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METALLURGICAL CONTROL OF FATIGUE CRACK GROWTH IN HIGH-STRENGTH ALUMINUM ALLOYS

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COLUMBUS, OHIO

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13. ABSTRACT

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Crack growth rate-ΔK measurements have also been converted into S-N curves for cracked members. These curves illustrate the influence of flaw size, stress range, R and K_c on the cyclic life of the 7075-T6 and 2024-T3 grades. The S-N curves show that the cyclic life of 2024-T3 is about 3 x that of 7075-T6 in laboratory air, about 5x that of 7075-T6 in humidified air, and 10x that of 7075-T6 if ΔK is in proportion to the yield strength. Finally, recent studies of the mechanisms of cyclic growth and other observations bearing on the contribution of metallurgical factors are examined. Effects associated with composition, heat treatment, small amounts of cold work, hard particles and inclusions, grain boundaries, the dislocation substructure produced by cyclic straining, and slip offsets are discussed.

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FOREWORD

This report was prepared by Battelle, Columbus Laboratories, Columbus, Ohio, under USAF Contract No. F33615-71-C-1107. The contract was initiated under Project No. 7351, "Metallic Materials," Task No. 735106, "Behavior of Metals." The program was monitored by the Metals and Ceramics Division, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with Dr. W. H. Reimann (AFML/LLD) as project scientist.

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This technical report has been reviewed and is approved.

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ABSTRACT

The results of 22 different investigations of cyclic crack growth, principally on the 2024-T3 and 7075-T6 alloys, but including results for unalloyed and other 2-, 5-, 6-, and 7-thousand series alloys, have been examined and compiled with a view to separating metallurgical effects from other factors. The various crack growth measurements show good agreement when the comparisons involve the same R-value, environment and cyclic frequency. Both the 2024-T3 and 7075-T6 alloy can display widely different rates of growth for the same ΔK-value. The highest growth rates are for tests in humid air, the lowest growth rates for tests in dehydrated air with high cyclic frequencies. These extremes point to a moisture assisted corrosion process capable of producing a 20-fold increase in the growth rate at low ΔK-levels.

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I INTRODUCTION

Much effort has gone into characterizing cyclic crack growth in aluminum alloys, but the prospects and means of reducing growth rates metallurgically through control of composition and microstructure, have not been established. At the present time, the first-principle-rout to the metallurgy of the problem is still blocked by an incomplete understanding of the mechanisms of cyclic growth. The experimental approach involves the large number of variables, including: (1) the stress intensity range ΔK, (2) the stress ratio R†, (3) the corrosivity of the environment, particularly moisture, (4) cyclic frequency, (5) loading spectrum, and (6) section thickness, which complicate comparisons and interpretations.

This study was conceived as a first step towards identifying the metallurgical factors governing the rates of fatigue crack-growth in 2000 and 7000 series alloys. It includes a thoroughgoing review of existing crack growth-rate measurements, updating the compilation published by Forman, Kearney, and Engle[1] in 1966, with a view to separating metallurgical effects from other factors. The results of 22 different investigations of crack growth,[2-27] principally on the 2024-T3 and 7075-T6 alloys, but including results for unalloyed and 2-, 5-, 6-, and 7-thousand series alloys, have been examined. Crack growth rate-ΔK measurements have also been converted into S-N curves for cracked members. These curves illustrate the influence of flaw size, stress range, R, K_c and moisture on the cyclic life of the 7075-T6 and 2024-T3 grades. Finally, recent studies of the mechanisms of cyclic growth, and other observations bearing on the contribution of metallurgical factors are examined.

The review illustrates surprisingly good agreement among the crack growth measurements that have been conducted in different laboratories. Differences among the ΔK-growth rate curves reported for 7075-T6 and 2024-T3 alloys can be traced for the most part, to accelerated growth in the presence of moisture, either to: (1) differences in the moisture content of the air or (2) the cyclic frequency dependence of the corrosion process. Some effects of composition and microstructure are connected with the sensitivity of the material to moist air. Other metallurgical effects are identified with the fatigue substructure, with grain size and with second phase particles. As a result, the life of precracked 7075-T6 components in moist air can be as little as 1/5 the life of 2024-T3 for the same ΔK-value, 1/10 the life if ΔK is in proportion to the yield strength.

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† R ≡ minimum stress/maximum stress.

II PROCEDURE

The 22 different crack growth rate studies, which were examined, are identified in Table I. To simplify the task of comparing measurements from so many sources, $\Delta K-\frac{da}{dn}$ - data† collections are represented by a single average curve. Differences among the various data collections could not be expressed in terms of the simple power law approximation††, and this relation was not employed. To eliminate the stress ratio R as a variable, all crack growth measurements involving a finite R-value were reduced to R = 0 by means of the Forman, et al[1] correction:

$$\left.\frac{da}{dn}\right|_{R=0} = \left.\frac{da}{dn}\right|_{R} \cdot f(R) = f(\Delta K) \qquad (1)$$

where

$$f(R) = \frac{(1-R)K_c-\Delta K}{K_c-\Delta K} \qquad (2)$$

and K_c is the fracture toughness‡, and ΔK the stress intensity range‡‡. The results of Hartman[10,11], Hartman, et al[13], Hartman and Schijve[25], and Hudson and Scardina[20], which involve systematic variations of R, all provide convincing evidence that the Forman correction is a reasonably accurate description of the influence of the stress ratio both in dry and humid environments. Equation (1) is similar but not identical to the form employed by Hartman and Schijve[25] which cancels out the singularity at $\Delta K = K_c$. An alternative based on the work of Elber[28] deserves considerations as more results in the low ΔK-range become available.

