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Failure of Structural Alloys by Slow Crack Growth

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CONTENTS

ABSTRACT

Structural alloys are susceptible to failure by slow crack growth caused by fatigue and corrosion-fatigue. Laboratory studies have provided quantitative engineering data on the resistance of various steels and titanium alloys to slow crack growth. The rate of crack growth per cycle of repeated load was shown to be a function of the fracture mechanics crack tip stress-intensity factor. Methods were shown for relating these results to structural parameters, nominal stress, and flaw geometry. The influence of a salt water environment on slow crack growth and interaction with stress-corrosion cracking were explored.

PROBLEM STATUS

This report completes one phase of a continuing problem.

AUTHORIZATION

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NATURE OF THE PROBLEM

A high probability exists that any large, complex welded structure will contain sharp discontinuities or flaws resulting from fabrication. Under the action of repeated loading and environment, such flaws can serve as sites for initiation of fatigue cracks. The cracks, once initiated and if left unchecked, will undergo a period of slow growth caused by repeated service loads which can lead to terminal failure. Such failures can be brittle fracture, gross plastic overload deformation, or leakage in a pressure vessel. For the high-strength alloys discussed in this report, failure is defined as plane strain instability fracture.

Figure 1 shows the crack growth aspect of the fatigue failure process, and how a small subcritical flaw located in a cyclically loaded member slowly grows in size with repeated loading until it reaches a critical size for failure. This report describes engineering research into the growth of subcritical flaws by fatigue and corrosion-fatigue, and discusses how the results of these studies can be combined with fracture toughness, proof testing, and nondestructive testing data to prevent structural failures.

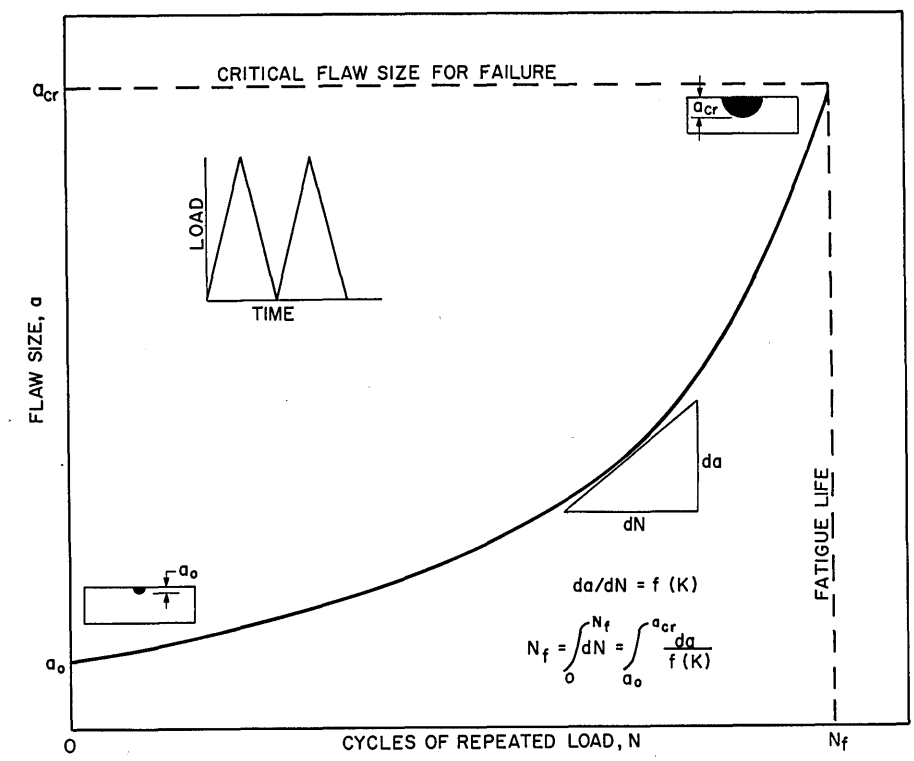

Fig. 1 - Schematic illustration of slow crack growth in a cyclically-loaded structural element

APPROACH TO THE PROBLEM

The fatigue life of a large structure depends on the size, shape, location and growth rate of initial flaws, and the fracture toughness of the material. Proof testing or nondestructive testing can provide information regarding pre-existing flaws prior to service. Fracture toughness data on the specific material can be applied to determine the critical flaw size for the service conditions. Information concerning fatigue crack growth rate is then the link between initial and terminal conditions that permits prediction of the fatigue life of a structure.

