GENERALIZED FATIGUE-FAILURE DIAGRAMS
FOR TITANIUM ALLOYS

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Titanium alloys are important constructional materials because they combine high fatigue strength with corrosion resistance and stability on cooling. They are used not only in aviation engineering and space science but also in shipbuilding, power machine construction, the chemical industry, and other branches of the economy. There is an ongoing need to evaluate the most suitable designs for extreme operating conditions, which should be such that catastrophic failure does not occur. In recent years, there have been significant advances in research on the static and cyclic cracking resistance in titanium alloys in air and in corrosive media [1, 2], but these do not yet allow one to evaluate the results quantitatively by reference to generalized (basic) fatigue failure diagrams designed to indicate the working life such as have been designed for steels [3-5].

Published data [6-90] are used here on the effects of various factors on the cyclic cracking resistance in titanium alloys in air and corrosive media to formulate basic fatigue failure diagrams for the two titanium alloys most extensively researched.

Effects of Various Factors on Cyclic Cracking Resistance in Titanium Alloys in Inert Media. The cyclic cracking resistance in a titanium alloy resembles that in a steel in being governed by three groups of parameters, which characterize the structure of the alloy, the loading, and the medium. Structure features mean that titanium alloys are more sensitive to some factors than are steels.

In media that do not react with the titanium alloy (inert ones such as argon, nitrogen, and dry air), and also under vacuum, the fatigue failure diagrams for titanium alloys (Fig. 1a) take the form of S-shaped curves, which are bounded by two limiting values for the stress intensity factors SIF: the lower one \( K_{th} \) and the upper one \( K_{ic} (K_c) \) [6-10]. The lowest rate of fatigue crack growth occurs under vacuum, and the highest in air. The values are very slightly affected [11-13] or almost unaffected [14, 15] by the loading frequency. They are substantially raised in the regions of the lower and upper parts of the fatigue failure diagram as the cycle asymmetry coefficient increases [16-33], in which they can be represented as relationships between the crack growth rate and the amplitude or range \( \Delta K \) (Fig. 1b).

The fatigue crack growth rate in a titanium alloy is dependent on the microstructure [1, 7, 8, 12, 17-19, 34-59], which is characterized by numerous parameters (the sizes of the \( \alpha \) and \( \beta \) grains, the amounts of the \( \alpha \) and \( \beta \) phases, the distance between the particles of the \( \alpha \) phase, the thickness and length of the \( \alpha \)-phase plates, etc.), and can also be affected by the heat treatment under various conditions (tempering temperature, cooling rate, and ageing temperature and time). Test results have been obtained on cyclic cracking resistance for various states of heat treatment [35, 36, 40, 43, 52], which can affect the fatigue crack growth rates sometimes by more than an order of magnitude. For example it has been found that Ti–6Al–4V titanium alloy has the maximum cyclic cracking resistance after \( \beta \) decomposition, and the minimum after heat treatment in salt solutions and tempering [52]; alloys containing the platy \( \alpha \) phase in most cases have cyclic cracking resistance lower than for the globular form of the \( \alpha \) phase [38]; and as the grain size increases, the fatigue crack growth rate decreases, particularly at low \( \Delta K \) [23, 44-46, 48].

The fatigue crack growth rate is also affected by the texture and can alter by a factor 2-3 on that account [52]. Cracks in the rolling direction expand more rapidly than ones transverse to the rolling [10, 32, 60, 61].

Research has shown that there is accelerated fatigue crack growth over fairly wide temperature ranges (from 93 to 813 K) [62-68].

Effects of a Corrosive Medium on Cyclic Cracking Resistance in Titanium Alloys. The cracking resistance in corrosive media differs from that in inert ones in being described by fatigue failure diagrams of two types [14], which characterize various alloy-medium systems.
In the first case (Fig. 1b, curves 2-4), the diagram is similar to the diagram in an inert media (there are S-shaped curves, but with displacement to the left the larger the less the SIF. There is an acceleration of the stress corrosion cracking SCC in a titanium alloy as the loading frequency decreases throughout the range in the SIF. That type of diagram and the tendency to variation with the loading frequency are characteristic of titanium alloys used in distilled water or methanol solutions [6, 14, 15, 32, 69-72].

In the second case (Fig. 1c, curves 2-4), the diagram for a titanium alloy has a kink on the usual S-shaped curve, which goes over to a plateau, within which the SCC growth rate does not vary with the SIF [6, 14, 15, 32, 69, 70, 73-76]. The points in this diagram are also displaced to the left relative to those for an inert medium by an extent that increases as the SIF decreases. Such diagrams show an inversion in the SCC growth rate as the loading frequency varies [14, 69, 70, 73]: at low ΔK, it increases, while at high ΔK, it decreases as the frequency rises. The stepout on the SCC growth rate is the more pronounced the less the frequency. Such diagrams and trends with loading frequency occur for titanium alloys in solutions that contain Cl⁻ and Br⁻, and are considered to be due [14, 77] to the combined action of corrosion fatigue and corrosion cracking, which becomes less as the loading frequency increases. The SCC growth rate is affected by the shape of the loading curve and particularly by the duration of the dwell at the maximum SIF in the cycle [14, 78].

In a corrosive medium, there are the same general tendencies for the effects from the various structural and mechanical parameters, although they are more pronounced in cyclic cracking than in an inert medium [6, 14, 15, 32, 50, 52, 59, 67, 68, 71, 73, 74, 78-84]. The SCC growth rate is influenced also by characteristics of the medium (such as the pH, the ionic composition and concentrations, the temperature, the polarization potential, etc.), whose effects for titanium alloys have not yet been adequately researched [14, 85].

The medium has the largest effect on the fatigue crack growth rate in the regions of the lower and middle parts of the fatigue failure diagram for a titanium alloy, which confirms the finding for steel that the medium has no effect at high fatigue crack growth rates [91].

Relationship between Cyclic Cracking Resistance Characteristics for Titanium Alloys. The analysis shows that the fatigue crack growth rate in a titanium alloy, as in a steel [92], is subject simultaneously to structural, mechanical, and physicochemical factors, which have various effects in the different parts of the cyclic cracking diagram for a titanium alloy (Fig. 2). At low fatigue crack growth rates (part I), where the cracks grow by cleavage [22, 57, 84], the growth rate is affected not only by the structure but also to a considerable extent by the asymmetry coefficient, the loading frequency, the medium, and the temperature if high (over 560 K), at which some structural changes may occur in the alloy. The same effect occurs at medium rates (part II) with the ridge mechanism for fatigue crack growth [22, 56, 87]. Only at high rates (range III), where the fatigue cracks grow by micropore coalescence [9, 52], does the effect of the physicochemical factors become much less and the structural and mechanical factors dominate.