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RIPPLE-LOADING EFFECTS ON STRESS-CORROSION CRACKING IN STEELS

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ABSTRACT

Stress-corrosion cracking (SCC) under ripple-loading conditions was investigated in three quenched-and-tempered steels ranging in yield strength from 860 to 1210 MPa (125 to 175 ksi). These studies involved precracked cantilever-beam specimens exposed to 3.5 percent NaCl aqueous solutions at room temperature and at two electrode potentials, freely corroding and -1.0 V versus Ag/AgCl. Ripple-loads were applied at a cyclic frequency of 0.1 Hz and load ratios (R = minimum load/maximum load) between 0.90 and 0.975. Measured in terms of time-to-failure as a function of initial Mode I crack-tip stress-intensity (K_I), the primary responses to ripple-loading were no effect in one instance and strongly detrimental in another. Where ripple-loading was observed to significantly affect SCC, threshold values under ripple-loading appeared to agree with the fatigue crack growth rate threshold (ΔK_{th}) for comparable loading and environmental conditions. These observations suggest that ripple-loading effects on SCC in steels may be primarily mechanical in origin.

INTRODUCTION

More than 20 years ago, B. F. Brown and coworkers at the Naval Research Laboratory began to study the stress-corrosion cracking (SCC) properties of high-strength alloys using precracked specimens. One enduring outcome of their work was the development of the fracture mechanics SCC threshold parameter, K_{Iscc} [1]. In intervening years, laboratory methods for measuring K_{Iscc} have been systematically examined by several organizations [2-4]. Also, the concept of an SCC threshold parameter which serves as a valid measure of a material's resistance to SCC has been sufficiently well accepted that K_{Iscc} data appear in materials properties handbooks widely used by government agencies and their contractors [5].

The most common test methods for measuring K_{Iscc} involve essentially static loading. Typically, precracked specimens are either dead-weight loaded or are loaded to a fixed crack-mouth-opening displacement [2-4].

However, starting about 10 years ago, a few investigators began to report that environmentally-induced cracking could occur in alloys at crack-tip stress-intensity (K_I) levels well below static threshold (K_{Iscc}) conditions, if small-amplitude cyclic loading was applied to test specimens simultaneously with the static loading normally applied [6-8]. It is interesting to note that these observations include both low- and high-strength, and ferrous and nonferrous alloys. This combination of static loading with superimposed small-amplitude cyclic loading is termed "ripple loading". For the purposes of this paper, ripple-loading will primarily refer to cyclic loading conditions involving load ratios (R = minimum load/maximum load) equal to or greater than 0.90.

The recent observations involving SCC under ripple-loading are considered by the present authors to be potentially significant in asssessing the SCC resistance of engineering alloys because, in actual service, some sort of periodic load perturbation is a far more likely condition than the purely static loading traditionally favored for measuring SCC threshold values. In other words, K_{Iscc} values carefully measured under static loading may, in fact, provide a nonconservative estimate of SCC resistance under service conditions involving even very small amplitude cyclic loading.

Finally, this is an area of materials behavior which has not received a great deal of attention by researchers. Typically, crack growth under cyclic loading in aggressive environments is termed "corrosion fatigue" and involves much larger amplitude loading and lower R values. It remains to be seen whether SCC under ripple-loading is a special case of SCC involving synergisms between cyclic and static loading, or is simply near-threshold fatigue crack growth rate behavior under conditions involving high R-ratios and a corrosive environment.

MATERIALS

The steels studied in this investigation include a 3Ni-Cr-Mo-V forged material, and 5Ni-Cr-Mo-V and AISI 4340 rolled plate materials. Chemical compositions are given in Table I and tensile properties are given in Table II.