Linear elastic fracture mechanics provides an analytical approach to subcritical flaw growth (1). The basic equation which describes the growth of fatigue cracks can be expressed as

$$da/dN = C(\Delta K)^m , \quad (1)$$

where

da/dN = crack extension per cycle of load (fatigue crack growth rate),

ΔK = stress-intensity factor range,

C, m = numerical constants.

The validity of Eq. (1) has been verified by numerous researchers (1). The stress-intensity factor is an important parameter for predicting both terminal fracture and slow crack growth, and its use enables a unified approach to the problem.

Using established fracture mechanics procedures, the results of laboratory crack-growth studies expressed as a function of stress-intensity can be interpreted in terms of structural parameters, stress level, and flaw size. The stress-intensity factor is a function of applied stress and crack geometry, and as such its significance is not limited to the particular conditions of a given laboratory test (2). The experimental data presented here were obtained from controlled tests conducted on notched bend-bar specimens. However, for purposes of structural interpretation these results will be related to the predicted behavior of a tension loaded plate containing an embedded surface flaw which closely simulates actual structural situations.

RESULTS OF FATIGUE CRACK GROWTH STUDIES AND THEIR STRUCTURAL INTERPRETATION

Fatigue crack growth studies have been conducted on numerous materials. Two groups of materials of particular interest are high-strength steels and titanium alloys which have been studied for applications of Navy interest. The results of laboratory studies on representative samples of these materials are shown in Figs. 2 and 3. In each figure the fatigue crack growth rate data from the two generic classes of materials fall within a scatterband. Four high-strength steels followed the relationship $da/dN = C_1 (\Delta K)^{2.5}$, and two samples of Ti-6Al-4V alloy followed the relationship $da/dN = C_2 (\Delta K)^{3.5}$. The strength level and fracture toughness of the various samples within each group are similar, despite differences in alloy content or heat treatment.

These data were obtained from tests conducted on cantilever-bend bar specimens cycled zero-to-tension in an ambient room air environment at a frequency of 5 cpm. Although stress-intensity provides a common basic analytical parameter which can be used to translate information obtained from one geometry to predict performance in another

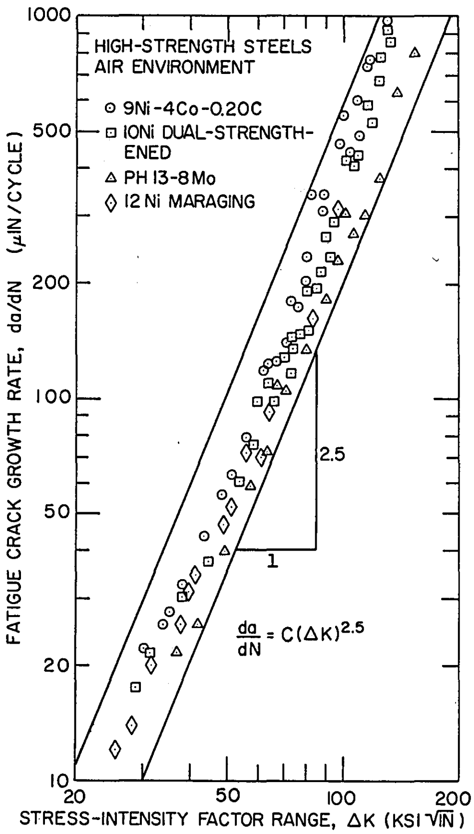

Fig. 2 - Plot of fatigue crack growth rate (da/dN) as a function of stress-intensity factor range (ΔK) for four 180-ksi-yield-strength steels. These data were obtained from single-edge-notched (SEN) cantilever bend specimens cycled zero-to-tension at 5 cpm in a room air environment.