The review was confined to measurements involving cycles of constant or gradually changing ΔK-amplitude; the influence of loading spectrum was not considered. Section thickness was excluded as a significant variable here in view of the extensive study by Feddersen and Hyler[23] which shows that crack growth rates $\frac{da}{dn} \lesssim 10^{-4}$ in. per cycle are essentially independent of thickness.

"S-N" curves for precracked specimens were obtained by numerical integration of the measured $\Delta K-\frac{da}{dn}$ curves:

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† $\frac{da}{dn}$ = per cycle crack advance or growth rate.

†† $\frac{da}{dn} = A\,\Delta K^m$, where A and m are an empirical coefficient and exponent, respectively.

‡ The following values of K_c were adopted unless specified by the authors: 7075-T6: $K_c = 44$ MNm$^{3/2}$, 2024-T3: $K_c = 66$ MNm$^{-3/2}$, but the calculations are not particularly sensitive to the value of K_c selected.

‡‡ For center cracked panels, $\Delta K = \Delta\sigma\sqrt{\pi a}\left[\frac{2w}{\pi a}\tan\frac{\pi a}{2w}\right]^{1/2}$; $\Delta\sigma$ is the nominal stress range, 2a the crack length

TABLE 1. SUMMARY OF EXPERIMENTAL STUDIES

[illegible]	ALLOYS	THICKNESS (in.)	SPECIMEN DIMENSIONS (in.)	FREQUENCY (CPS)	R	ENVIRONMENT
[illegible] (1952)	2024-T3 7075-T6	0.090	[illegible] (un-notched)	20-25	- 1.0-0.6	Lab air
[illegible]	7075-T6	0.[illegible] 0.[illegible]	[illegible] × 17, center notched 12 × [illegible], center notched	30	~ 1	Lab air
Frost (1959); Frost and [illegible] (1958); [illegible]	[illegible] strength [illegible] psi				0.[illegible]-0.87	
Donaldson and Anderson* [illegible]	7075-T6					
[illegible] and Hardrath ([illegible])						
[illegible] and Schijve (1963)	7075-T6 (clad) 2024-T3 (clad)	[illegible].078	(?), center notched	33	0.06-0.66	Air
[illegible] and [illegible] (1965)*	2024-T3	0.064 0.094 0.126	8-in.-wide center notched sheets	60-133	0.1-0.3	Lab air
			[illegible]-in.-wide single edge notched sheets	0.5-0.75	0.1-0.2	Lab air
Schijve and de Rijk (1966)	2024-T3	0.079	4-in.-wide center notched sheets	53	0.04-0.47	Lab air
Hartman, Jacobs, Nederveen and de Rijk (1967); Hartman and Schijve (1970); Hartman (1964, 1965)	7075-T6 (clad) 2024-T3 (clad)	0.079	2.6 × 4.5, center notched	57 (0.5-57)	0.03-0.6	(a) Dry air, < 25, 50 ppm (b) Wet air, 100% relative humidity
Wei (1968)	7075-T651 (bare)	0.25	3 × 12, center notched	143	0	(a) Argon, -140°C dew point (b) Oxygen, -140°C dew point (c) Hydrogen, -140°C dew point (d) Distilled water
Meyn (1968)	2024-T3	0.25	2.8 × 0.5 cantilever bend	2.5, 12	0	(a) Air, 20-60% humidity (b) Vacuum, 1-3 · 10^{-6} Torr

* [illegible]

TABLE I. (Continued)

STUDY	ALLOYS	THICKNESS (in)	SPECIMEN DIMENSIONS (in)	FREQUENCY (CPS)	R	ENVIRONMENT
Broek (1969)	7075-T6 2024-T3	0.079	2.8 x 9, center notched		0.05	Air
Hudson and Scardina (1969)**	7075-T6	0.090	12 x 35, center notched	0.6-14	- 1-0.8	Lab air, ethyl alcohol
Wei and Landes (1969)	7075-T651 (base)	0.25	3.75 x 16, center notched	5	0	(a) Argon, -140°C dew point (b) Distilled water (c) D_2O (99.98% purity
Bates and Clark (1969)	5456-H321 7079-T6	1.0	1T-Compact fractured toughness specimen	30	0	Lab air
Liu and Iino (1969)*	2024-T351	0.25	4 in.-wide center-notched		0.1	Air
Feddersen and Hyler (1970)	7075-T7351	0.06-1.0	8, 16, and 36 in.-wide, center notched panels	10-25	0.1-0.5	Air, 50% relative humidity
Feeney, McMillan and Wei (1970)	2024-T3 7075-T6 7178-T6	0.160	16 x 9, center notched	9	0.5	(a) Desiccated air < 10% relative humidity (b) Wet air > 90% relative humidity (c) Distilled water (d) 3.5% NaCl solution
Crooker (1971)	2219-T87 5456-H321 6061-T651 7005-T63 7075-T7351 7106-T63	0.45	2.5 x 17.25 in. single-edge-notched	0.1	0	(a) Lab air (b) 3.5% NaCl

* $\Delta K = 10\sqrt{K_c}$.

