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A COMPARISON OF ENVIRONMENTALLY-INFLUENCED NEAR-THRESHOLD FATIGUE CRACK GROWTH BEHAVIOR IN HIGH AND LOWER STRENGTH STEELS AT CONVENTIONAL FREQUENCIES

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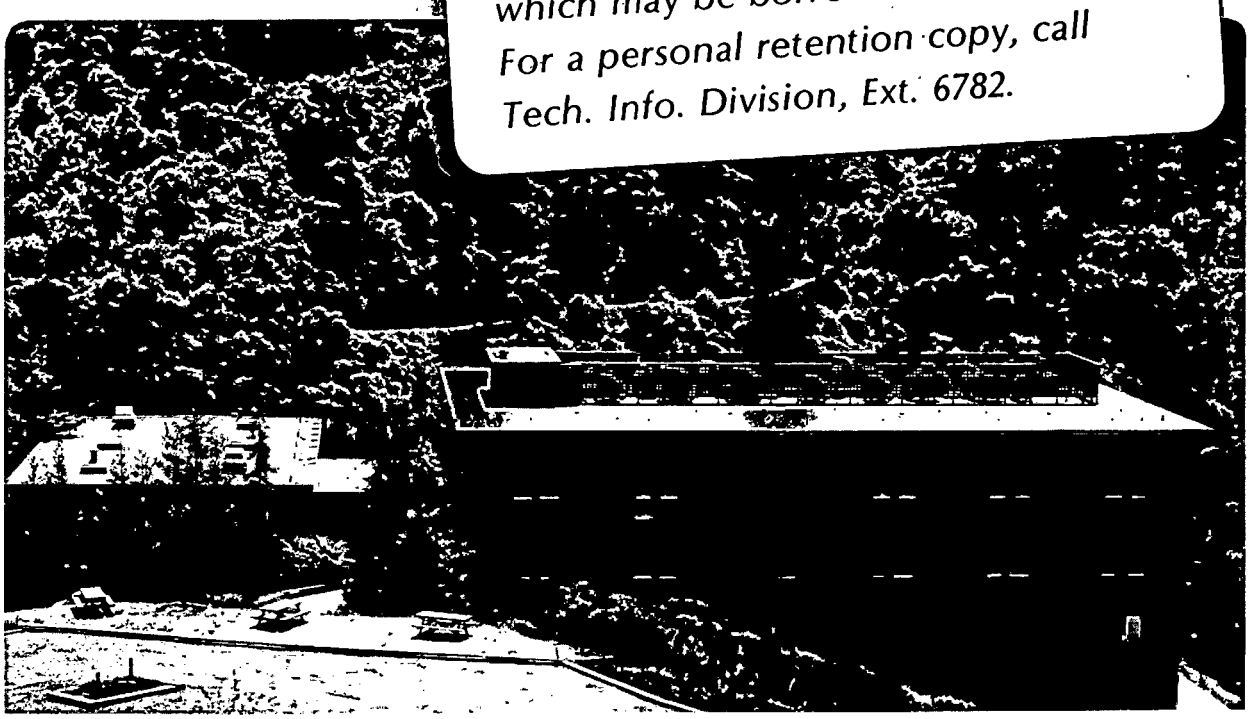

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A COMPARISON OF ENVIRONMENTALLY-INFLUENCED NEAR-THRESHOLD FATIGUE CRACK GROWTH BEHAVIOR IN HIGH AND LOWER STRENGTH STEELS AT CONVENTIONAL FREQUENCIES*

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A COMPARISON OF ENVIRONMENTALLY-INFLUENCED NEAR-THRESHOLD FATIGUE CRACK GROWTH BEHAVIOR IN HIGH AND LOWER STRENGTH STEELS AT CONVENTIONAL FREQUENCIES*

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Recent studies in a wide variety of steels, of yield strengths ranging from 290 to 1740 MPa, have indicated that environmental influences on corrosion fatigue crack propagation at near-threshold levels (growth rates below $\sim 10^{-6}$ mm/cycle), may be markedly different from those at higher growth rates. In this paper, the effect of such environments, specifically dry gaseous hydrogen and moist room air, on near-threshold cyclic crack growth is reviewed and comparisons made between behavior in high and lower strength steels. It is shown that, in lower strength steels (yield strength $\lesssim 700$ MPa), near-threshold growth rates in dry hydrogen exceed those in moist air by up to two orders of magnitude at low load ratios only, whereas for steels of strength levels above ~ 700 MPa, the presence of hydrogen results in lower near-threshold growth rates compared to moist air regardless of load ratio. Such behavior is rationalized in terms of the competing effects of hydrogen embrittlement and oxide-induced crack closure mechanisms.

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Introduction

In recent years there has been considerable interest, both academically and technologically, in the behavior of fatigue cracks at very low crack propagation rates approaching the so-called threshold stress intensity ΔK_{TH}, below which cracks remain dormant or grow at experimentally undetectable rates (1). Such behavior, known as near-threshold fatigue, involves crack velocities typically below 10^{-6} mm/cycle approaching a lattice spacing per cycle. Although fundamental crack extension mechanisms for such crack growth are still lacking, there is now a large body of evidence documenting the strong microstructural (i.e., grain size, strength level), mechanical (i.e., load ratio, crack size) and environmental factors which specifically influence near-threshold crack propagation resistance, as opposed to behavior at higher growth rates (see ref. 1 for a review). This specificity aspect is particularly evident for the role of environment in affecting cyclic crack advance where, on the basis of recent studies in steels, environmentally-influenced fatigue crack growth behavior at near-threshold levels appears quite different from reported trends at higher growth rates (2-14). It has been noted, for example, that in ultrahigh strength steels, which are markedly susceptible to hydrogen embrittlement, near-threshold crack growth rates in hydrogen gas are actually slower than in moist air (7,12,13), whereas in lower strength steels, which are traditionally regarded as being less prone to such embrittlement, near-threshold growth rates (at low load ratios*) are up to two orders of magnitude faster in dry hydrogen compared to air (3-5,8,9).

In an attempt to rationalize such environmentally-influenced near-threshold fatigue behavior in steels, a mechanism has recently been proposed based on the concept of oxide-induced crack closure (2-6). Moist environments, whilst capable of inducing faster crack growth rates due to "conventional" corrosion fatigue processes such as hydrogen embrittlement and active path corrosion, may also retard crack growth rates at low stress intensities through the formation of copious oxide deposits on freshly formed fracture surfaces at the crack tip. Such oxide deposits, which are promoted at near-threshold levels by fretting oxidation (15), aided by plasticity-induced crack closure (16) and Mode II crack tip displacements (17,18) can wedge the crack at low load ratios, thus raising the minimum stress intensity, and hence reducing the effective stress intensity range (ΔK_{eff}) at the crack tip. The effects of such oxide-induced closure appear to be greatest in moist environments, at low load ratios and in low strength materials where cyclic crack tip opening displacements (ΔCTOD) approach the size-scales of the thickness of the oxide debris (5,8,9). Accordingly, observations (3,5) of faster near-threshold growth rates in lower strength steels, such as 2¼Cr-1Mo tested at R = 0.05 in dry gaseous hydrogen (or helium), compared to humid room air, can be interpreted as principally arising from a reduced role of crack closure, i.e., dehumidified atmospheres such as hydrogen and helium act primarily as dry, oxygen-free environments which minimize crack surface oxidation and thus reduce the decelerating influence of oxide-induced crack closure.