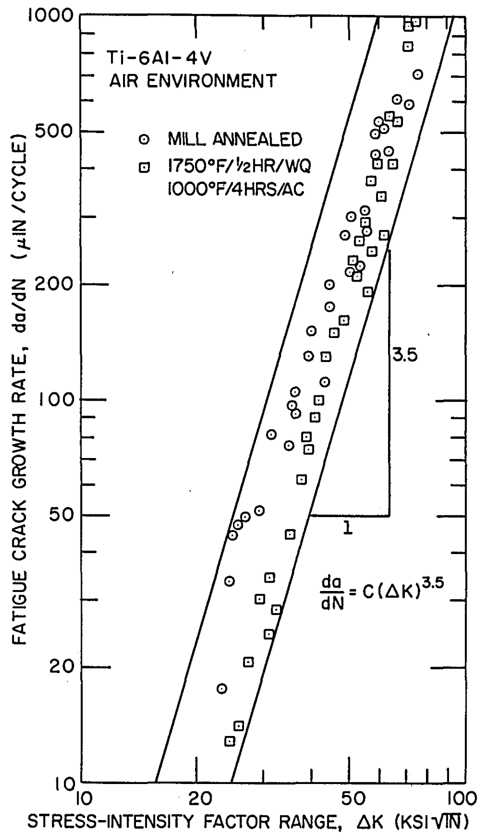

Fig. 3 - Plot of da/dN vs ΔK for two 120-ksi-yield-strength samples of Ti-6Al-4V alloy

geometry without "size effect" or other scale factors, it is recognized that environment, frequency, and mean loads do exert a significant influence on these results. However, data such as these do provide the baseline characterization and performance curves for new high-strength materials and are presented here as representative examples of research procedures into the failure of materials by subcritical crack growth.

Figures 4 and 5 provide a structural interpretation of these results in terms of stress level and flaw size parameters. These figures refer to the predicted behavior of a surface crack in a structural element cycled from zero-to-tension at low frequency in an air environment. Also indicated are the lower bound estimates for critical flaw sizes in plane strain fracture. In the region below the fracture line, subcritical flaw growth, the loci of constant rates of crack growth, increasing by incremented orders of magnitude, are indicated.

The constant growth rate contours represent regions of constant stress-intensity, since growth rate is a function of stress-intensity, Eq. (1). For the structural geometry shown in Figs. 4 and 5, stress-intensity is expressed as follows (3)