** $\Delta K = 10\sqrt{K_c}$, and units of coordinates incorrectly labelled on graphs.

$$n = \int_{a_o}^{a^*} \frac{f(R)}{f(\Delta K} \, da \qquad (3)$$

where a* is the critical flaw size for unstable fracture. These calculations are for an idealized component: a 6 in.-wide center-cracked panel subjected to cyclic load of constant amplitude. The calculations were carried out for a number of initial flaw sizes, R- and K_c-values, but emphasize a flaw size of a = 1.27 mm (0.050 in.) which is representative of the lower limit for reliable detection.

III RESULTS

Figures 1a and 2a illustrate there is surprisingly, good agreement among the crack growth measurements of different laboratories provided the comparisons involve comparable R-values, environments and cyclic frequencies. The agreements are probably even better than indicated by Figures 1a and 2a since the results plotted in these two graphs involve tests in laboratory air of uncontrolled humidity. In three cases[6,14,21], published curves seem to depart widely from the trends shown, but the discrepancies arise from the omissions of the factor $\sqrt{\pi}$ in the formulation of ΔK, and are not real. The crack growth rate characteristics of the 2024-T3 and 7075-T6 prove to be similar in many respects, and are discussed together in the following paragraphs.

Effects of Environment and Cyclic Frequency

The substantial influence of moisture on the crack growth rate is revealed by arbitrarily grouping the various sets of measurements into three categories:

(i) Tests conducted in humidified air, water, or NaCl solutions (see Figures 1b and 2b)

(ii) Tests conducted in laboratory air of uncontrolled humidity or in dehydrated environments with intermediate cyclic frequencies, e.g., < 20 cps (see Figures 1a and 2a)

(iii) Tests conducted in dehydrated environments with high cyclic frequencies, e.g., > 20 cps (see Figures 3a and 3b).

Results for tests in these three categories are summarized in Figures 3a and 3b. The graphs show that for a given ΔK, growth rates in humidified environments fall on the high side of the band for tests in (laboratory or dehydrated) air. Growth rates in dehydrated air under high cyclic frequencies fall on low side of the band when $\frac{da}{dn} \lesssim 10^{-1}$ μm per cycle. The stratification for the 7075-T6 alloy also correlates with moisture content. The results of Feeney, et al[24], Wei and Landes[22], and Hartman, et al[13], which reflect dehydrated environments, fall generally below the other curves, which represent tests in laboratory air where the humidity was not controlled. It is also interesting to note that the rather dramatic reduction in growth rates attending high cyclic frequencies is supported by two independent studies, those of Wei[16] and Hartman, et al[3,25] (see Figure 3a). Furthermore, it is difficult to attribute the frequency effect to a noncorrosion mechanism because it is much less pronounced in humidified air (compare results of Hartman, et al[13] in Figure 2b).

The relative positions of the curves in Figures 3a and 3b are consistent with the idea that moisture has a minimal effect both on rapidly growing cracks where the fatigue component of growth, presumably, dominates, and at high

