

Effect of Tension-Compression Cycling on Fatigue Crack Growth in High-Strength Alloys

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ABSTRACT

Virtually all of the fatigue crack propagation data reported in the literature for structural alloys are generated under simple zero-tension cycling. The direct application of this data to problems involving large welded structures subjected to operating stress cycles approaching fully-reversed tension-compression is questionable. The present study shows that the compression portion of fully-reversed tension-compression cycling can contribute substantially to fatigue crack growth rates in plate-thickness, medium-to-high-strength alloys. Data from several alloys show a 50 percent increase in fatigue crack growth rates due to tension-compression cycling. The implications of these findings and methods for applying the results of this study are discussed.

PROBLEM STATUS

This report completes one phase of the problem; work on other aspects of the problem is continuing.

AUTHORIZATION

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EFFECT OF TENSION-COMPRESSION CYCLING ON FATIGUE CRACK GROWTH IN HIGH-STRENGTH ALLOYS

INTRODUCTION

Crack growth by low-cycle fatigue is a potential failure mechanism for large welded structures. Most fatigue crack propagation data reported in the literature are generated under zero-tension cycling. However, critical regions in cyclically-loaded structures frequently undergo more complex loading than simple zero-tension because of service loads and residual stresses from fabrication and/or shakedown. Therefore, it is of considerable practical interest to study the relationships between data obtained from simple laboratory tests and more complex loading which can be anticipated in actual structural service.

One of the most common aspects of complex loading which has occasionally been recognized, but which has not received adequate attention, is the contribution that the compression portion of tension-compression cycling can make to fatigue crack growth. Illg and McEvily (1) obtained fatigue crack propagation data on 2024-T3 aluminum alloy sheet and reported that crack growth rates were only slightly faster under fully-reversed tension-compression cycling. Donaldson and Anderson (2) made a comparison among Illg and McEvily's data and other zero-tension (or slightly offset tension-tension) data on 2024-T3 aluminum from several sources and concluded that the results for the two types of loading were not greatly different. Hudson and Scardina (3) studied fatigue crack growth in 7075-T6 aluminum alloy sheet under both types of loading and concluded that the compression portion of the loading cycle did not significantly affect crack growth in their tests.

Based upon these results obtained from sheet aluminum alloys, it was generally concluded that the compression portion of tension-compression cycling could safely be ignored in all design situations (4,5). However, it has been noted in low-cycle fatigue tests on a plate-thickness high-strength steel (6) that notched specimens failed significantly earlier in crack propagation under fully-reversed tension-compression cycling than under zero-tension cycling at the same load amplitude. Gurney (7) has made similar observations on ferrous alloys, and he has proposed an equivalent stress concept to account for the accelerating effects of tension-compression cycling on fatigue crack growth.

With this background in mind, it was decided to determine if the compression portion of tension-compression cycling does contribute substantially to crack growth in several high-strength alloys, and if so, to determine the magnitude of these effects so that researchers and designers relying upon zero-tension data reported in the literature could reasonably estimate how these data would apply to fully-reversed tension-compression cycling.

EXPERIMENTAL DETAILS

Axial-loaded plate specimens containing embedded surface cracks were cycled under (a) constant-load-amplitude zero-tension and (b) fully-reversed tension-compression cycling.

The materials studied included 9Ni-4Co-0.20C and HY-80 quenched-and-tempered steels and Ti-6Al-4V alloy. All test materials were received as 1-in.-thick rolled plate stock. The tensile properties of the test materials are shown below.

Tensile Properties of Test Materials

Material	0.2% Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Reduction of Area (%)	Elongation (%)
9Ni-4Co-0.20C steel	183	201	66.0	17.8
HY-80 steel	109	127	68.9	20.5
Ti-6Al-4V	123	135	25.0	10.0

The materials were tested as axial-loaded surface-cracked plate specimens (Fig. 1). An Elox surface notch of semicircular shape (i.e., a depth-to-length ratio of 0.50) was used as the crack starter. Macrofeatures of the fatigue surfaces indicated that crack front profiles remained semicircular throughout the duration of their growth. Therefore, the assumption was carried forth that a uniform stress-intensity distribution existed around the periphery of the crack front. The equation (Ref. 8) used to calculate crack tip stress-intensity factors is

$$K = \sqrt{1.21 \pi \sigma^2 a/Q}$$

where K is the stress-intensity factor, σ is the nominal gross section stress, a is the crack depth, and Q is a flaw shape parameter. Maximum nominal stress levels encountered in fatigue cycling varied between 50 and 60 percent of yield strength stress. Crack length observations were made on the surface of the specimens using an optical micrometer. The crack depth a was assumed to be equal to half the total surface crack length 2c.