$$K_I = \sqrt{1.21\pi\sigma^2(a/Q)}, \tag{2}$$

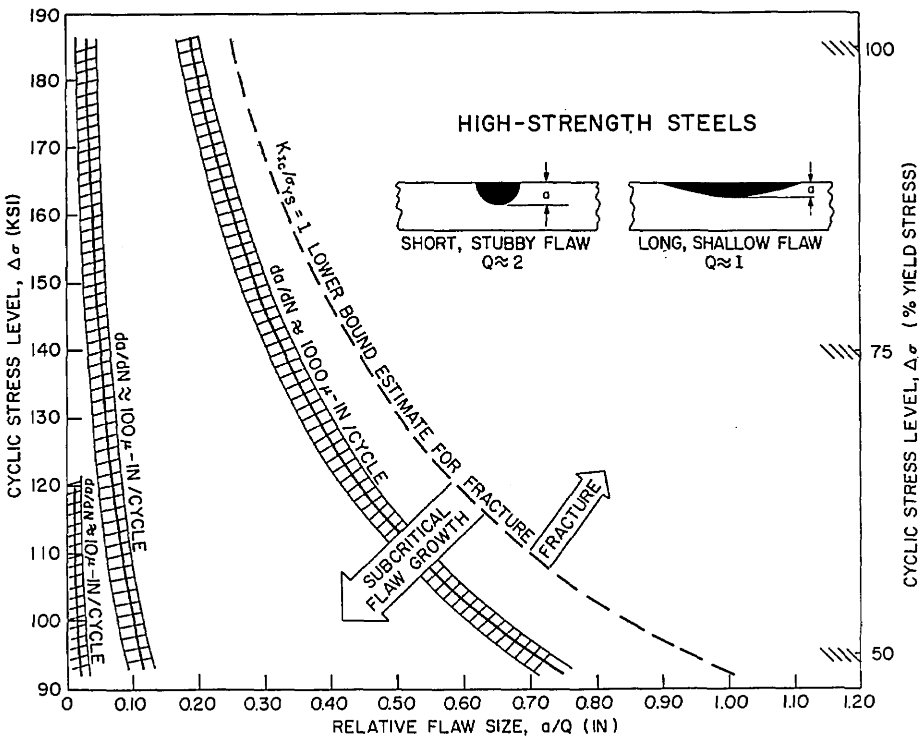

Fig. 4 - Plot of cyclic stress level ($\Delta\sigma$) vs relative flaw size (a/Q) relationships showing the loci of constant fatigue crack growth rates (constant ΔK) levels for the high-strength steel data from Fig. 2. The curves apply to the predicted behavior of a tension-loaded plate containing a surface crack, and the lower bound estimate for plane strain fracture (K_{I_c} = 180 ksi $\sqrt{\text{in.}}$) is indicated.

where

σ = nominal gross stress,

a = flaw depth,

Q = flaw shape parameter.

Therefore, knowing the functional relationship between growth rate and stress-intensity, and between stress-intensity and stress level and flaw geometry, the rate of crack extension per cycle of repeated load can be graphically illustrated in terms of structural parameters.

The prime application of this type of analysis for fatigue crack growth is in evaluating the potential hazard created by a given size and shape flaw in a structural element. The traditional approach to structural design for fatigue deals with the number and magnitude of stress cycles required to initiate a crack in a smooth element. However, this approach is not relevant to heavy section structures which cannot safely be assumed to be flaw free.

These crack growth studies seek to define two questions relating to stress levels and material selections imposed by design requirements for assuring a safe-life period. First, are subcritical flaw sizes, prior to failure, large enough to be readily detected by

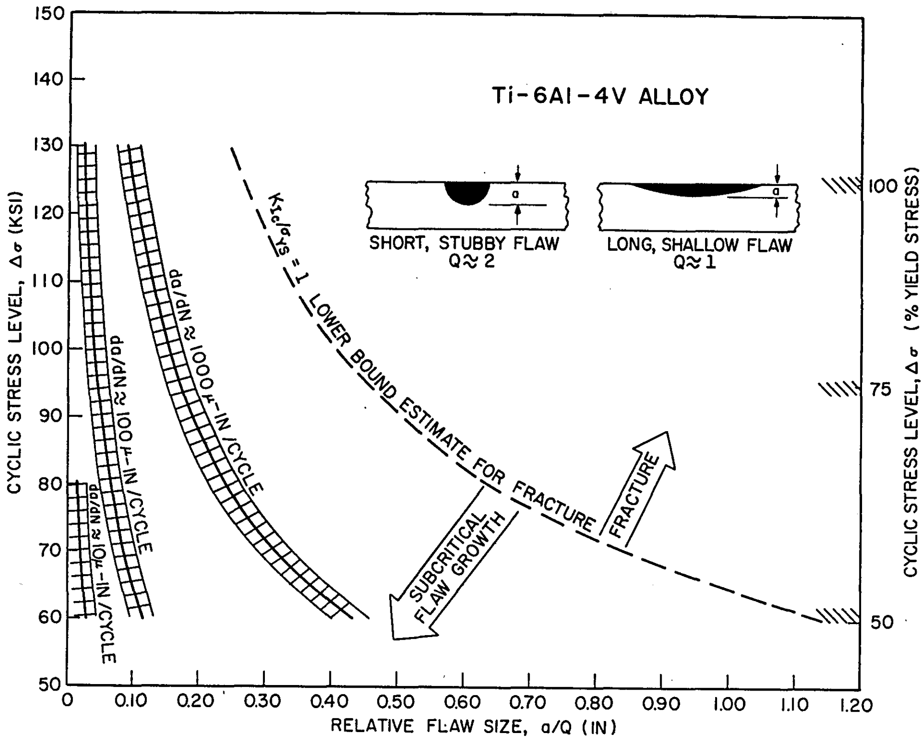

Fig. 5 - Plot of $\Delta\sigma$ vs a/Q relationships for the Ti-6Al-4V data from Fig. 3. The lower bound estimate for plane strain fracture (K_{Ic} = 120 ksi $\sqrt{\text{in.}}$) is indicated.

nondestructive inspection methods? Second, is there a sufficient safe-life period for a flaw to be detected before it is growing rapidly enough to present a structural hazard?

