FATIGUE OF STRUCTURAL MATERIALS AT HIGH-FREQUENCY CYCLIC LOADING

V. A. Kuz'menko

Institute for Problems of Strength, Ukrainian SSR Academy of Sciences, Timiryazevskaya str. 2, Kiev, USSR

ABSTRACT

The analysis of high-frequency (thousands and tens of thousands hertz) methods and of fatigue tests results has been carried out. The possibility and the necessity is shown to use them in both the development of structural components which operate at the high frequencies mentioned and accelerated evaluation of conventional fatigue characteristics, in particular, for accelerated comparative tests and for the simulation of a fatigue process when studying the effect of different factors. The comparison of the characteristics obtained for different loading frequencies at the same temperature of specimens showed that if the test basis is expressed in loading cycles, the increase in frequency will always cause the increase in the endurance limit and the decrease in the fatigue cracks propagation rate.

KEYWORDS

Fatigue, cyclic loading, high-frequency fatigue tests, endurance limit, crack growth rate.

INTRODUCTION

The operating conditions of many devices of modern engineering are based on intensive periodic or random vibration at high sonic or ultrasonic frequencies which may be the reason for fatigue of structural components. This is the equipment for ultrasonic technological processes (for cleaning, welding, treatment, etc.), sonar equipment, fast-response components of a number of systems, etc. In the process of operation of some components of modern structures (for examples, in gas turbine blades, in skins and in other flying vehicles components, in some electromechanical devices) undesirable high-frequency intensive vibrations may be excited which may also become the reason for fatigue fracture. Since the devices of modern engineering mentioned above find ever growing application the need in experimental characteristics of cyclic strength applicable for calculations at high-frequency loading becomes urgent. The use of low-frequency characteristics for these calculations is not always adequate because in many cases fatigue characteristics depend essentially on the frequency of cyclic deformation of the material.

Thus, one of basic reasons for the investigation of high-frequency cyclic loading (HFCL) fatigue is stimulated by the requirements of high-frequency engineering itself. This can be assumed to be the first trend of application of HFCL fatigue test results. But there is still another reason and, accordingly, another trend of application of HFCL fatigue test results. The point is that in many cases there is no information even for low-frequency cyclic loading (LFCL) fatigue. This is because of ever increasing variety of structural materials and their modifications due to which the amount of necessary information on fatigue characteristics appears to be enormous, and the realization of all the tests using conventional low-frequency set-ups requires much time and expense because low-frequency tests with the preset test basis (number of loading cycles) last for a very long time. When the fatigue test basis is particularly high (of the order of $10^9 \div 10^{10}$ loading cycles), the accomplishment of such tests on low-frequency set-ups becomes unreal. In fact, even at relatively high frequency (100Hz), which is the maximum attainable one for modern electrohydraulic testing machines, it will take 115 days and nights of continuous work to conduct the test with the test basis of 10^9 loading cycles. It means that it will take a year to obtain a fatigue curve for only a single material using a single testing machine, the test basis being 10^9 cycles, and not less than four months in case several testing machines are used.

The use of fatigue testing set-ups operating at high sonic and ultrasonic frequencies shortens appreciably the duration of the test and might be thought of as a solution for the fatigue test acceleration problem. But this solution appears to be not absolute because of the above-mentioned influence of cyclic loading frequency upon the fatigue characteristics. Indeed, when this influence is small or its magnitude is known, the use of HFCL can really solve the problem of fatigue test acceleration. But if this is not the case, this second trend of application of HFCL fatigue tests appears inappropriate. To find a well-founded solution of this problem and to make an assessment of the works accomplished along the lines of the first trend one has to analyse the full volume of fatigue data, obtained at various cyclic loading frequencies, including ultrasonic ones.

RESULTS AND DISCUSSION

The HFCL fatigue tests ($15 \div 25$ kHz) are performed on set-ups with piezoelectric, magnetostrictive or pneumatic excitation of resonance vibration of rod-shaped or plate specimens. Pneumatic vibration exciters become ineffective at higher frequencies. They were used to excite transverse vibrations in specimens. To excite ultrasonic longitudinal vibrations in specimens Mason type set-ups are usually used involving concentrator rods along with piezoelectric or magnetostrictive vibrators. In this case both fully-reversed and oscillating load cycles of uniform tension-compression of the specimen can be obtained. These set-ups are described in books on high-frequency fatigue tests (Kuz'menko, 1963, 1979; Serensen, 1970), and in other works listed by Kuz'menko, 1979; Stickler, 1982; Willertz, 1980.