TABLE I - CHEMICAL COMPOSITIONS (Weight percent)

Material	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V
3Ni-Cr-Mo-V	0.27	0.24	0.006	0.002	0.06	-	3.66	1.79	0.39	0.13
5Ni-Cr-Mo-V	0.13	0.82	-	0.002	0.24	0.05	5.20	0.44	0.52	0.05
4340	0.41	0.74	0.01	0.016	0.21	-	2.0	0.74	0.26	0.05

TABLE II - TENSILE PROPERTIES

Material	0.2% Yield Strength, MPa(ksi)	Ultimate Tensile Strength, MPa(ksi)	Elongation in 2-in.,%	Reduction in Area,%
3Ni-Cr-Mo-V	860 (125)	972 (141)	72	24
5Ni-Cr-Mo-V	965 (140)	1,014 (147)	-	-
4340	1,207 (175)	1,282 (186)	25	11

PROCEDURES

Time-to-failure data were generated using precracked cantilever-beam specimens, Fig. 1. Precracking was conducted in fatigue at maximum crack-tip stress-intensity (K_f) levels well below the K_I levels used in subsequent SCC tests, in accordance with precracking recommendations previously outlined by the authors [4]. The stress-intensity expression used to calculate K_I values is that given by Tada et al [9]. In all instances reported in this paper, the term "failure" refers to specimen fracture.

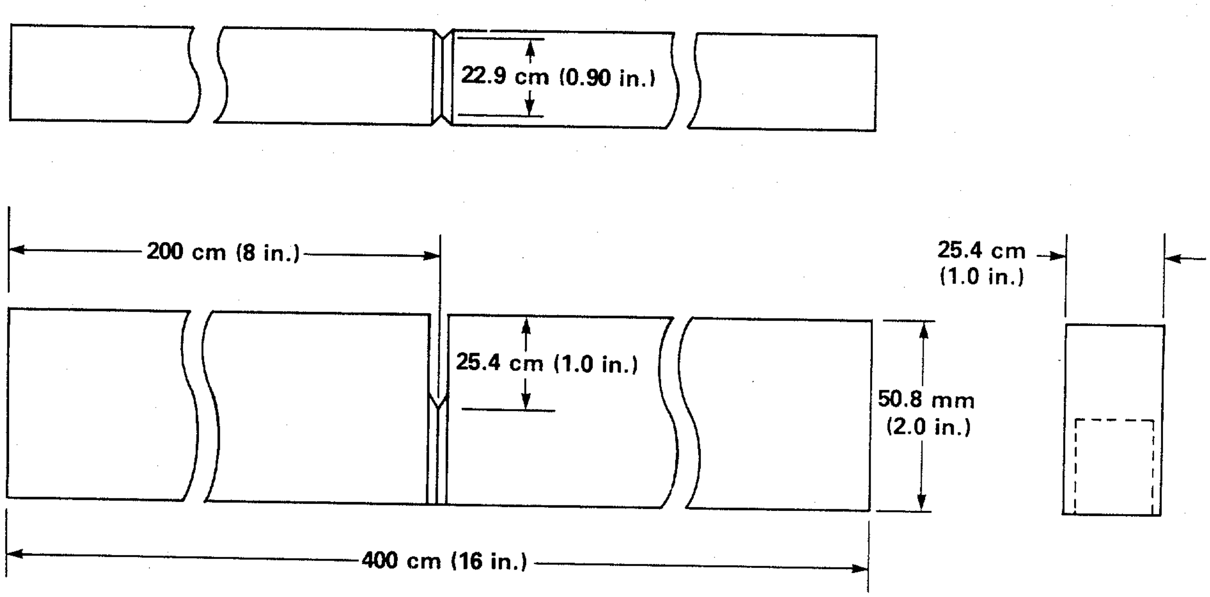

Figure 1 - Details of the precracked cantilever-beam test specimen.

In each instance, ripple-loading data were compared with reference data obtained under static dead-weight loading. For two of the steels, 5Ni-Cr-Mo-V and 4340, static tests resulted in the measurement of K_{Iscc} threshold values in accordance with previously evaluated and recommended procedures [2-4]. For tests involving ripple-loading, the dead-weight loading fixtures were modified by using a simple system consisting of a motor-driven cam and springs to vary the dead-weight loading in a controlled manner. This arrangement permitted the ripple-loading to be obtained by periodically relieving a small portion of the dead-weight load. Thus, comparisons between static and ripple-loading are made using common maximum stress-intensity (K_{max}) values, Fig. 2.