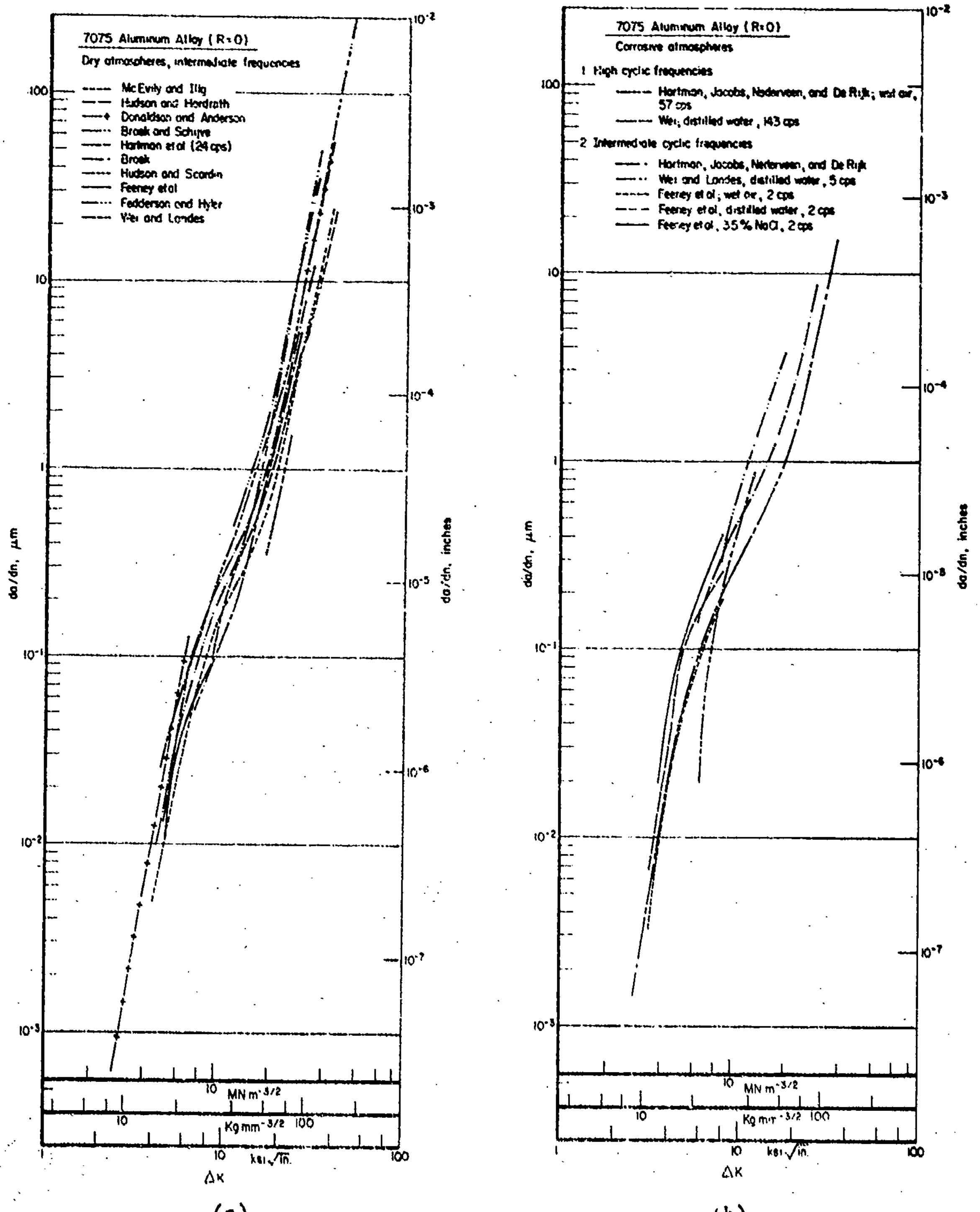

FIGURE 1. FATIGUE CRACK GROWTH-RATES IN THE 7075-T6 ALUMINUM ALLOY FOR R = 0: (a) dehydrated atmospheres and laboratory air for intermediate cyclic frequencies (0.5-30 cps), and (b) humidified air, water and 3.5% NaCl solution at intermediate and high frequencies.

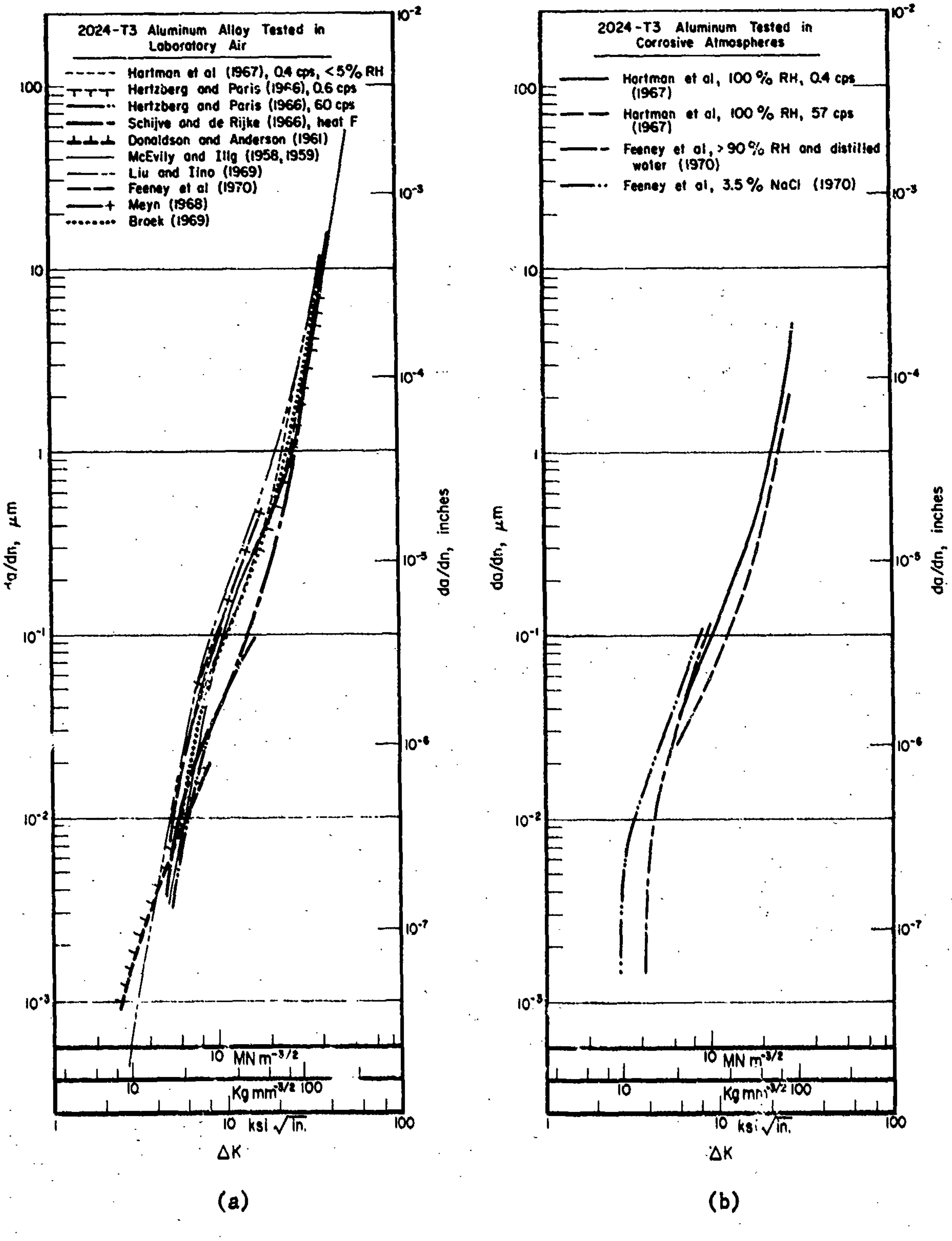

FIGURE 2. FATIGUE CRACK GROWTH-RATES IN THE 2024-T3 ALUMINUM ALLOY FOR R = 0: (a) dehydrated atomospheres and laboratory air for intermediate cyclic frequencies (0.5-30 cps), and (b) humidified air, water and 3.5% NaCl solution at intermediate and high frequencies.