Although environmentally-influenced near-threshold crack growth behavior in lower strength steels can be so interpreted in terms of a dominant role of closure, the effects of such mechanisms on behavior in

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*Load ratio R is defined as the ratio of minimum to maximum stress intensity, K_{min}/K_{max}.

high strength steels (yield strength levels above typically 700 MPa), appear less relevant. First, growth rates appear slower in hydrogen compared to room air, and the effect is seen at both low and high load ratios. Second, Auger measurements on fracture surface corrosion debris in such steels indicate no significant build-up of oxide deposits at near-threshold levels, which suggests that crack growth rates are hardly influenced by oxide-induced closure (7,12).

The object of the present paper is to compare and contrast the role of gaseous environment in influencing near-threshold fatigue crack propagation in high and lower strength steels by extensively reviewing existing near-threshold data for steels, ranging in yield strength from 290 to 1740 MPa, tested in air and dry hydrogen environments (3,5,7-14). Mechanisms for the observed behavior are described in terms of the competing effects of oxide-induced crack closure and hydrogen embrittlement processes. The results of this work, although pertaining strictly to fatigue crack extension mechanisms at conventional frequencies (i.e., 50 to 120 Hz), are briefly discussed in the light of their potential relevance to crack growth behavior at ultrasonic frequencies.

Experimental Procedures

Near-threshold fatigue data were examined in a wide variety of commercial steels ranging in yield strength from 290 to 1740 MPa (42 to 252 ksi). These included several classes of 2¼Cr-1Mo pressure vessel steels (SA387, SA542-3 and SA542-2), a pipeline steel (SA516-70), a silicon-modified 4340 steel (300-M), and several rotor steels (NiMoV, NiCrMoV, 2NiCrMoV and 3½NiCrMoV). Chemical composition and ambient temperature mechanical properties are listed in Tables I and II respectively. Details on heat-treatment procedures and microstructures are described elsewhere (3-5,7-14).

Table I. Chemical Composition in Wt Percent of Alloys Investigated

Material	C	Mn	Si	Ni	Cr	Mo	P	S	Cu	V
SA387	0.12	0.42	0.25	0.14	2.48	1.06	0.013	0.020	0.16	--
SA516-70	0.23	1.20	0.25	--	--	--	0.006	0.019	--	--
SA542-3	0.12	0.45	0.21	0.11	2.28	1.05	0.014	0.015	0.12	--
SA542-2	0.14	0.44	0.22	0.61	2.28	0.92	0.010	0.020	--	--
2NiCrMoV	0.18	0.55	0.22	2.05	1.09	0.49	0.016	0.016	--	0.11
3½NiCrMoV	0.19	0.30	0.29	3.50	1.55	0.44	0.007	0.008	--	0.12
NiMoV	0.28	0.40	0.23	3.50	0.15	0.38	0.010	0.007	--	0.08
NiCrMoV	0.24	0.28	0.04	3.51	1.64	0.39	0.005	0.012	--	0.11
300-M	0.42	0.76	1.59	1.76	0.76	0.41	0.007	0.002	--	0.10

Table II. Ambient Temperature Mechanical Properties of Steels Investigated

Material	Yield Strength (MPa)	U.T.S. (MPa)	Redn. Area (%)	K_{Ic} (MPa$\sqrt{m}$)	K_{Iscc} (H_2 gas) (MPa$\sqrt{m}$)
SA387[1]	290	500	76	286	>80
SA516-70[2]	327	496	70	233	>80
SA542-3[3]	500	610	77	295	85
SA542-2 (T690)[4]	575	697	65	-	-
2NiCrMoV[3]	575	718	35	-	-
3½NiCrMoV (T650)[3]	602	726	71	-	-
NiMoV[3]	661	786	58	-	-
SA542-2[4]	769	820	56	-	80
NiCrMoV[3]	780	882	63	-	-
3½NiCrMoV[4]	1070	-	-	-	-
300-M (T650)[4]	1070	1200	56	152	-
300-M (T300)[4]	1740	2000	40	65	18

[1]bainite/ferrite microstructure
[2]ferrite/pearlite microstructure
[3]bainite microstructure
[4]martensite microstructure

Crack propagation tests were performed on electro-servo-hydraulic and Amsler Vibraphore testing machines using frequencies in the range 50 to 120 Hz (sine wave) at load ratios ($R = K_{min}/K_{max}$) from 0.05 to 0.90. Both compact tension (CT) and wedge-open-loading (WOL) test specimen geometries were employed. Near-threshold growth rate measurements were performed, using d.c. electrical potential and elastic compliance monitoring techniques, under decreasing stress intensity range (load-shedding) conditions with either manual or computer control. Threshold stress intensities (ΔK_{TH}) for no crack growth were defined in terms of a maximum growth rate of 10^{-7} to 10^{-8} mm/cycle (4×10^{-9}-10^{-10} in/cycle). Tests were conducted at 23°C and 93°C in environments of laboratory air (30% relative humidity) and dehumidified gaseous hydrogen. Hydrogen gas environments were dried through molecular sieves and a liquid nitrogen cold trap, and were preserved, at pressures between 138 and 448 kPa, in small O-ring sealed chambers locally mounted on the test piece.

Fracture surfaces were examined in the scanning electron microscope and with Auger spectroscopy to assess the extent of crack surface corrosion deposits. Details on the latter procedures are described in Ref. 9.

Results

Behavior in Lower Strength Steels

Typical results showing the influence of dry gaseous hydrogen and moist air on fatigue crack propagation in lower strength steels are shown in Fig. 1 for SA542-3 2¼Cr-1Mo steel tested at 50 Hz frequency at load ratios

between 0.05 and 0.75 (5). At intermediate growth rates above $\sim 10^{-5}$ mm/cycle, hydrogen can be seen to enhance propagation rates, with respect to air, as reported by numerous other authors, reflecting a (sustained load) hydrogen embrittlement contribution to cracking. This effect is promoted by decreasing frequency and increasing load ratio, and occurs above a critical maximum stress intensity, termed K^T_{max}, which is approximately 20 MPa$\sqrt{m}$ in this steel. Concurrent with the onset of hydrogen-assisted crack growth in this regime a fracture mode change from predominately transgranular to intergranular failure is also apparent.

As growth rates are reduced to near-threshold levels below $\sim 10^{-6}$ mm/cycle, however, growth rates in hydrogen became significantly faster than in air (by up to two orders of magnitude) although the effect is only pronounced at low load ratios. At R = 0.05, threshold ΔK_{TH} values are 48% higher in air, although no change in fracture morphology (predominately transgranular) is evident. Similar studies in SA542-2 and other low strength steels suggest that the near-threshold behavior depicted in Fig. 1 for dry gaseous hydrogen is typical for dehumidified environments, such as helium, argon, dry air and dry oxygen (3,5,8,9). Further, the behavior in moist air is similar to behavior reported for distilled water and moist hydrogen gas. It is apparent that in such lower strength steels, near-threshold growth rates are significantly faster in dehumidified environments, both inert and hydrogen-producing, but this marked environmental influence is confined only to low load ratios.