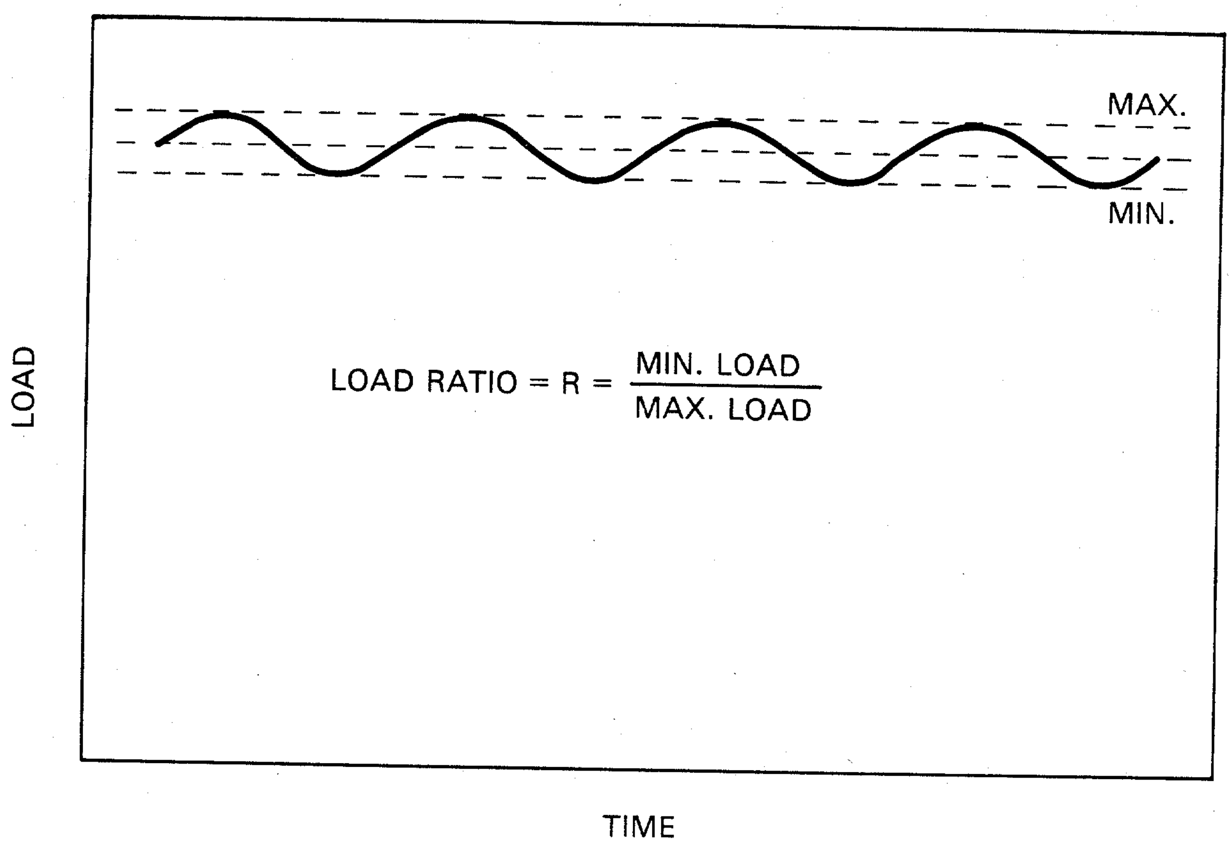

Figure 2 - Schematic illustration of ripple-loading involving high load-ratio (R) values.

The frequency of the ripple-loading was 0.10 Hz (6 cpm), with a skewed triangular load-time waveform having a nine second rise time and a one second fall. This waveform was chosen on the basis of evidence that damaging metal-environment reactions occur on the rise portion of the load-time waveform, when fresh metal surfaces are being formed [10]. Ripple-loading data were obtained at R values ranging from 0.90 to 0.975.

All tests were conducted in quiescent 3.5 percent aqueous NaCl solution at ambient laboratory temperatures. Corrosion cells were placed so that the solution surrounded the precracked center span of the specimens. Evaporated water was replaced daily, as required, and the solution in each corrosion cell was replaced weekly.