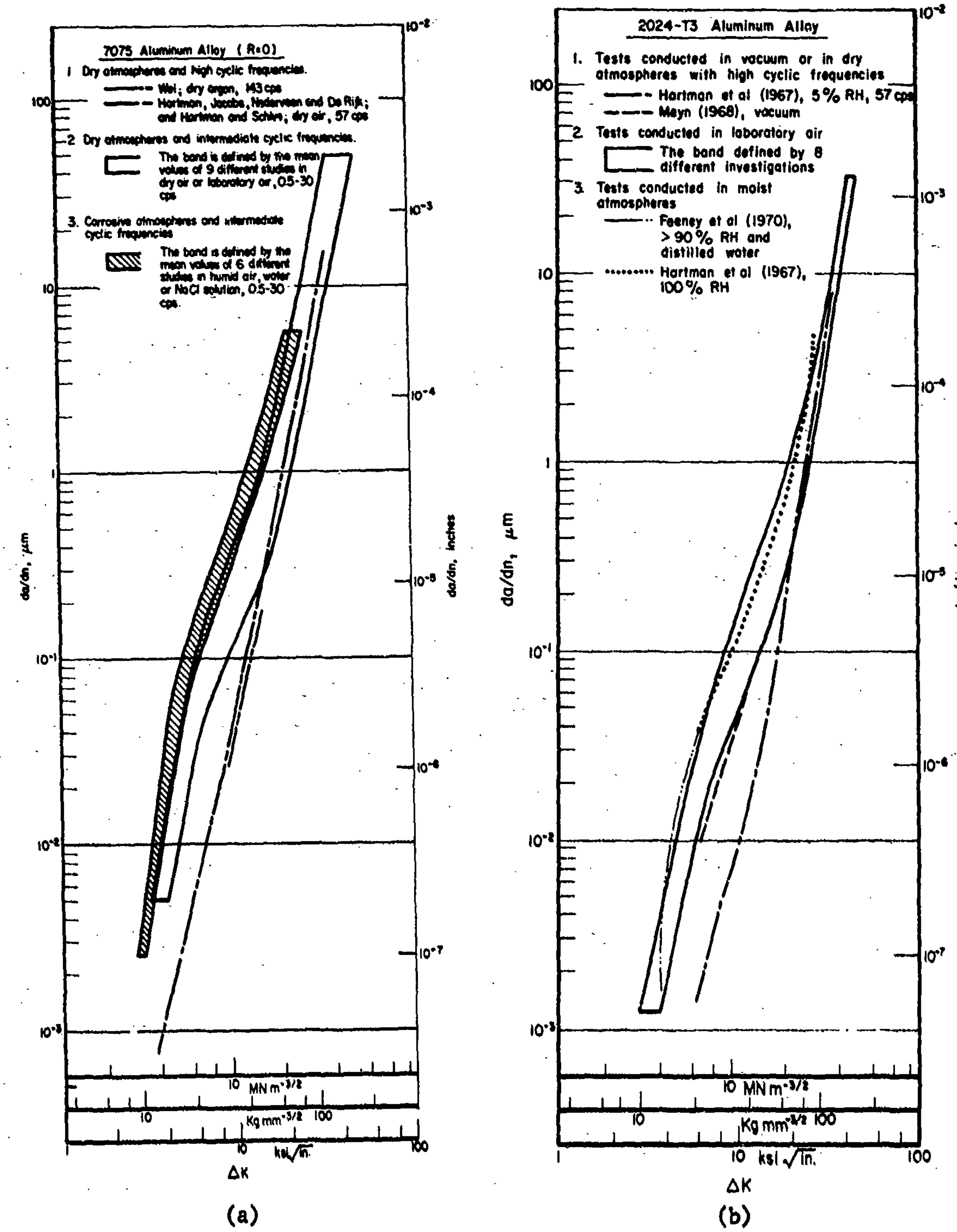

FIGURE 3. SUMMARY OF FATIGUE CRACK GROWTH RATES FOR: (a) the 7075-T6 and (b) 2024-T3 Aluminum Alloys.

frequencies, where the reaction time is limiting. The aggressive effects become noticeable when $\frac{da}{dn} \lesssim 1$ μm/cycle for tests in air at intermediate cyclic frequencies, and seem to saturate when $\frac{da}{dn} \lesssim 4.10^{-2}$ μm/cycle under these conditions. At the onset of this last stage, which corresponds to $\Delta K \approx 8$ $MNm^{-3/2}$, both the 2024-T3 and 7075-T6 alloy display growth rates that are 20x greater in humidified air at intermediate frequencies, than in dehydrated air at high frequencies. The large differences between the growth rates in humid and "dry" environments imply that the corrosion component must be comparable to the total crack advance per cycle in humid air when $\frac{da}{dn} \lesssim 1$ μm/cycle.