Behavior in High and Ultrahigh Strength Steels

Analogous results (7) showing the influence of dry gaseous hydrogen and moist air on fatigue crack propagation in high strength steels are shown in Fig. 2 for 300-M steel (300°C temper) tested at 5 and 50 Hz at R = 0.05. Although the role of hydrogen in accelerating crack propagation rates above 10^{-5} mm/cycle is quite similar to behavior in lower strength steels (cf. Fig. 1), the influence of the environment at near-threshold levels can be seen to be distinctly different. Below $\sim 10^{-6}$ mm/cycle, there is a small but definite trend of what appears to be a deceleration in growth rates in hydrogen (138 kPa pressure) with the threshold ΔK_{TH} values being $\sim$14% lower in air. This environmental effect, however, is not confined to low load ratios, and is apparent at both R = 0.05 and 0.70, as shown for 300-M tempered at 650°C in Fig. 3. Similar results (13) are seen with higher pressure dry hydrogen (448 kPa) and moist air (30-35% relative humidity), as shown for Ni-Mo-V steel tested at R = 0.1 and 0.8 at 93°C (Fig. 4). In all cases, the values of the threshold ΔK_{TH} are seen to be higher in hydrogen gas compared to moist air, regardless of load ratios, over the frequency range tested (50-120 Hz). This is especially clear in Fig. 5, where the variation in ΔK_{TH} with load ratio R is plotted for tests in air and hydrogen gas for Ni-Mo-V and Ni-Cr-Mo-V steels (13,14).

Similar to behavior in lower strength steels, fractographically little difference could be observed in fracture mechanisms for both environments at near-threshold levels. In all cases, a fine-scale transgranular morphology was seen with isolated intergranular facets (<10%). However, there was no evidence of a characteristic fracture morphology in hydrogen despite the observed difference in growth rates compared to air environments.

Thus, unlike behavior in lower strength steels where moist environments, such as humid air, retard near-threshold growth rates (and enhance thresholds) principally at low load ratios, behavior in high strength steels is characterized by faster near-threshold growth rates (and lower thresholds) in moist air, compared to dry hydrogen, over the entire range of

positive load ratios.

Using threshold ΔK_{TH} data collected for the range of steels tested, representing yield strengths from 290 to 1740 MPa (Table III), this contrasting near-threshold behavior in high and low strength steels can be demonstrated by plotting the ratio of ΔK_{TH} in hydrogen to ΔK_{TH} in air as a function of yield strength for low (≤ 0.15) and high (≥ 0.7) load ratios (Fig. 6). As stated above, threshold ΔK_{TH} values are only larger in air at low load ratios for steels with yield strengths below 600-800 MPa. Interestingly, behavior at high load ratios for all strength levels resembles the low load ratio behavior of high strength steels in that threshold ΔK_{TH} values in hydrogen (with the exception of one data point) are marginally larger than, or equal to, threshold values in air.

Table III. Threshold Data for High and Lower Strength Steels in Air and Dry Hydrogen

Material	Yield Strength (MPa)	Temperature (°C)	Load Ratio (K_{min}/K_{max})	ΔK_{TH} (MPa$\sqrt{m}$) air	ΔK_{TH} (MPa$\sqrt{m}$) hydrogen
SA387	290	23	0.05	9.0	7.1
			0.80	5.1	4.4
SA516-70	327	23	0.15	7.2	5.7
			0.75	3.8	3.9
SA542-3	500	23	0.05	7.7	5.2
			0.75	3.2	3.3
SA542-2 (T690)	575	23	0.05	8.6	6.9
2NiCrMoV	575	23	0.10	7.0	4.8
			0.92	2.2	2.5
3½NiCrMoV (T650)	602	23	0.10	7.8	4.2
			0.90	2.2	2.4
NiMoV	661	23	0.10	4.0	4.5
	661	93	0.10	4.5	5.5
		93	0.80	2.9	3.9
SA542-2	769	23	0.05	7.1	4.6
			0.75	2.8	2.8
NiCrMoV	780	93	0.10	4.2	4.8
			0.80	2.9	3.2
3½NiCrMoV	1070	23	0.03	2.8	2.9
300-M (T650)	1070	23	0.05	8.7	9.8
			0.70	2.7	3.1
300-M (T300)	1740	23	0.05	3.1	3.7

Discussion

The majority of data reported in the literature describing the role of environment in influencing fatigue crack propagation behavior have been obtained at intermediate to high growth rates (i.e., above $\sim 10^{-5}$ mm/cycle). As shown in Figs. 1 and 2, such data clearly indicate that fatigue crack growth rates in the presence of hydrogen are accelerated with respect to room air or inert environments, a phenomenon attributed to mechanisms of hydrogen embrittlement. Although precise mechanisms are still uncertain, hydrogen gas is considered to physi-adsorb and dissociate on freshly exposed surfaces at the crack tip, thereby releasing hydrogen atoms which enter the iron matrix leading to some form of embrittlement within the material (19). What is intriguing about the environmentally-influenced near-threshold data (growth rates $\lesssim 10^{-6}$ mm/cycle) reviewed in the current paper is that at first glance behavior at ultra-low growth rates appears totally inconsistent with such hydrogen embrittlement mechanisms. Firstly, near-threshold growth rates in hydrogen are only faster than in room air at low load ratios in lower strength steels. In higher strength steels, which are generally regarded as being far more susceptible to hydrogen embrittlement, near-threshold growth rates are actually slower in hydrogen. Secondly, the latter trend of slower growth rates (and higher thresholds) in hydrogen appears to be the case for all steels at high load ratios, although differences can be much smaller.

Such behavior can be interpreted by considering the competing influence of two mechanisms generated by the presence of moisture at near-threshold levels, namely the decelerating effect of corrosion deposits formed at the crack tip, termed oxide-induced crack closure, and the accelerating effect of hydrogen released by such oxidation in embrittling the material, i.e., hydrogen embrittlement. As discussed below, it appears that closure mechanisms dominate behavior in the lower strength materials whereas hydrogen embrittlement mechanisms dominate in the high strength materials. We now examine each mechanism in turn:

Oxide-Induced Crack Closure

Recent studies (2-6) on low strength steels tested in moist environments have demonstrated the importance of crack surface oxidation products formed during fatigue crack propagation at low load ratios. At stress intensity ranges where the thickness of this debris is comparable in size with local cyclic crack tip opening displacements, i.e., at near-threshold levels, such oxides provide a mechanism for increased crack closure by essentially wedging the crack above the minimum load of the fatigue cycle, thereby reducing the effective stress intensity range actually experienced at the crack tip, i.e., the minimum stress intensity K_{min} is effectively increased. For near-threshold crack extension in moist environments, the oxide films are thickened at low load ratios by a process of fretting oxidation, from a continual breaking and reforming of the oxide scale behind the crack tip to create new zones of fresh surface due to contact between the crack surfaces as a result of plasticity-induced crack closure and large Mode II displacements (which are characteristic of crack advance at low stress intensities). Auger spectroscopy analyses (9) of near-threshold fracture surfaces have shown that the corrosion deposits grow to a thickness comparable in size to the cyclic crack tip opening displacements at the threshold ΔK_o in lower strength steels, and this fact may provide a physical explanation for the very existence of a threshold (5). However, with increasing strength level, the extent of excess corrosion debris formed on the near-threshold crack tip surfaces diminishes to size-scales comparable with the thickness of naturally-formed oxides (i.e., oxide formed on

polished samples exposed to the same environment for similar time periods), as shown in Fig. 7. This presumably arises because in higher strength steels the extent of plasticity-induced closure and Mode II displacements are reduced and the base metal becomes too hard to be susceptible to extensive fretting oxidation at low stresses (7). Thus, oxide-induced crack closure phenomena will be principally effective in lower strength materials, and particularly at low load ratios where contact can occur between crack surfaces at positive loads to promote the fretting oxidation formation.

Conventional Corrosion Fatigue Processes (Hydrogen Embrittlement)

The near-threshold fatigue crack growth data presented for lower strength steels clearly indicate that, at lower load ratios, moist or aqueous environments result in lower crack propagation rates compared to dry gaseous media (i.e., hydrogen and helium). Such results together with the thickness measurements of crack face corrosion deposits, show that crack closure phenomena influence near-threshold behavior in these steels more significantly than any of the conventional corrosion fatigue processes, such as hydrogen embrittlement or active path corrosion, at the frequencies utilized for near-threshold measurements (>50 Hz). The observation (Fig. 1) that behavior in moist and dry environments is similar at high load ratios, where closure effects in general are minimal, is consistent with this argument.

However, related observations of near-threshold fatigue behavior in higher strength steels (e.g., Figs. 2 and 3) reveal that the presence of moisture leads to slightly higher growth rates, compared to dry environments, at all positive load ratios. For this class of materials, closure effects appear to be minimal because of limited plasticity, less fretting and consequently less crack face oxidation. However, such steels in general possess a higher susceptibility to hydrogen embrittlement (19) and this is manifest at near-threshold levels in marginally faster growth rates in moist environments. The reason why water or water vapor environments should be more potent than gaseous hydrogen in inducing hydrogen embrittlement at very low growth rates is currently not understood but it is conceivable that cathodic hydrogen produced concomitantly with even limited oxidation in moist media is a more effective process for embrittlement than the physi- and chemisorption of gaseous hydrogen. Such notions are analogous to those recently proposed for high strength aluminum alloys (20,21).

Thus the environmentally-influenced near-threshold fatigue crack growth behavior of steels can be interpreted in terms of a competition between two concurrent processes: crack closure due to corrosion debris (which increases the threshold ΔK_o) and hydrogen embrittlement arising from the production of hydrogen vis-a-vis the oxidation process (which decreases the threshold ΔK_o). Whereas closure phenomena appear to dominate behavior in lower strength steels (at low load ratios), conventional corrosion fatigue processes appear to dominate in high strength steels, as shown schematically in Fig. 8.

Relevance to Fatigue at Ultrasonic Frequencies

The relevance of the mechanisms discussed above for near-threshold corrosion fatigue crack growth at ultrasonic frequencies (i.e., 21 kHz) is currently uncertain but one can postulate that in general closure effects would be less influenced by increasing frequency than say hydrogen embrittlement. Since rate-limiting steps for such embrittlement have been related to such processes as crack tip oxidation of iron, chemisorption of hydrogen and gas phase transport (22), it would seem unlikely that these processes would

have sufficient time to be active at ultrasonic frequencies. However, evidence of "conventional" corrosion fatigue behavior has been claimed for ultrasonic fatigue data showing marginally faster near-threshold growth rates in NaCl solution, compared to silicone oil environments, for mild steel tested at 21 kHz (23). Although a full mechanistic analysis has not been presented for such results, we would question any interpretation in terms of hydrogen embrittlement or active path corrosion in view of the extremely high frequencies involved. Rather we would suggest that the slower crack growth rates observed in the oil environment may result, not from an absence of any environmental contribution to cracking, but rather from the hydrodynamic wedging action of the oil, inside the crack, in promoting closure. This idea (24) of a viscous fluid providing a mechanism for crack closure in near-threshold cracks is currently under investigation in our laboratory (25).

Conclusions

The near-threshold fatigue crack propagation behavior of a wide variety of steels, ranging in yield strength from 290 to 1740 MPa, has been studied with specific reference to the role of environment at non-ultrasonic frequencies (i.e., 50-120 Hz). It is found that in lower strength steels (yield strength below ∿700 MPa), near-threshold crack growth rates are significantly slower in moist environments compared to dry hydrogen or helium gas atmospheres at low load ratios, although behavior is virtually identical in these environments at high load ratios. Higher strength steels (yield strength above ∿700 MPa), on the other hand, show a small acceleration in near-threshold growth rates in moist air compared to dry hydrogen which is observed at both high and low load ratios. Such behavior is interpreted in terms of a competition between two concurrent processes: oxide-induced crack closure to due corrosion debris, which retards crack growth and conventional corrosion fatigue mechanisms (hydrogen embrittlement, active path corrosion) which accelerate crack growth. Whereas closure mechanisms appear to dominate behavior in lower strength steels (at low load ratios), such mechanisms become less important with increasing strength level such that behavior in high strength steels is more a function of conventional corrosion fatigue processes.

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FIGURE CAPTIONS

Fig. 1: Influence of dehumidified hydrogen gas and moist air on ambient temperature fatigue crack propagation in lower strength 2¼Cr-1Mo SA542-3 steel at R = 0.05-0.75.

Fig. 2: Influence of dehumidified hydrogen gas and moist air on ambient temperature fatigue crack propagation in ultrahigh strength 300-M steel (300°C temper) at R = 0.05.

Fig. 3: Influence of dehumidified hydrogen gas and moist air on ambient temperature fatigue crack propagation in high strength 300-M steel (650°C temper) at R = 0.05 and 0.70.

Fig. 4: Influence of hydrogen gas and moist air on fatigue crack propagation at 93°C in high strength Ni-Mo-V rotor steel at a) R = 0.1 and b) 0.8.

Fig. 5: Variation in fatigue crack growth threshold stress intensity range ΔK_{TH} with load ratio R for bainitic rotor steels tested at 93°C in air and hydrogen. Data for a) Ni-Mo-V and b) Ni-Cr-Mo-V steels.

Fig. 6: The influence of yield strength on threshold fatigue crack growth behavior in moist air and dry hydrogen environments at low and high load ratios. Plotted is the ratio of the threshold stress intensity range in hydrogen to the threshold stress intensity range in air as a function of yield strength for a) low load ratios (R = 0.05-0.15) and b) high load ratios (R = 0.7-0.9).