Electrode potentials were monitored using a Ag/AgCl reference electrode. The 4340 steel was tested at the freely corroding potential and at -1.0 V, obtained by using a potentiostat. The 3Ni-Cr-Mo-V steel was tested only under potentiostatically-controlled conditions at -1.0 V. The 5Ni-Cr-Mo-V steel was tested at a potential of approximately -1.0 V obtained by coupling to zinc anodes, except for two tests under potentiostatic control at -1.0 V as noted in the data. For tests involving zinc anodes, a pair of anodes were placed alongside the specimen within the corrosion cell.

RESULTS

Experimental results obtained on the 5Ni-Cr-Mo-V and 4340 steels are given in Figs. 3 and 4. These are semilogarithmic plots of initial stress-intensity (K_I) versus time-to-failure. For tests involving ripple-loading, K_I corresponds to K_{max} as shown in Fig. 2.

For the 5Ni-Cr-Mo-V steels, a static K_{Iscc} was established at 110 MPa$\sqrt{m}$ (100 ksi$\sqrt{in.}$) based upon multiple long-term tests exceeding 10,000 hours. Ripple-loading data were obtained at R values of 0.90, 0.925, 0.95 and 0.975. Except for R = 0.975, all ripple-loading conditions resulted in reduced values of time-to-failure and/or lower apparent threshold values. For R = 0.975, the apparent threshold equaled the static K_{Iscc}. For R = 0.95 and 0.90, the apparent thresholds were 80 and 44 MPa$\sqrt{m}$ (74 and 40 ksi$\sqrt{in.}$), respectively. However, neither of these threshold values had been validated for the recommended 10,000-hour exposure at the time that this paper was prepared. As noted in Fig. 3, two ripple-loading tests were conducted under potentiostatic control to achieve a cathodic polarization of -1.0 V, rather than using zinc anodes. In both instances, potentiostatic control appeared to extend the life of specimens for reasons which are unknown. In previous studies involving comparisons between the two methods of cathodic polarization under static loading, the opposite comparison was observed [4]. Comparisons of this type are considered to be important because when zinc anodes are used for cathodic polarization purposes in long-term tests, a significant volume of hydrated zinc oxide is formed on surfaces within the corrosion cell leading to concerns as to what effect this corrosion product may have on test results.