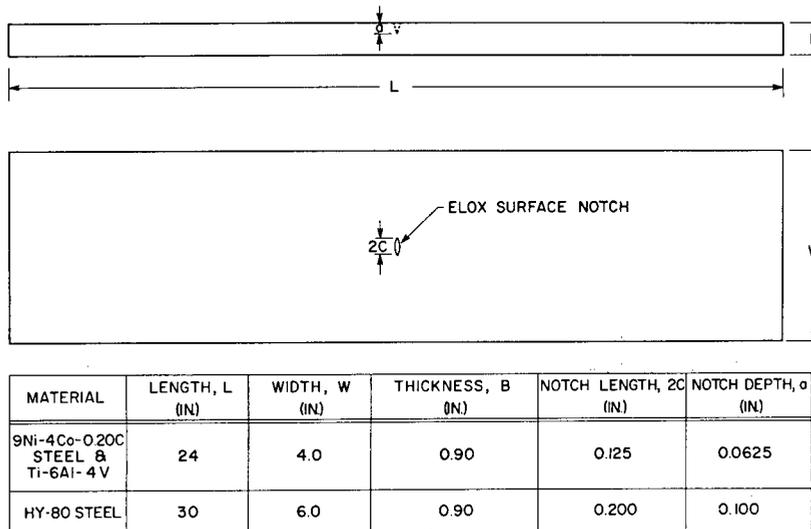


Fig. 1 - Dimensions and configuration of the test specimens and crack-starter notch

Specimens were cycled under (a) constant load amplitude zero-tension and (b) fully-reversed tension-compression cycling (Fig. 2). These loading cycles correspond to load ratios R (where $R = \text{minimum load}/\text{maximum load}$) of zero and -1.0 , respectively. In each case, companion specimens of a test material were cycled to failure at a constant-load amplitude with $R = 0$ and $R = -1.0$. All stress-intensity factor values reported were calculated using only the tension portion of the loading cycle.