Fig. 7: Variation of maximum excess oxide thickness, measured on the fracture surface at ΔK_{TH}, with yield strength for steels tested in moist air at R = 0.05.

Fig. 8: Schematic representation of environmentally-influenced near-threshold fatigue crack growth behavior in high and lower strength steels, tested in dry hydrogen gas and moist air, at low and high load ratios. Behavior is interpreted in terms of a competition between oxide-induced crack closure (OICC) and hydrogen embrittlement (HE) processes.

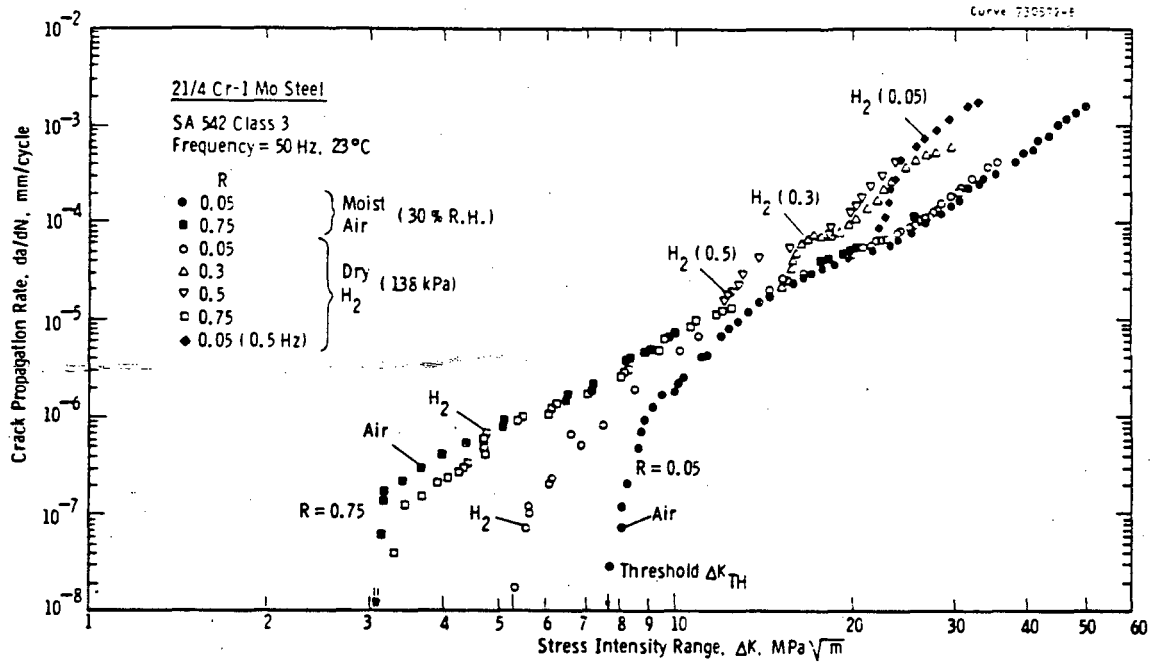


Fig. 1: Influence of dehumidified hydrogen gas and moist air on ambient temperature fatigue crack propagation in lower strength $2\frac{1}{4}$Cr-1Mo SA542-3 steel at R = 0.05-0.75.

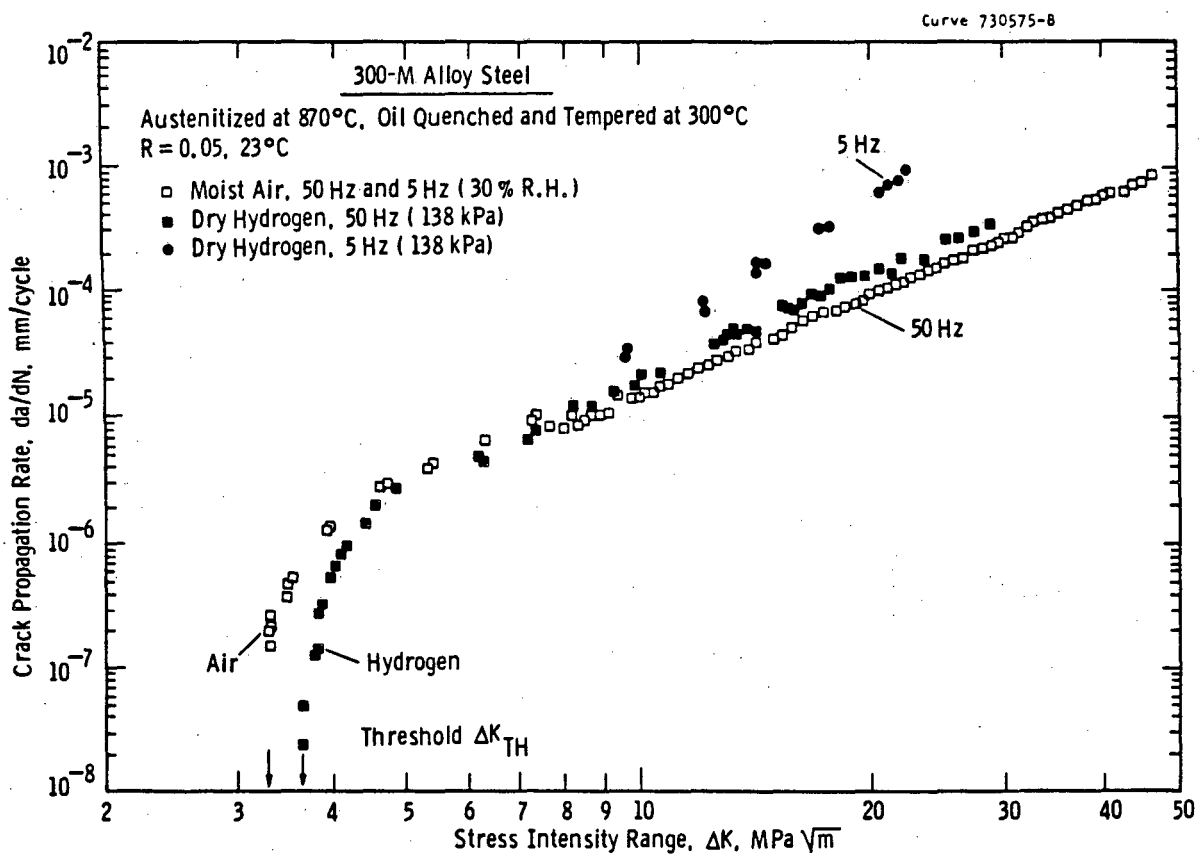


Fig. 2: Influence of dehumidified hydrogen gas and moist air on ambient temperature fatigue crack propagation in ultrahigh strength 300-M steel (300°C temper) at R = 0.05.

