracture from the structure geometric concentrators begins in the volume of the body in many cases.

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