At present, the experimental results in the form of fatigue curves for individual frequencies ranging from 10 to 25 kHz have been obtained for many types of structural materials, such as carbon and alloyed steels, nickel-, titanium-, aluminium-, copper- and other metal-based alloys, different conventional and piezoelectrical ceramics, glass, pyroceramics and some composites. These data (the corresponding literature is listed by Kuz'menko, 1979; Willertz, 1980 and the information can be found in "Strength", 1980) can be used for assessment and calculation of cyclic strength and fatigue life of ultrasonic system elements, under condition that at least an approximate correspondence exists between the temperature regimes and the environment during the tests of the specimens and during the operation of the elements. Since the process of fatigue damaging of HFCL test specimens is similar to that of LFCL and can be described via conventional fatigue terms and characteristics, it is permissible and expedient to use the calculation techniques applicable in conventional LFCL for the above-mentioned evaluations at HFCL. Attempts of some investigators to invent, under the pretext of extraordinarity of ultrasonic fatigue tests, some new terms and diagrams for the description of cyclic strength may lead only to discrepancies and incongruities of HFCL test results and prevent their use for LFCL fatigue strength assessments.

In respect to such a characteristic as endurance limit (EL) for a specific number of load cycles, a general regularity is observed for all structural materials without exception which is in that under conditions of equal temperature of specimens and equal test basis the values of EL under HFCL are always higher than those under LFCL. This phenomenon is accounted for by the effect of the strain rate. At high frequencies of cyclic loading, i.e. at high strain rates, the fatigue damage accumulation in the material (which is largely dependent upon the viscous-plastic deformation processes connected with the duration of the loading half-cycles) will inevitably be lower than that at low frequencies of cyclic loading, stress amplitudes being identical. The high-frequency EL values may be equal or even lower than the low-frequency ones in cases when the specimens are heated so much (due to intense energy dissipation in the material at the ultrasonic frequency of deformation) that it causes a decrease in fatigue resistance.

This regularity appears particularly distinct when similar specimens of the same material are fatigue-tested at several frequencies (including conventional low and high ultrasonic frequencies) and the results are compared not only at two limiting frequencies but at the intermediate frequencies as well.

Such experimental data for different materials for room temperature are shown in Fig.1. The X-coordinates are test frequencies f in log scale and the Y-coordinates are ratios of EL values on the 10^8 cycle test basis to the ultimate strength values, the ratio being denoted by η .

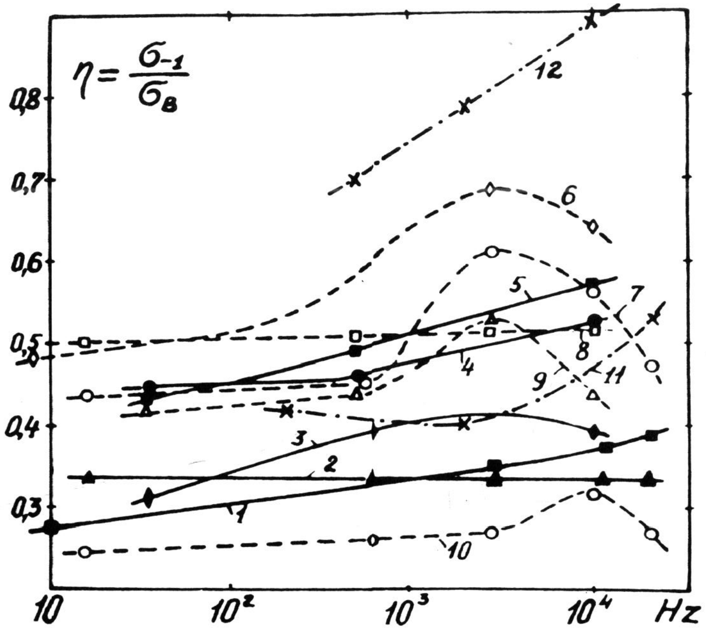

Fig. 1. Cyclic loading frequency effect on the endurance limit of different materials.

When, in the course of increasing the frequency of cyclic loading, the intensity of cooling the specimen tested is sufficient, the EL values may increase monotonically as is seen from the trajectories of curves 1,5 and 8 for carbon steel 45, low-alloyed steel 1Kh2M and titanium alloy VT22M, respectively. For specimens of aluminium alloy D16T (curve 10) and titanium alloys OT4, OT4-1 and VT20U (curves 6,7 and 9) tested under forced air cooling only, the monotone increase of EL values is observed only at the beginning of the frequency range considered, after which the EL values decrease due to insufficient heat removal and the $\eta(f)$ curve exhibits a maximum. The EL values for glass (curve 11) do not practically decrease with the increase in frequency, while for pyroceramics (curve 12) they increase.