The region of greatest interest on these curves is where the stress level approaches the yield strength. Critical elements in welded structures, which contain high residual stresses, will approach yield stress loading even when subjected to modest service loads. Thus it can be clearly seen that the margin for subcritical crack growth prior to reaching fracture conditions is small in both steel and titanium high-strength alloys.

CORROSION-ASSISTED FATIGUE AND ITS RELATIONSHIP TO STRESS-CORROSION CRACKING

Virtually all high-strength alloys undergo accelerated crack growth when exposed to a marine environment. The nature and extent of such acceleration cannot be readily determined and is the subject of current research. Two typical examples shown here, a 12Ni maraging steel in Fig. 6 and a Ti-6Al-4V alloy in Fig. 7, represent contrasting forms of behavior.

The steel exhibits maximum environmental acceleration when cycled at low stress-intensity levels, and the environmental effects diminish with increasing cyclic stress-intensity. By way of contrast, the titanium alloy is insensitive to the environment when cycled at low stress-intensity levels and undergoes a sharp acceleration in crack growth at higher cyclic stress-intensities.

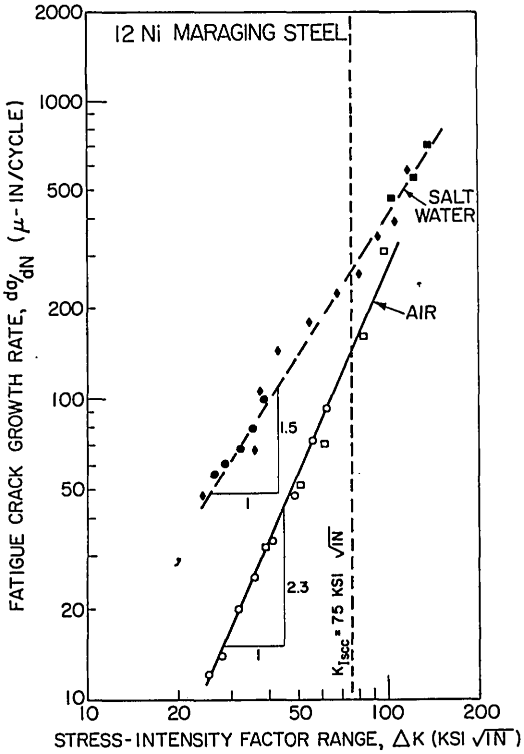

Fig. 6 - Plot of da/dN vs ΔK for a high-strength steel showing the effect of a salt water solution on fatigue crack growth. The threshold stress-intensity level for stress-corrosion cracking to occur (K_{Iscc}) is indicated.

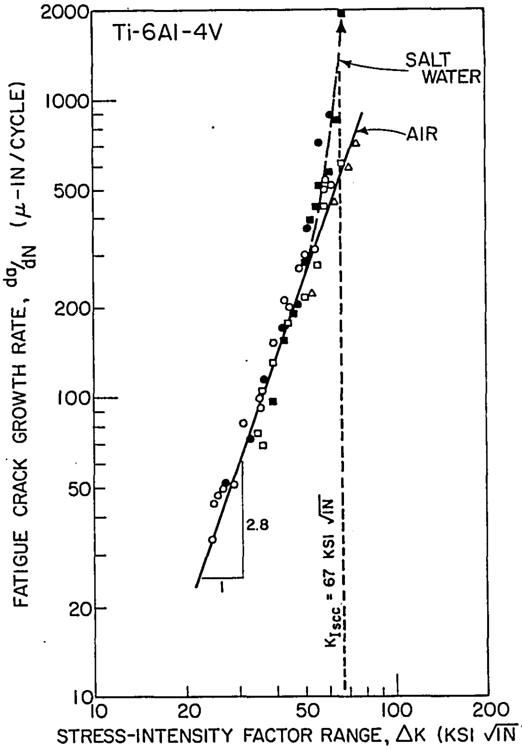

Fig. 7 - Plot of da/dN vs ΔK for a Ti-6Al-4V alloy in air and in salt water

The effect of the salt water environment on the growth rate of cracks in the two metals also points out the relationships between corrosion-fatigue and stress-corrosion cracking. The necessary stress state for stress-corrosion cracking to occur from a static load is defined by the parameter K_{Iscc} (4), which simply states that above this threshold value of stress-intensity, in plane strain, stress-corrosion cracking can occur. The K_{Iscc} levels for each material are indicated on Figs. 6 and 7.