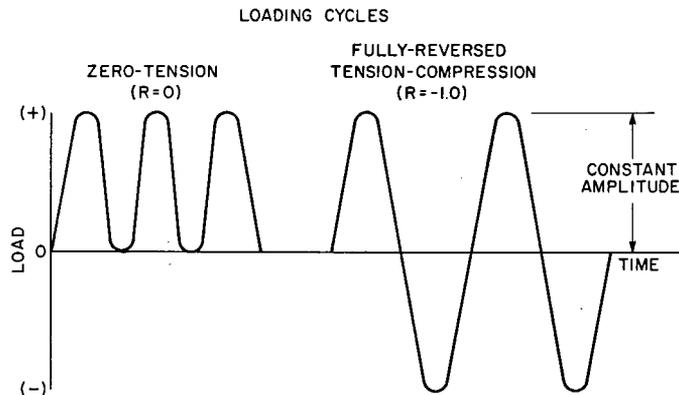


Fig. 2 - Schematic of the two loading cycles used in the tests

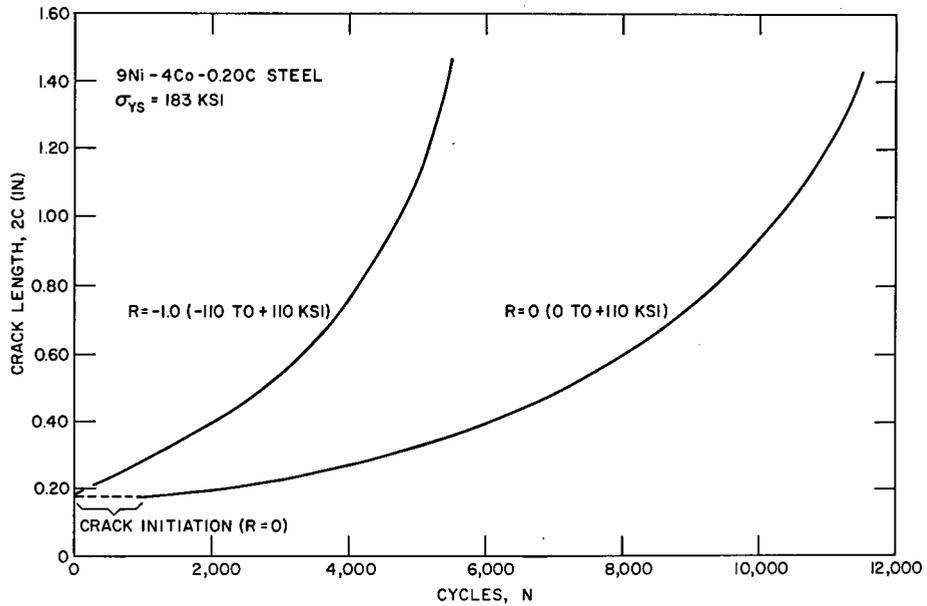
RESULTS

The results of this study are given in Figs. 3 and 4. In every instance, specimens which were tension-compression cycled failed significantly sooner than companion specimens cycled at zero-tension. Both crack initiation from the crack-starter notch and crack propagation were accelerated under tension-compression cycling. Typical examples of the differences in crack propagation life between zero-tension and tension-compression cycling are shown in Fig. 3. Companion specimens of each test material were cycled to maximum nominal stresses of 50 to 60 percent of the yield strength stress. These plots show that crack propagation occurred more rapidly at all stages of crack growth under tension-compression cycling. These plots also show that in high-strength alloys, such as 9Ni-4Co-0.20C steel and Ti-6Al-4V, fatigue failures in the low-cycle life region (i.e., less than 100,000 cycles) can occur at cyclic stress levels well below yielding. In fact, in all of the 0.90-in.-thick plate specimens tested, including HY-80, it was possible to obtain through-thickness flaws from small starting notches in well under 100,000 cycles.

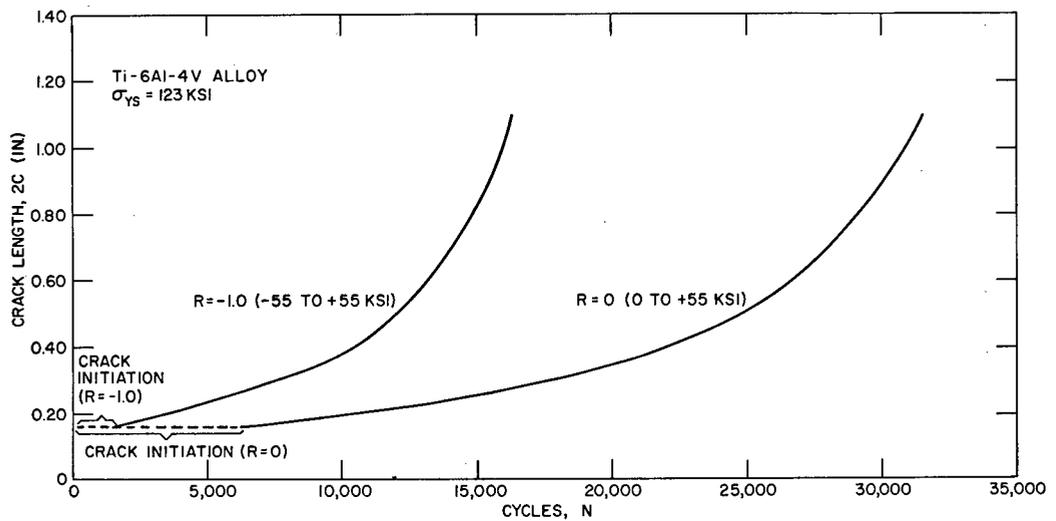
Log-log plots of fatigue crack growth rates dc/dN as a function of the tension stress-intensity factor range ΔK for all three materials studied are shown in Fig. 4. In each case the data for the two loading cycles fall along separate curves, with the tension-compression cycling exhibiting faster crack growth rates over the entire range of ΔK values examined. Tension-compression cycling accelerated crack growth rates by approximately 50 percent in each material.