Metallurgical Effects

Figure 4 which compares the crack growth rates of two different heats of 2024-T3 and two heat treatments, and Figures 5a and 5b which compare results for different alloys tested in air illustrate the magnitude of effects attributable to the composition and microstructure. The results for the 2024-T3 in Figure 4 represent the widest spread observed by Schijve and de Rijk[14] among 7 different heats from different manufacturers. Since the difference in growth rate increases with decreasing growth rate, in a fashion similar to the changing sensitivity to moisture, it is possible that the metallurgical changes involved here have altered the sensitivity of the alloy to moisture. Schijve and de Rijk[14] suggest that the superior performance of heat F may be connected with a higher chromium content. At the same time, it is appropriate to note that Hyatt and Quist[30] have found that overaging combined with a somewhat higher Cu content and zinc/magnesium ratio enhances the cyclic life of 7-thousand series alloys by as much as 50 to 100%. Greater sensitivity to moisture may also distinguish the behavior of 7005-T63 and 7106-T63 from the other alloys described in Figure 5a. These two grades display the greatest resistance to cyclic growth among this group in the high growth rate range, e.g., when $\frac{da}{dn} \gtrsim 2$ μm/cycle, and the least resistance when $\frac{da}{dn} < 1$ μm/cycle, the range where the effect of moisture on 7075-T6 and 2024-T3 is apparent.

Figure 5b illustrates that growth rates in the 7075-T6 are generally higher than in the 2024-T3 alloy: the band for the 7075-T6 nearly superimposes on the one for 2024-T3 if the latter is shifted an amount equivalent to a 3-fold increase in growth rate. This could be a reflection of either: (1) a greater sensitivity on the part of 7075-T6 alloy to moisture or (2) an inherently lower resistance to fatigue crack growth. The first possibility is in accord with measurements of stable crack growth under sustained loading[31] which show 7075-T6 to be more susceptible to stress corrosion cracking than 2024-T3. However, this may not be meaningful since the results of those studies do not show a consistent correlation between corrosion effects under sustained and cyclic loading. The sustained loading study shows that 7075-T73 and 7075-T7351 are superior to 2024-T3. In contrast, the cyclic crack growth measurements of Feddersen and Hyler[23] for 7075-T7351, reproduced in Figure 1a are inferior to 2024-T3 and comparable to 7075-T6. Furthermore, crack growth rates tend to be more rapid in the 7075-T6 than in 2024-T3 at rates of growth in excess of 1 μm/cycle, where moisture effects do not seem important. These agreements provide some basis for believing that metallurgical factors unconnected with the tendency for stress corrosion could be having a significant effect on crack growth rates.

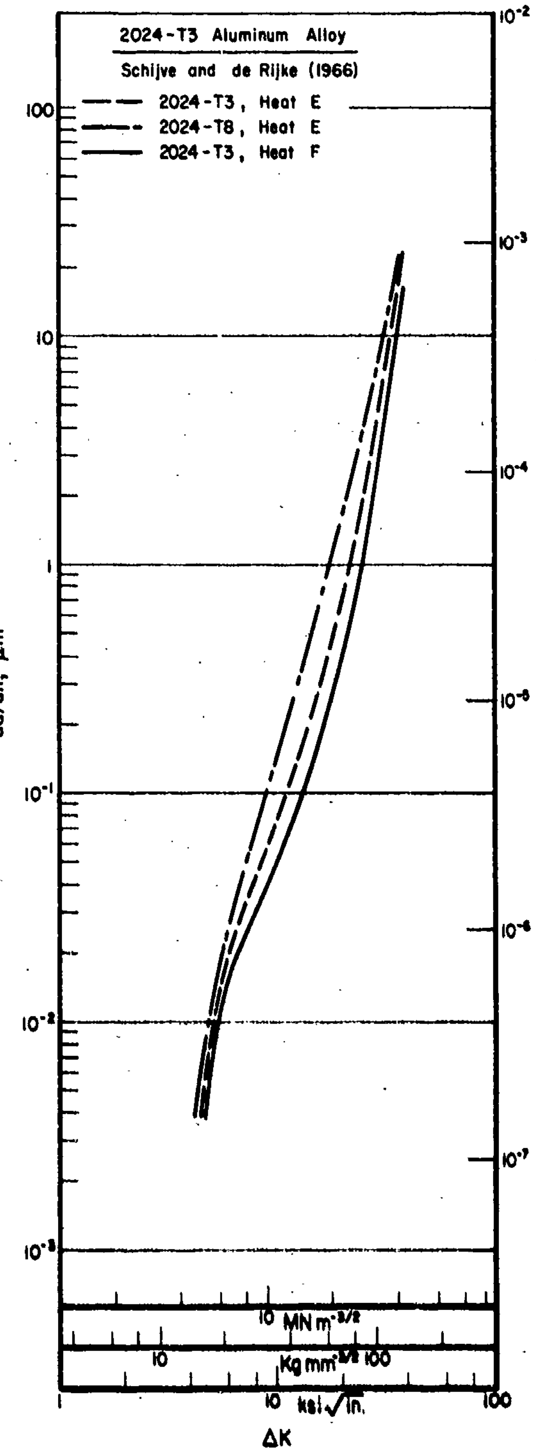

FIGURE 4. INFLUENCE OF HEAT-TO-HEAT VARIATIONS AND HEAT TREATMENT ON THE FATIGUE CRACK GROWTH RATES IN 2024-T3.