For steels with high energy dissipation and low heat conduction, as for stainless steel Kh18N9 (curve 3), heat removal is not always sufficient even at intense liquid cooling. Steels with high nickel content such as KhN35VT steel (curve 2) and nickel alloys exhibit a very weak $\eta(f)$ dependence. Steel 1Kh2M, apart from water cooling tests (curve 5), was tested at heating up to 350°C (curve 4).

It is seen that the comparison of EL values obtained at limiting frequencies only (conventional and ultrasonic) may lead to wrong conclusions about the direction and the degree of high frequency effect upon the EL. Unfortunately, there are examples of such insufficiently founded conclusions in the literature.

A $\eta(f)$ dependence plotted basing at least on 3-4 EL values ranging from conventional to ultrasonic frequencies as in Fig.1, enables one to make a confident opinion about the character and extent of cyclic loading frequency effect upon the EL values and, above all, to assess the EL values for many other loading frequencies on the basis of the results obtained at a single loading frequency. One might suspect here a "vicious circle" situation, that is, to realize the advantages of ultrasonic high frequency fatigue tests, one has to previously perform fatigue tests at conventional loading frequency, i.e. to spend the same, if not greater, time and money as in usual approach to the fatigue tests. Such a statement would be fully justifiable and the attempts to use ultrasonic or high sonic frequencies for accelerating fatigue tests of materials would be quite hopeless, were it not for the following favourable circumstances.

Firstly, modes of EL frequency dependences for materials of the same class (say for carbon steels, aluminium alloys, etc.) are approximately similar, which enables one to consider the rates of EL growth with increasing f as being the same for every such class of materials (within the technological degree of accuracy) and to calculate the EL values on the basis of high-frequency EL value using some suitable equation (Kuz'menko,1981). This approach allows to save time and money at the expense of unification of many materials and their modifications into gross classes for which the frequency dependence of EL is already known. Therefore, for a new material modification it suffices only to find the EL value at high sonic or ultrasonic frequency.

Secondly, the vital problem of obtaining fatigue characteristics within a short period of time under conditions of superlarge number of loading cycles has to be solved on the basis of high-frequency tests. Though the results of these tests are known to be not fully adequate to those which could be obtained from the low-frequency tests due to the frequency effect, the usefulness of high-frequency tests is doubtless since their results can be helpful in determining the upper boundary of low-frequency EL values, this fact being of importance in view of absence of any other experimental data for superhigh test basis.

Thirdly, HFCL is of great importance for accelerated comparative fatigue tests. This seems to be the most significant field of high-frequency tests application in fatigue problem. These tests make it possible to classify within a short period of time many structural materials according to their fatigue fracture resistance criterion or, using the same criterion, to determine in a short time the optimum technological parameters of the manufacturing and machining of materials and structural components, as well as of their welding, soldering, etc. The corresponding high-frequency fatigue tests are widely used and save much time and money (Kuz'menko,1979; "Strength...",1980).

Fourthly, high-frequency fatigue tests appear to be a means to simulate many aspects of fatigue for the investigation or determination of the effect of different factors on the fatigue damage of materials. These are stress concentration, the type of stress state, temperature, the mode of loading,etc.

Thus, though within the framework of the second trend of application of high-frequency fatigue tests mentioned, the significance of the latter is actually lower than it might be superficially thought, the role of the fatigue tests considered within the scope of fatigue problem is, nevertheless, very important and is, therefore, of essential interest for different branches of engineering.

Fatigue fracture diagram in the form of a fatigue crack propagation rate dependence on the stress intensity factor (SIF) range is extensively used during the last two decades along with such a classical characteristic of fatigue fracture strength as a fatigue curve. These diagrams are also plotted basing on the HFCL test results (Hoffelner,1982; Stickler,1982). Ultrasonic loading frequency tests show exceptionally low fatigue crack growth rates of the order of 10^{-14} m/cycle which is essential for studying the threshold SIF values. Information on the crack propagation rate under cyclic loading at operation frequencies is also of importance in designing of reliable ultrasonic systems because the total lifetime of a structural component may depend on the propagation rate of the defects of cracks type present in the material. Accelerated plotting of fatigue fracture diagrams using ultrasonic loading frequencies is also of definite value. Therefore, the problem of cyclic loading frequency effect is important for both fatigue fracture diagrams and fatigue curves. Unfortunately, the amount of comparable experimental data on fatigue crack propagation rate obtained for the same specimens at ultrasonic loading frequencies and at those usually used in fatigue tests is smaller than for EL values.