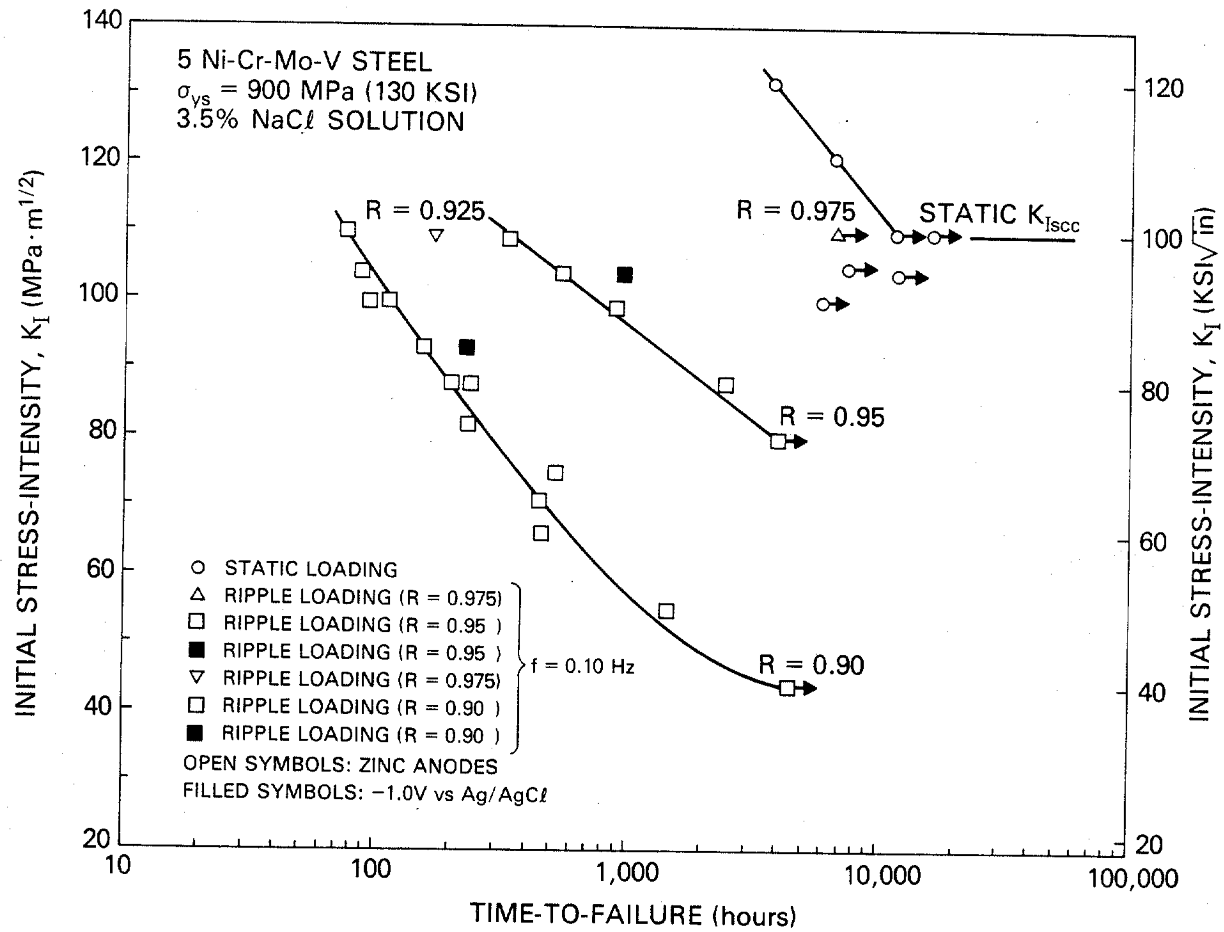

Figure 3 - Initial stress-intensity (K_I) versus time-to-failure data for 5Ni-Cr-Mo-V steel under static loading and ripple-loading.

For the 4340 steel, long-term static K_{Iscc} values were established for the freely corroding potential and for a potentiostatically-controlled potential of -1.0 V versus Ag/AgCl. These two values were 33 and 22 MPa√m (20 and 30 ksi√in.), respectively. Superimposed on these K_I-versus-time-to-failure data curves are two ripple-loading tests with R = 0.90 at the freely corroding potential and one at -1.0 V. No effect of ripple-loading on time-to-failure of K_{Iscc} was observed in the 4340 steel.

For the 3Ni-Cr-Mo-V steel, a single comparison was obtained between static and ripple-loading. This material had been previously characterized for SCC and was found to be highly resistant [11]. Further tests were undertaken to determine if ripple-loading had any possible effect on this high