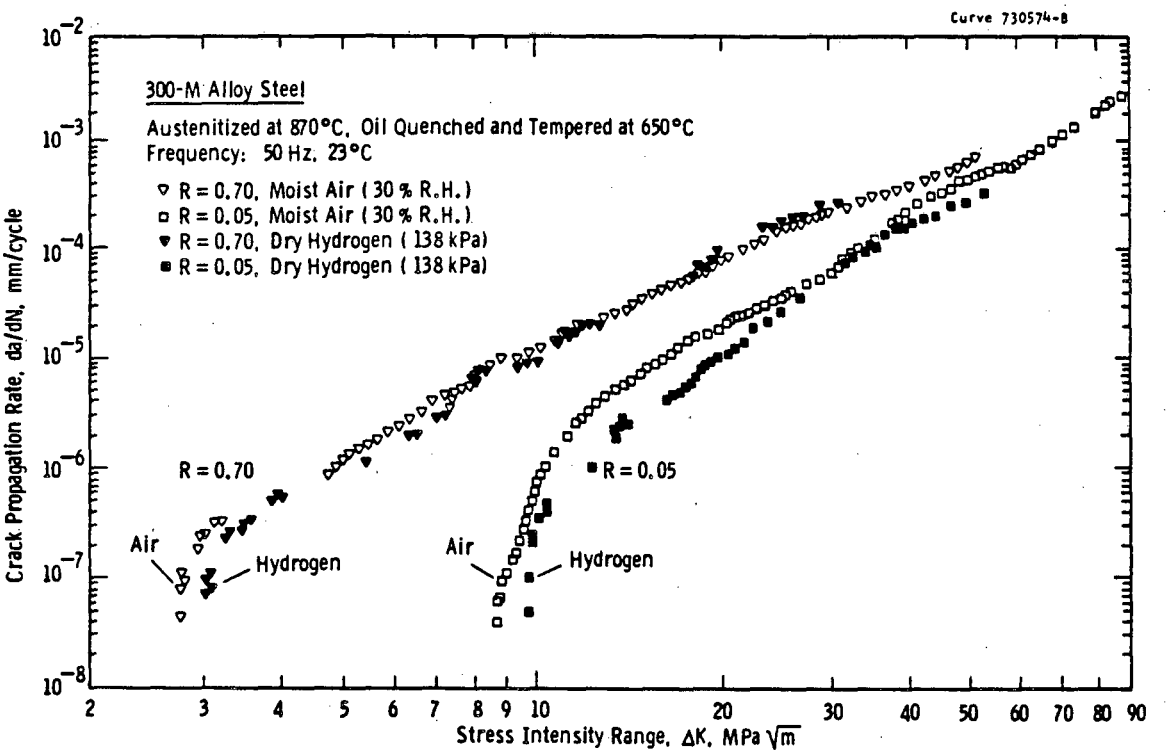


Fig. 3: Influence of dehumidified hydrogen gas and moist air on ambient temperature fatigue crack propagation in high strength 300-M steel (650°C temper) at R = 0.05 and 0.70.

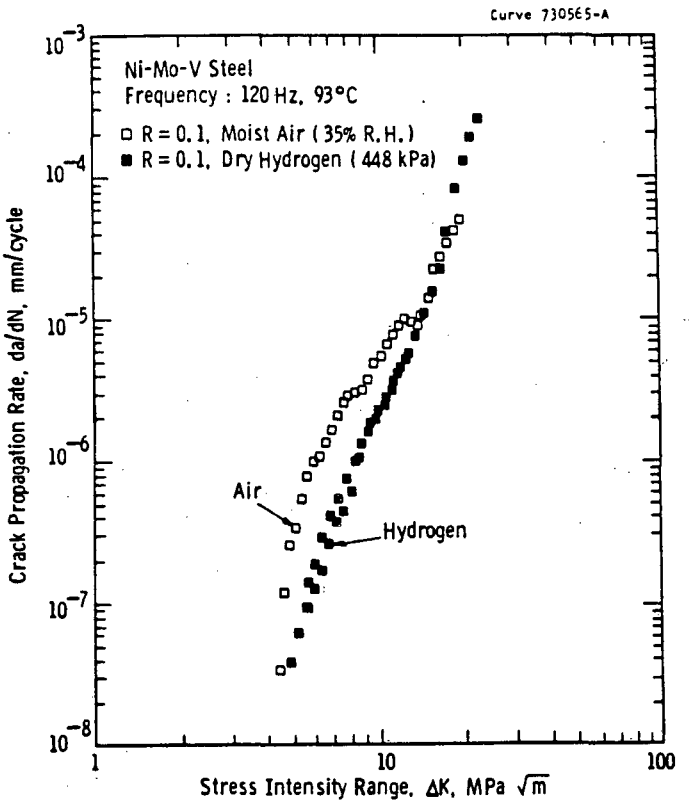


Fig. 4(a)

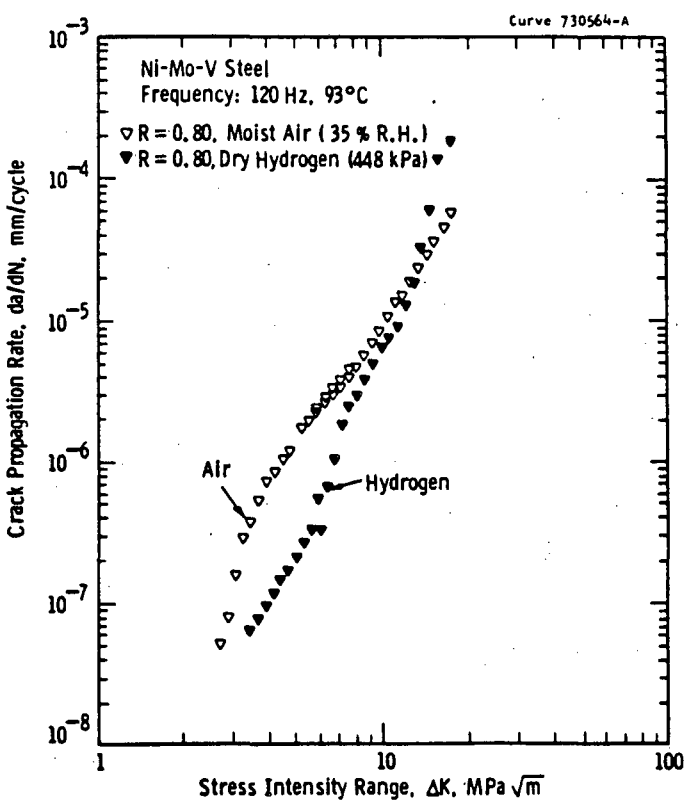


Fig. 4(b)

Fig. 4: Influence of hydrogen gas and moist air on fatigue crack propagation at 93°C in high strength Ni-Mo-V rotor steel at a) R = 0.1 and b) 0.8.