DISCUSSION

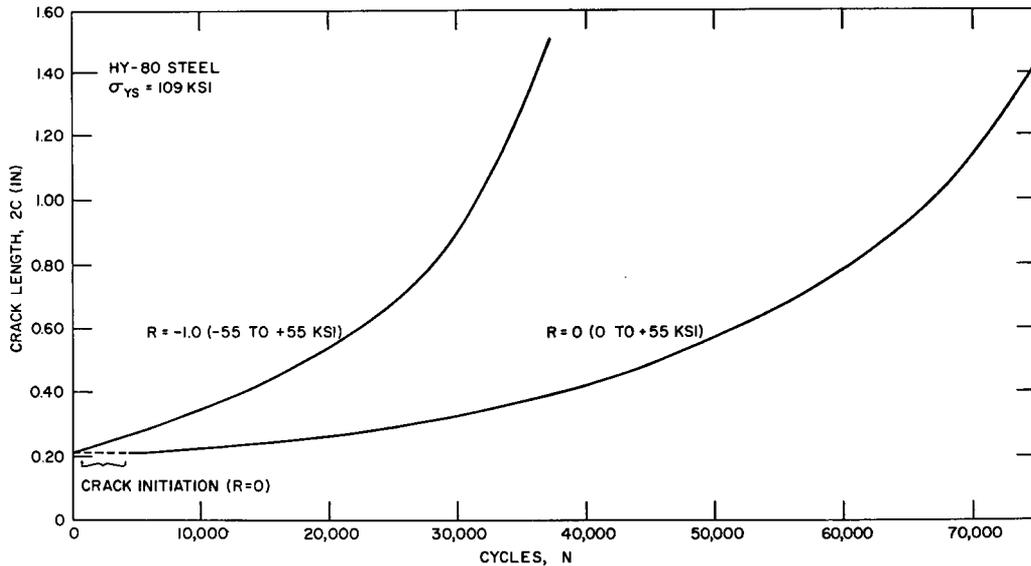
There are two viewpoints on fatigue crack propagation which can offer an explanation as to why nominal compressive loading can contribute to crack growth rates. Both



(a) plate specimens of 9Ni-4Co-0.20C steel subjected to zero-tension ($R = 0$) and tension-compression ($R = -1.0$) cycling



(b) Ti-6Al-4V plate specimens under constant-amplitude cycling with $R = 0$ and $R = -1.0$



(c) HY-80 steel plate specimens under constant-amplitude cycling with R = 0 and R = -1.0

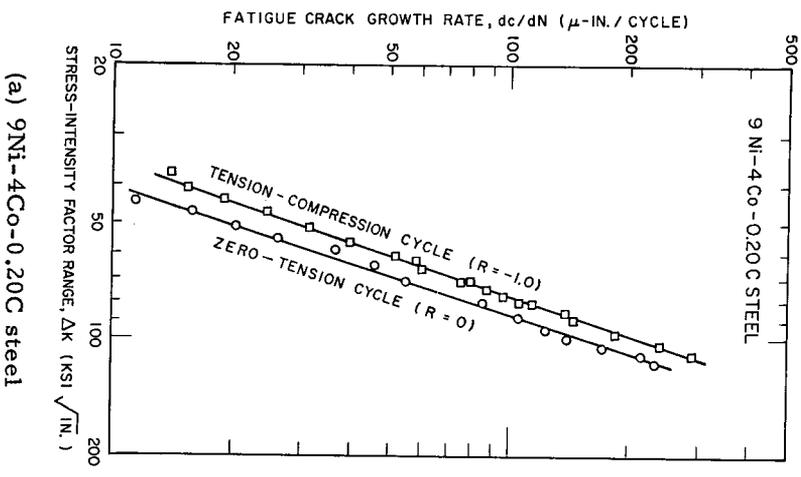
Fig. 3 - Total surface crack length 2c vs cycles of repeated load N

viewpoints recognize that fatigue crack propagation results from plastically deformed material residing at the tip of a sharp crack. Lehr and Liu (9) have proposed that fatigue crack propagation is the result of cumulative damage caused by plastic strain cycling of the material at the crack tip. The compression portion of tension-compression cycling contributes to crack tip deformation and, therefore, to crack growth rates. Hubbard (10) has observed fatigue crack growth under purely compressive cyclic loading. He postulated that cracks do not propagate under totally compressive stresses, and sought to define residual tensile stresses at crack tips under nominally compressive cycling. Although his work is not directly applicable to tension-compression cycling, it points out that crack tip stress fields do not necessarily follow in phase with nominal stresses under cyclic loading.