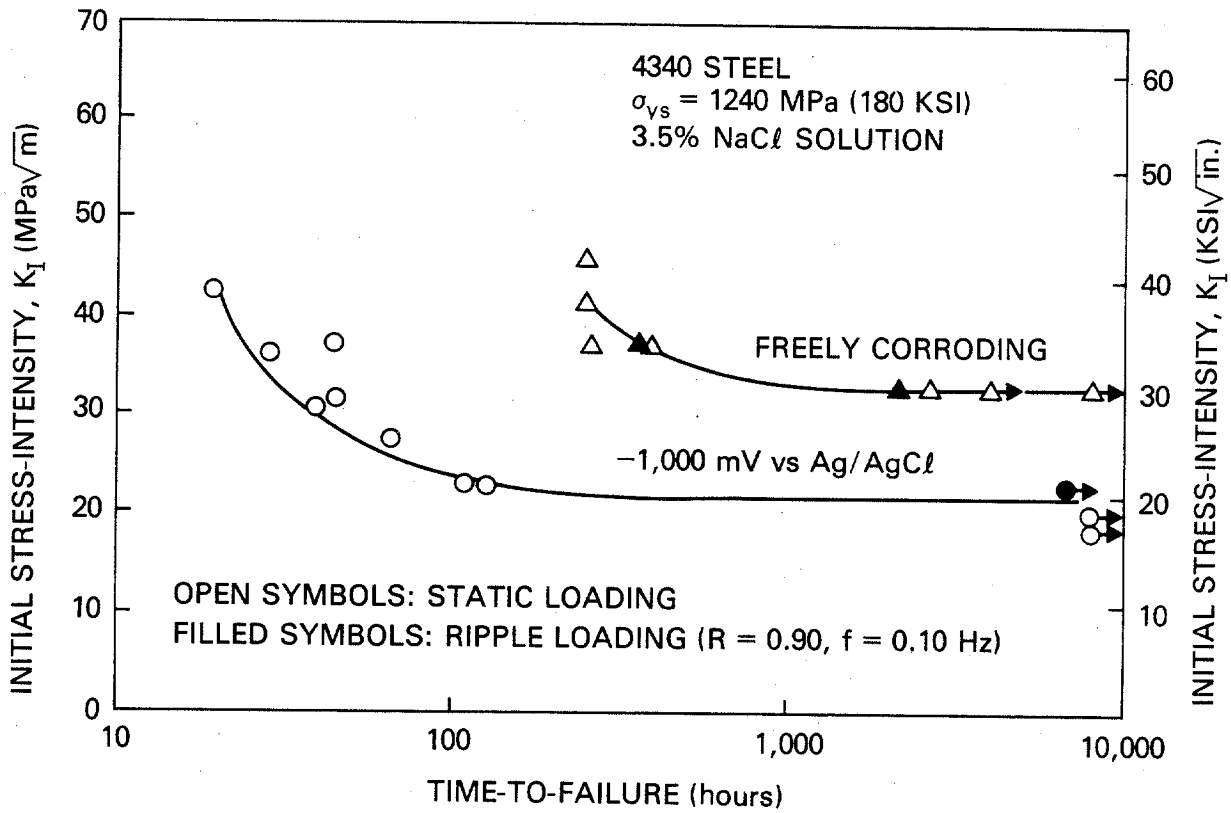

Figure 4 - Initial stress-intensity (K_I) versus time-to-failure data for high strength 4340 steel under static loading and ripple-loading.

level of SCC resistance. A pair of cantilever-beam companion specimens were tested at K_I = 132 MPa√m (120 ksi√in.) and -1.0 V versus Ag/AgCl; one was loaded statically and the other under ripple-loading with R = 0.97 and f = 0.10 Hz. In this instance, ripple-loading appeared to extend the time-to-failure, with the statically-loaded specimen failing in 159 hours and the ripple-loaded specimen failing in 430 hours.

Both of the 3Ni-Cr-Mo-V specimens were examined fractographically in a scanning electron microscope. No differences were observed between the fractographic features of the two specimens. Both specimens exhibited transgranular cracking with a blocky, intergranular characteristic and considerable secondary cracking, as illustrated in Fig. 5. No evidence of striation-like features, often associated with small-amplitude cyclic loading, could be found.