Figure 2 shows the experimental results obtained in our laboratory on specimens of titanium alloy VT1-0 and aluminium alloy AK4 (curves 1 and 2 respectively). Light points indicate the data obtained on electromagnetic set-up at the frequency of 150Hz, dark points denote data obtained on magnetostrictive set-up at 10kHz for a plane specimen with a central hole subjected to fully-reversed axial tension-compression at room temperature. A marked frequency dependence of the crack growth rate can be seen, particularly for the titanium alloy. This fact is now being verified in experiments with other titanium alloys.

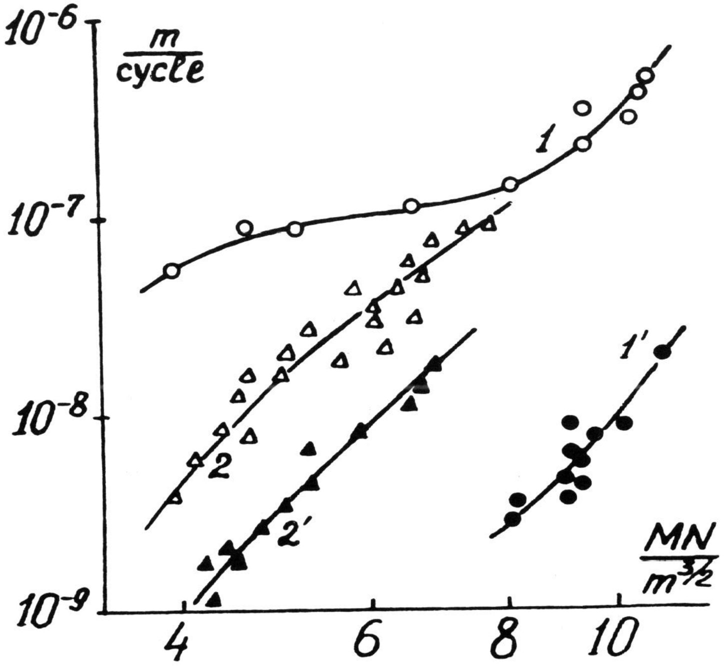

Fig. 2. Cyclic loading frequency effect on the fatigue cracks growth rate.

The cracks growth rate being lower at higher frequency is an ordinary fact consistent with numerous data for infrasonic and low-sonic frequencies. We also note that the very slight influence of 20 kHz frequency upon the fatigue crack growth rate in Ni alloy as compared to 60Hz frequency found by Hoffelner (1982), is generally in good agreement with weak EL dependence on frequency mentioned above for steels with high Ni content and for Ni alloys.

CONCLUDING REMARK

A general conclusion stemming from the material presented which concerns the use of fatigue characteristics obtained at conventional loading frequency for the assessment of cyclic strength of ultrasonic equipment components is as follows. Using the data on EL or on fatigue crack growth rate obtained for specimens with temperature under LFCL and taking that the temperature of the ultrasonic system components does not exceed T, we see from the curves in Figs. 1,2 that the difference between the fatigue characteristics due to different loading frequencies contributes to the increase in the safety factor and consequently in the lifetime of the component.

REFERENCES

Hoffelner, W., and P.Gudmundson (1982). A fracture mechanics analysis of ultrasonic fatigue. *Eng.Fracture Mechanics*, *16*, 365-371.

Kuz'menko, V.A., (1963). *Sonic and ultrasonic vibrations for dynamic tests of materials*. Kiev. p.152.

Kuz'menko, V.A., L.E.Matokhnyuk, G.G.Pisarenko, I.A.Troyan,and A.D.Shevchuk (1979). *High-frequency fatigue tests*. Kiev, p.335.

Kuz'menko, V.A.(1981). The use of a high-frequency fatigue test as a method for accelerated estimation of endurance characteristics of materials. *Acta Astronautica*, 8, 883-887.

Serensen,S.V., M.E.Garf, and V.A.Kuz'menko (1970). *The dynamics of a fatigue-testing machine*. Jerusalem. p.369.

Stickler,R., and B.Weiss (1982). Review of the application of US-fatigue test methods for the determination of crack growth and threshold behavior of metallic materials. *Proc. Int.Conf. on Ultrasonic Fatigue*, AIME, USA.

Strength of materials and structural components at sonic and ultrasonic loading frequencies (1980). *Collected papers of* the 2nd All-Union Seminar. Kiev. p.524.