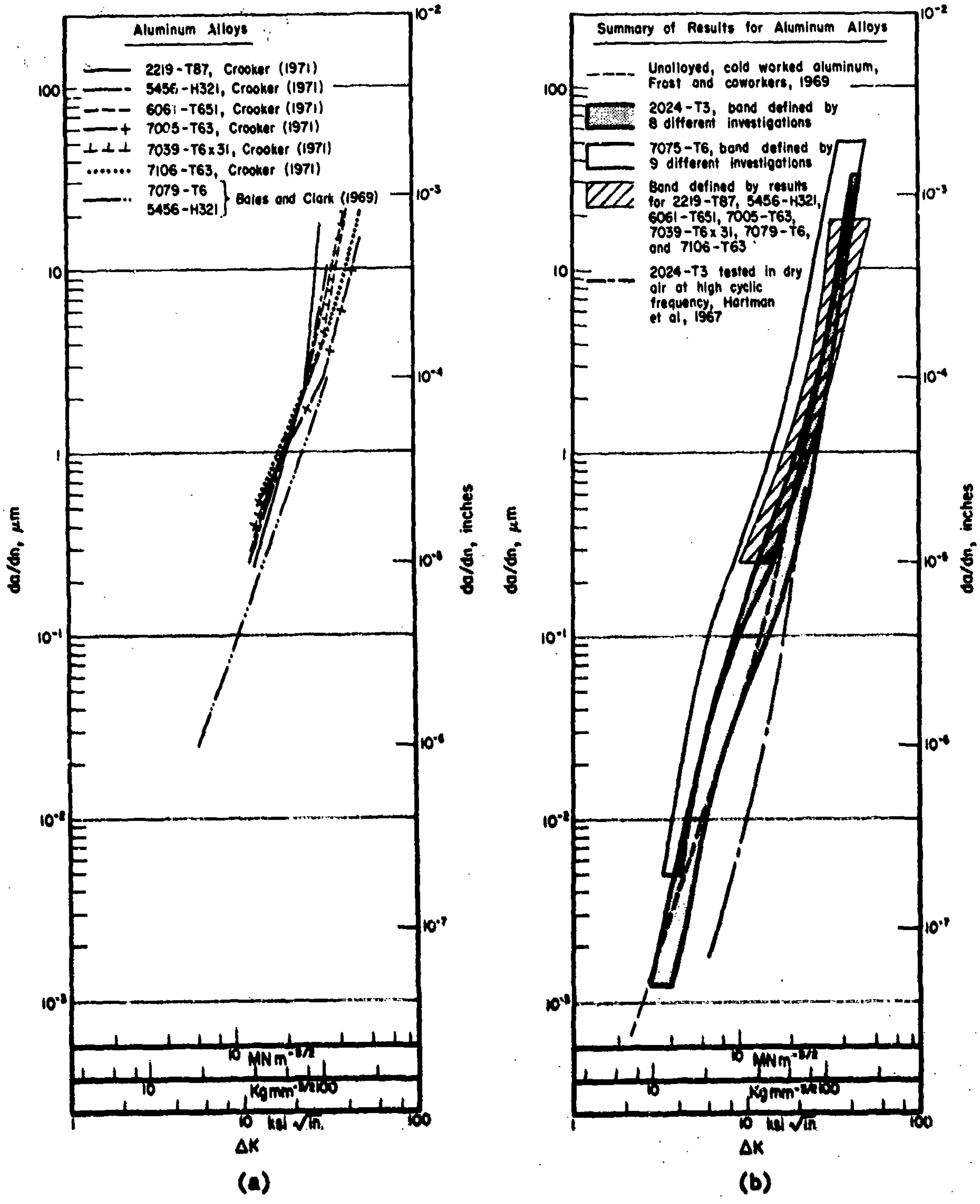

FIGURE 5. SUMMARIES OF FATIGUE CRACK GROWTH RATES FOR: (a) other 2-,5-, 6-, and 7-thousand series alloys, and (b) complete summary.

Evidence bearing on a number of metallurgical effects has been reported. The most potent of these are connected with the dislocation structure generated at the tip of the crack, and this is discussed in the last section of this report. Other effects are connected with brittle second-phase particles, inclusions or other weak interfaces, the grain size, and small amounts of cold work. A number of workers, Pelloux,[32] Broek[18], Bates and Clark[17], and most recently Kershaw and Liu[33] report a discrepancy between the average growth rate (deduced from gross changes in crack length) and the striation spacing observed in the microscope. The effect is noticeable when $\frac{da}{dn} > 10^{-1}$ μm/cycle.[33], with the average growth rate exceeding the striation spacing by factors of from about 2x to 3x when $\frac{da}{dn} \gtrsim 1$ μm/cycle. The effect is attributed to an extra contribution to growth arising from the fracture of brittle hard particles and inclusions in advance of the main crack. Similar observations have recently been reported by Evans, et al[34], for a high strength Ni-Cr-Mo steel. These workers were able to identify the ~ 2-4 fold reduction in growth rates obtained by purifying the steel with the absence of brittle grain boundary ruptures in the high purity material. Similar efforts by Pelloux[32] to retard growth by reducing the particle content of the 7178 alloy were not successful. Glassman and McEvily[35] were also unable to demonstrate a reduction in growth rate by going from 7075-T6 to a lower particle content X7275-T6; growth rates in the latter were actually higher. It appears that the exact origins of the discrepancy or the purity levels that will bring the growth rate in line with the striation spacing remain to be established for aluminum alloys. The influence of grain size is, also, only partly resolved. A number of workers have observed a tendency for fatigue cracks to terminate at grain boundaries: Lipsitt[36] and Thompson and Backofen[37] for Stage I fatigue; Hahn and coworkers[38] for crack branches in Stage II. The implication is that grain boundaries represent bigger obstacles to cyclic growth than the grain interiors, that a sufficiently large number of boundaries in the path of the crack will reduce the growth rate. Hoeppner[39] has examined the effect of grain size on cyclic crack growth in copper. His results, which involve grain diameters from 0.06 to 7 mm do not support a simple relation between growth rate and grain size. A modest improvement in the cyclic life of 2024 has also been obtained by Broek and Bowles[40] by stretching the material 1% after the solution treating without further aging. In this condition, the cyclic life was 35% longer than the T3-condition, 100% longer than after a solution treatment without stretching or aging.