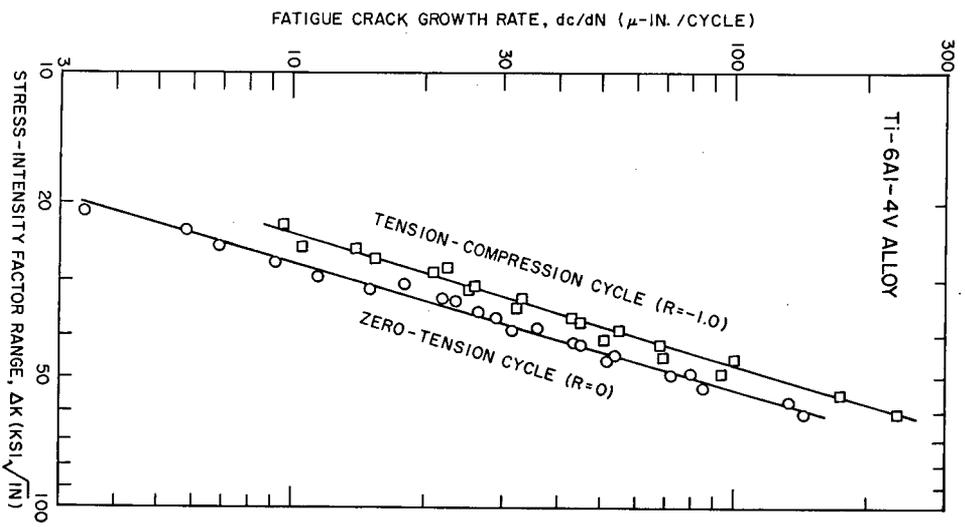
It is well recognized that service loads and residual stresses resulting from fabrication and/or shakedown can result in structural materials experiencing cycling which approaches fully-reversed tension-compression under loading from internal pressure. Since virtually all of the fatigue crack propagation data appearing in the literature are obtained under zero-tension cycling, the application of this data to structural design situations is not evident. The mathematical form of these data generally is

$$da/dN = C \Delta K^m$$

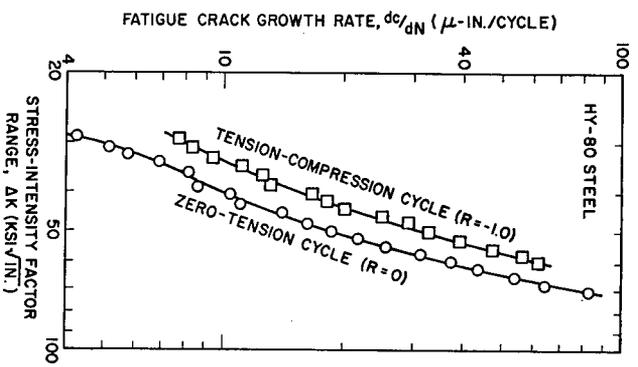
where da/dN (or dc/dN) is the crack growth rate, ΔK is the stress-intensity factor range for zero-tension or tension-tension cycling, m is the power law exponent, and C is a material constant. To ignore the compression portion of the cycle would tend to overestimate the fatigue life, as shown in the results of this study. To calculate ΔK based on the full range of loading would seriously underestimate fatigue life. Since m usually varies from approximately 2 to 4 for most steels (11), this would overestimate crack growth rates by factors of 4 to 16. Therefore, it is recommended that zero-tension crack growth rate data be increased by a correction factor of 1.5 for application to low-cycle-fatigue design situations involving tension-compression cycling. This procedure would be analogous to the adjustment for tensile mean stress effects which is included in the analysis for cyclic operation of nuclear vessels (12).



(a) 9Ni-4Co-0.20C steel



(b) Ti-6Al-4V alloy



(c) Hy-80 steel, for $R = 0$ and $R = 1.0$

Fig. 4 - Log-log plot of fatigue crack growth rate dc/dN as a function of the stress-intensity factor range ΔK . ΔK values were calculated using only the tension portion of the loading cycle

SUMMARY AND CONCLUSIONS

Low-cycle-fatigue crack propagation tests were conducted on HY-80 and 9Ni-4Co-0.20C steels and on Ti-6Al-4V alloys under constant load amplitude zero-tension and fully-reversed tension-compression cycling. It was observed that the compression portion of fully-reversed tension-compression cycling contributed substantially to crack growth and resulted in an approximate 50-percent increase in crack growth rates, as compared with zero-tension cycling. It is concluded that this effect of tension-compression cycling in fatigue crack growth should be included in the design of structures against low-cycle-fatigue failure where compressive loading is a significant factor. Laboratory crack growth rate data generated under ordinary zero-tension loading should be corrected by a factor of 1.5 to account for the effects of fully reversed tension-compression cycling.

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