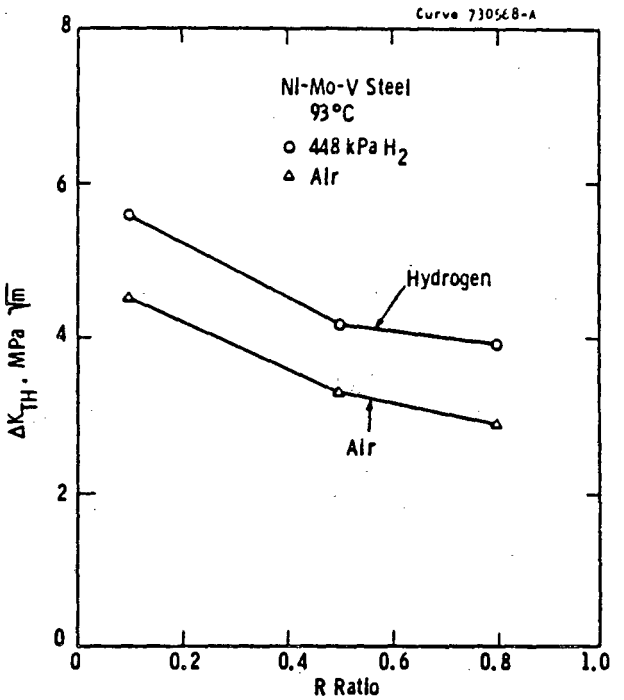


Fig. 5(a)

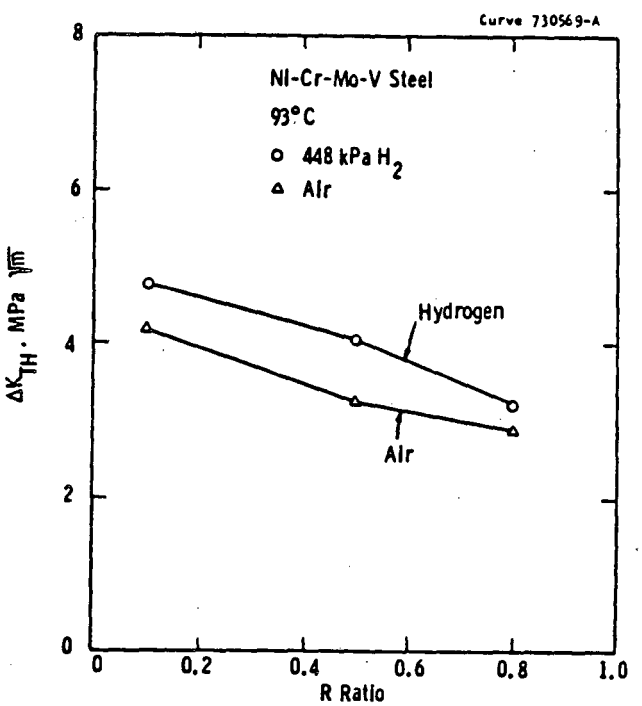


Fig. 5(b)

Fig. 5: Variation in fatigue crack growth threshold stress intensity range ΔK_{TH} with load ratio R for bainitic rotor steels tested at 93°C in air and hydrogen. Data for a) Ni-Mo-V and b) Ni-Cr-Mo-V steels.

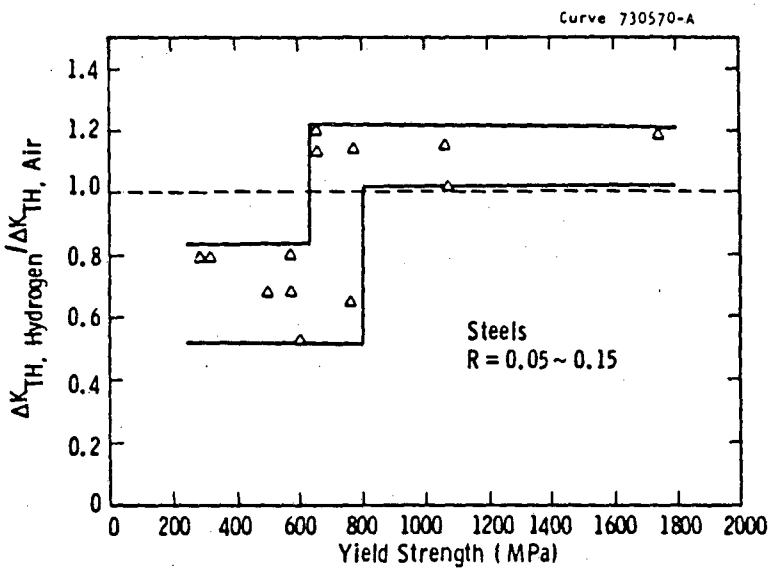


Fig. 6(a)

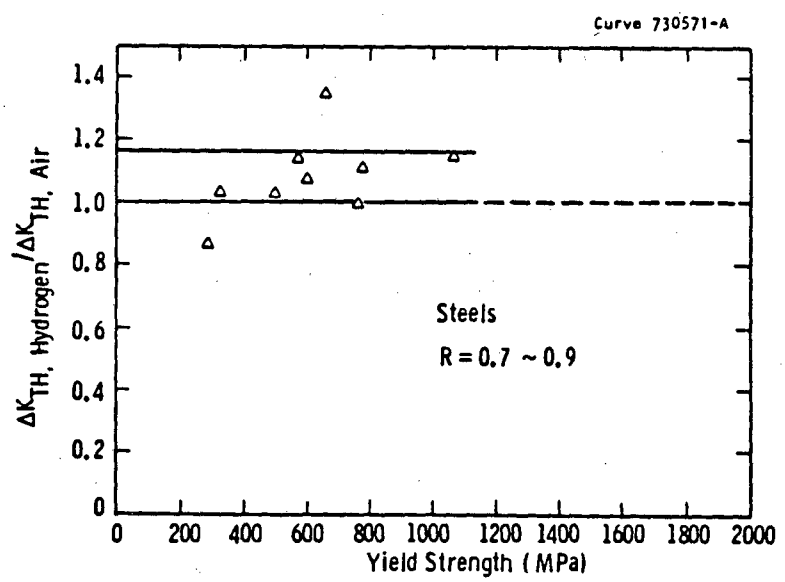


Fig. 6(b)

Fig. 6: The influence of yield strength on threshold fatigue crack growth behavior in moist air and dry hydrogen environments at low and high load ratios. Plotted is the ratio of the threshold stress intensity range in hydrogen to the threshold stress intensity range in air as a function of yield strength for a) low load ratios (R = 0.05–0.15) and b) high load ratios (R = 0.7–0.9).