The interrelationships between these two modes of subcritical crack growth, corrosion fatigue and stress-corrosion cracking are not well established. In comparing the data on Figs. 6 and 7, it can be seen that for the titanium alloy K_{Iscc} represents a limiting condition in corrosion fatigue due to accelerated crack growth. However, for the steel no such response was observed. A comparison of subcritical crack growth rate from stress-corrosion cracking, Fig. 8, reveals a possible explanation for this contrasting behavior.

Figure 8 is a typical schematic plot of stress-corrosion-cracking time-to-failure curves for steels and titanium alloys as a function of initial stress-intensity (K_I). Stress-corrosion cracks tend to propagate much more rapidly in titanium alloys than in steels. Direct measurements of this phenomenon are scarce, but an abundance of indirect evidence is available from numerous K_I versus time-to-failure plots. High-strength titanium alloys tend to be highly reactive to a marine environment at high K_I values, and the K_{Iscc} threshold is usually established within a matter of minutes; i.e., when a stress-corrosion cracking mechanism is activated, cracks propagate rapidly. Thus an environmental cracking mechanism can exert a strong effect on corrosion-fatigue

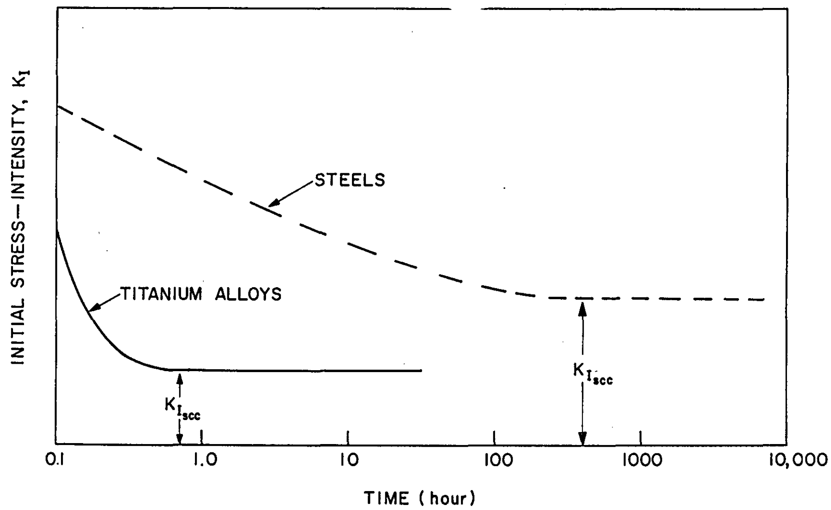

Fig. 8 - Schematic illustration showing typical stress-corrosion-cracking time-to-failure curves for steels and titanium alloys

even though the duration of peak loads is brief rather than sustained. On the other hand, many steels react very slowly to stress-corrosion cracking. Hundreds or thousands of hours are required to establish $K_{I_{scc}}$ because crack propagation occurs slowly. Under these conditions, stress-corrosion cracking does not appear to exert a significant acceleration in corrosion-fatigue crack growth. In terms of structural applications, these findings suggest that under fatigue loading in a marine environment nondestructive inspection of structures in titanium alloys will necessarily be more restrictive with respect to permissible flaw sizes than that required in steels.

SUMMARY

Laboratory studies of crack growth by fatigue and corrosion-fatigue have been conducted on several high-strength steels and titanium alloys. An analysis of the data shows that the rate of crack growth per cycle of repeated load can be expressed as a function of the fracture mechanics crack tip stress-intensity factor. This procedure permits a quantitative structural interpretation of crack growth in terms of stress level and flaw geometry.

In addition, preliminary findings from typical examples of corrosion-fatigue crack propagation in a salt water environment for steel and titanium alloys indicate that corrosion-fatigue crack propagation in titanium alloys is strongly influenced by stress-corrosion cracking, and the $K_{I_{scc}}$ threshold stress-intensity level represents a limiting condition for preventing rapid crack growth under cyclic loading. Similar evidence was not observed from tests on steels, indicating that corrosion-fatigue crack propagation in steels is not highly sensitive to the onset of stress-corrosion cracking.

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