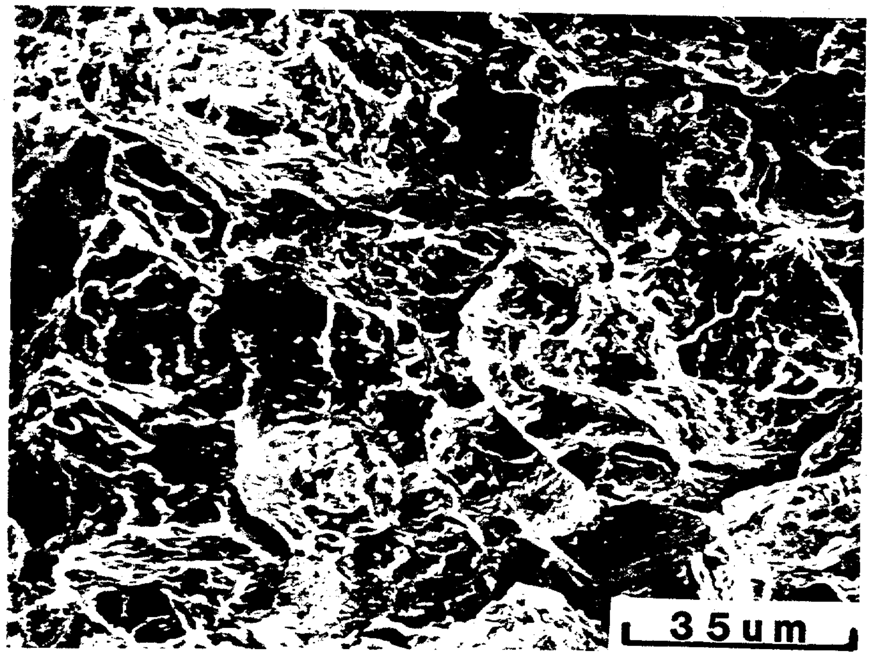

Figure 5 – Characteristic fractographic features of SCC in 3Ni-Cr-Mo-V steel under both static loading and ripple-loading.

DISCUSSION

Among the three materials studied in this investigation, three outcomes were observed regarding the effect of ripple-loading on SCC: (1) deleterious, (2) beneficial and (3) no effect.

Of these three outcomes, the most clearly demonstrable effects were observed in the 5Ni-Cr-Mo-V steel, where ripple-loading has a strongly deleterious effect on both time-to-failure and on apparent threshold levels. One of the first logical questions to ask regarding such deleterious ripple-loading effects is whether the behavior observed is not merely a manifestation of corrosion-fatigue crack propagation. That is, once a cyclic load, however small, is added to the static loading normally used in SCC tests does the failure process become one of corrosion-fatigue? Vosikovsky has conducted such tests on a 5Ni-Cr-Mo-V steel very similar to the one used in the present investigation [12]. Vosikovsky's corrosion-fatigue crack growth rate data, illustrated by trend lines in Fig. 6, are understandably somewhat scant in the near-threshold region; however for specimens coupled to zinc at low cyclic frequencies and an R-ratio of 0.90 , a ΔK_{th} value in the realm of approximately 4 MPa$\sqrt{m}$ is indicated. An examination of the data in Fig. 3 suggests that the ΔK_{th} for R = 0.90 is 4.4 MPa$\sqrt{m}$ and for R = 0.95 it is 4.0 MPa$\sqrt{m}$. It is of interest to note that, in the near-threshold region,

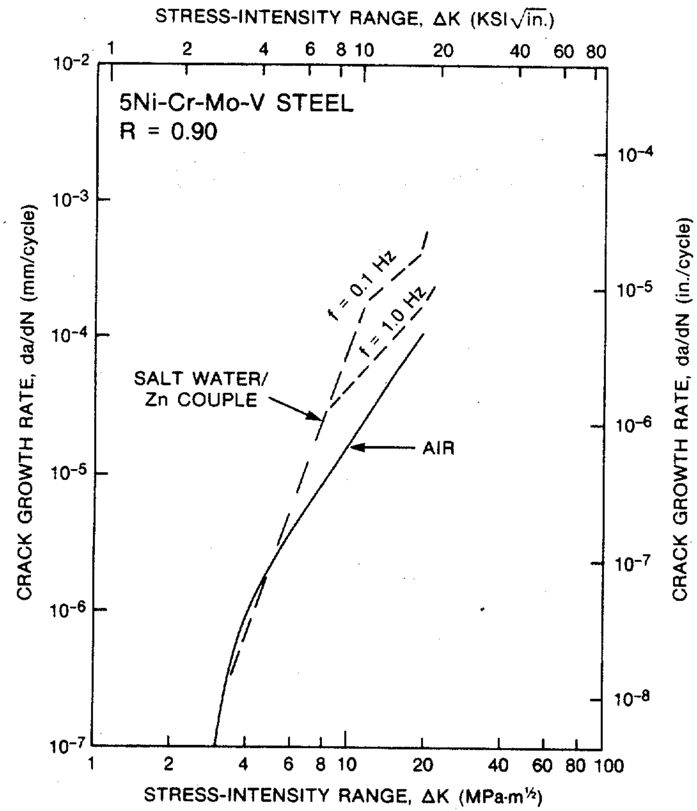

Figure 6 - Fatigue crack growth rate (da/dN) versus stress-intensity range (ΔK) data for 5Ni-Cr-Mo-V steel in an ambient air environment and in salt water with specimens coupled to a zinc anode for R = 0.90 and f = 1.0 and 0.1 Hz [12].