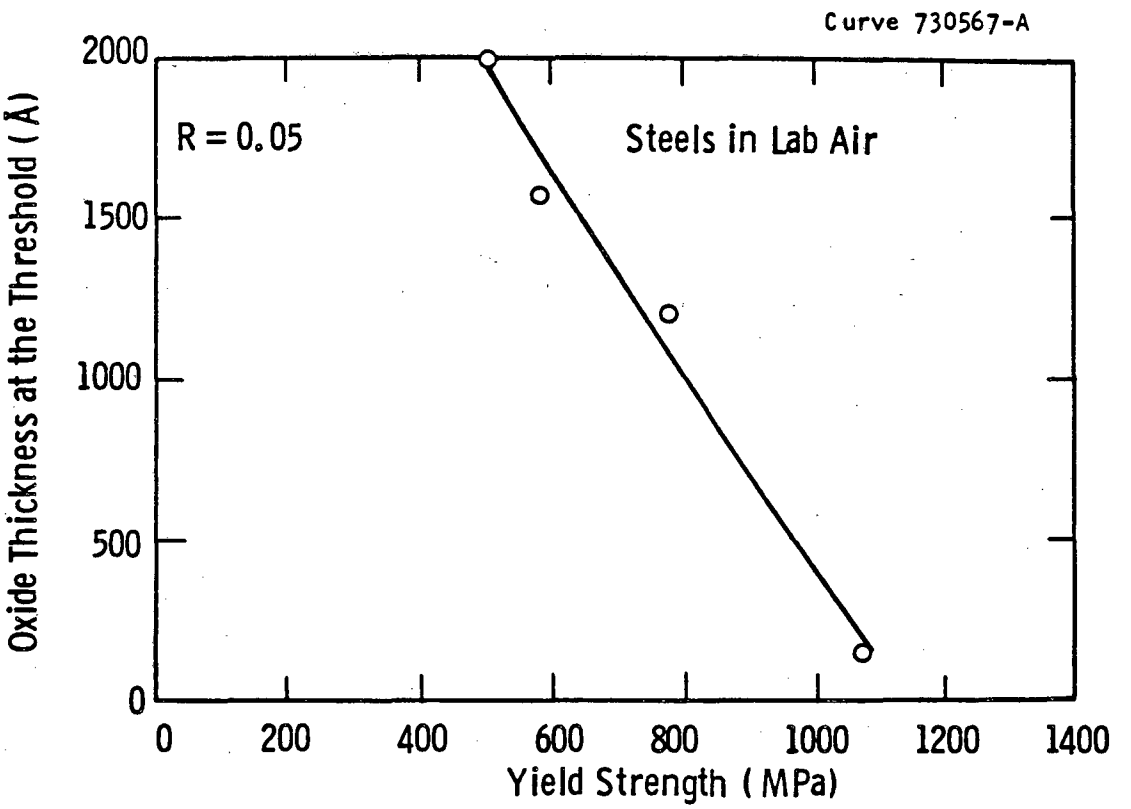
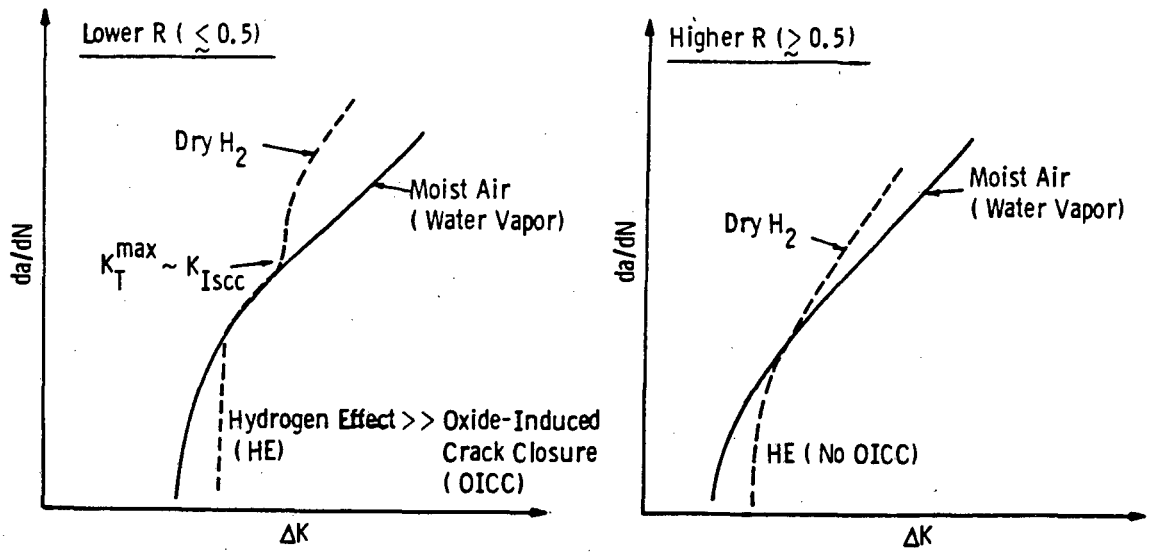


Fig. 7: Variation of maximum excess oxide thickness, measured on the fracture surface at ΔK_{TH}, with yield strength for steels tested in moist air at R = 0.05.

Curve 730576-B

A. Higher Strength Steels (Prone to Hydrogen Embrittlement)
(Yield Strength $\gtrsim$ 700 MPa)



B. Lower Strength Steels (Less Prone to Hydrogen Embrittlement)
(Yield Strength $\lesssim$ 700 MPa)

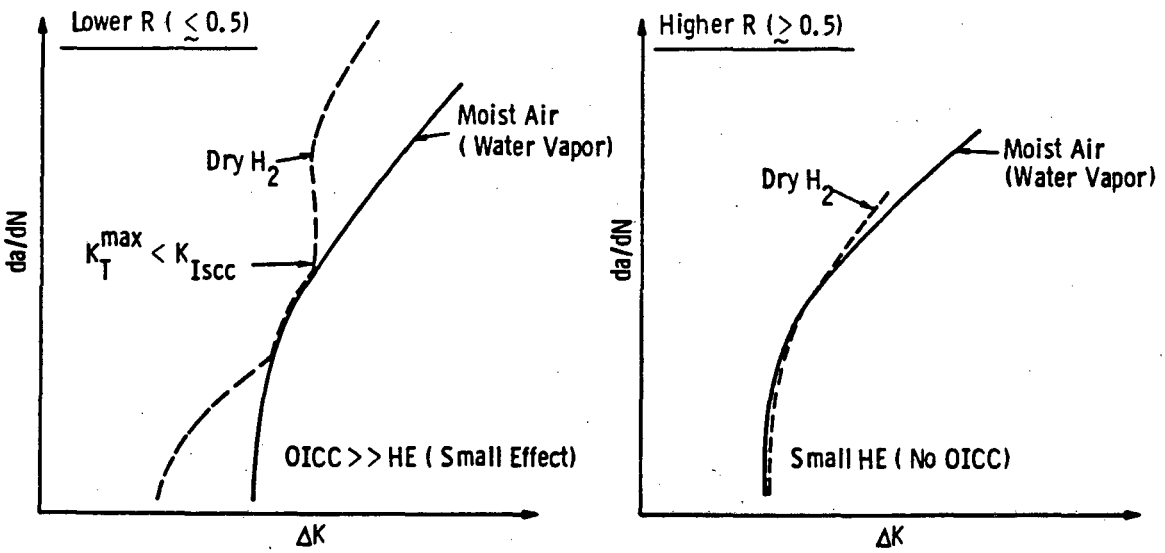


Fig. 8: Schematic representation of environmentally-influenced near-threshold fatigue crack growth behavior in high and lower strength steels, tested in dry hydrogen gas and moist air, at low and high load ratios. Behavior is interpreted in terms of a competition between oxide-induced crack closure (OICC) and hydrogen embrittlement (HE) processes.

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