Vosikovsky's data indicate that environment has little, if any, effect on crack growth. Thus, perhaps mechanical processes dominate the crack growth process under these conditions.

This approximate correlation between Vosikovsky's ΔK_{th} data and the apparent thresholds for R = 0.90 and 0.95 in Fig. 3 is excellent. It suggests that once even a small amount of cyclic loading is applied to a specimen undergoing SCC testing, the resulting threshold value is likely to be controlled by ΔK_{th}, not K_{Iscc}. The implications of this finding lie in the fact that ΔK_{th} values for most steels, especially in the intermediate strength regime such as 5Ni-Cr-Mo-V and especially at high R ratios, are far below K_{Iscc} values. With relatively few exceptions, typical ΔK_{th} values for steels at all R ratios are 10 MPa$\sqrt{m}$ and less [13].

The same explanation could be applied to the lack of ripple-loading response observed in the 4340 steel data shown in Fig. 4. In this instance, because of the much lower K_{Iscc} of this higher-yield-strength material (20 to 30 MPa$\sqrt{m}$ versus 110 MPa$\sqrt{m}$), the ΔK values involved in the ripple-loading ($2 < \Delta K > 4$ MPa$\sqrt{m}$) were perhaps too near threshold levels to influence the SCC failure process.

Kido et al have reached findings very much like those of the present authors [14]. In their studies, Kido et al examined SCC in pure water in a variety of steels ranging in yield strength from 872 to 1921 MPa (126 to 279 ksi) using sharply-notched (but not precracked) specimens. Using the delayed failure strength at 100 hours, expressed in terms of nominal stress, as the figure of merit, they found that superimposed small-amplitude cyclic loading at a frequency of 15 cpm did not affect SCC unless the cyclic stress exceeded 24.5 MPa (3.5 ksi). Assuming that the very sharp notch configuration used by Kido et al approximates a sharp crack, for the geometry of their specimen, this threshold stress equates to a ΔK_{th} of approximately 5 MPa$\sqrt{m}$ (4.5 ksi$\sqrt{in.}$). At alternating stress levels higher than 24.5 MPa, they found that the 100-hour delayed failure strength was significantly reduced by cyclic loading. Thus, their data suggest that the corrosion-fatigue threshold, ΔK_{th}, may, in fact, be the controlling parameter in SCC under ripple-loading for steels.

At present, the extended life under ripple-loading observed in the two replicate samples of 3Ni-Cr-Mo-V steel is insufficient evidence to suggest that potentially beneficial effects from ripple-loading are a significant possibility.

Since its introduction more than 20 years ago, the SCC threshold parameter, K_{Iscc}, has been a major focus of attention in characterizing the SCC susceptibility of high-strength steels. For steels which are susceptible to SCC, K_{Iscc} data are relatively easy to generate and provide an established common basis of comparison for assessing SCC as a function of metallurgical and electrochemical variables. However, little research has been undertaken to evaluate the significance of K_{Iscc} data in terms of describing the behavior of materials under anticipated service conditions. The work described in this paper strongly supports the suggestion that more attention should be given to crack growth in corrosive environments under cyclic, as opposed to purely static loading [15]. For those engineering situations where a threshold parameter is required for defining the onset of crack growth, K_{Iscc} data are likely in many instances to be a nonconservative measure of crack initiation in the presence of even small amounts of cyclic loading.

CONCLUSIONS

1. Ripple-loading can, under certain circumstances, significantly reduce time-to-failure and threshold values for SCC of steels.

2. Where the effects of ripple-loading are detrimental, apparent SCC threshold values under ripple-loading have been observed to correlate well with ΔK_{th} fatigue threshold values for similar environmental and loading conditions.

3. The results of this study, although preliminary in nature, suggest that ripple-loading effects on SCC in steels may be primarily mechanical, rather than environmental, in their origin.

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