Implications of Growth Rate Curves on the Cyclic Life of Cracked Members

Figures 6-8 illustrate some of the implication of the different growth rate curves with respect to cyclic life of cracked components. Figure 6, which shows the effect of initial flaw size also reproduces the S-N curve for an uncracked specimen tested under the same conditions. Comparisons of the S-N curves for the unnotched and precracked specimens show that the initiation and growth of a crack to a size of 0.050 mm, which corresponds roughly with Stage I, occupies 80 to 90% of the total life of an unnotched specimen for values of the cyclic stress in the range 250 to 350 MNm^{-2}.

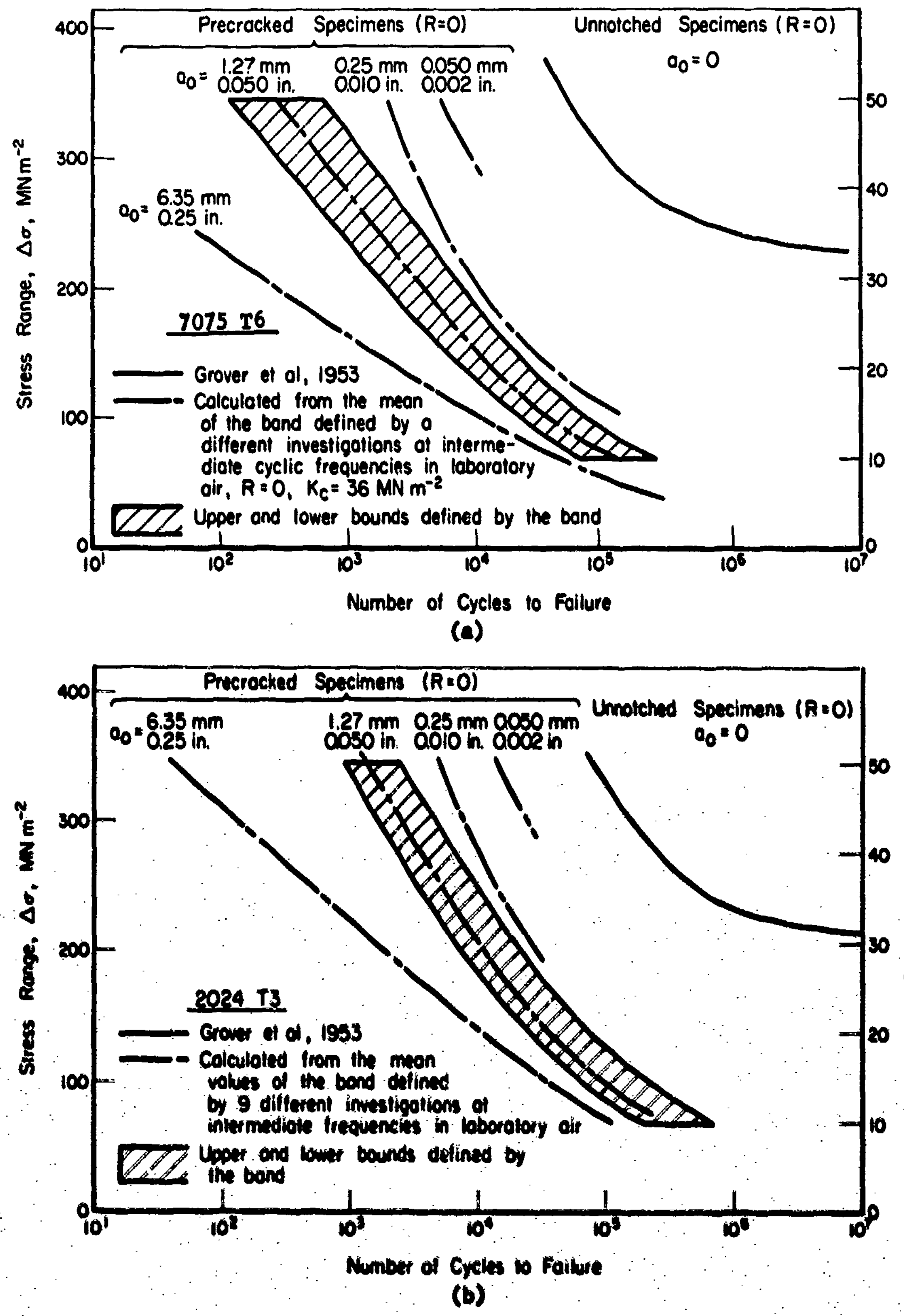

FIGURE 6. INFLUENCE OF THE INITIAL FLAW SIZE, a_0, ON "S-N" CURVES CALCULATED FOR PRECRACKED PANELS: (a) 7075-T6 and (b) 2024-T3.

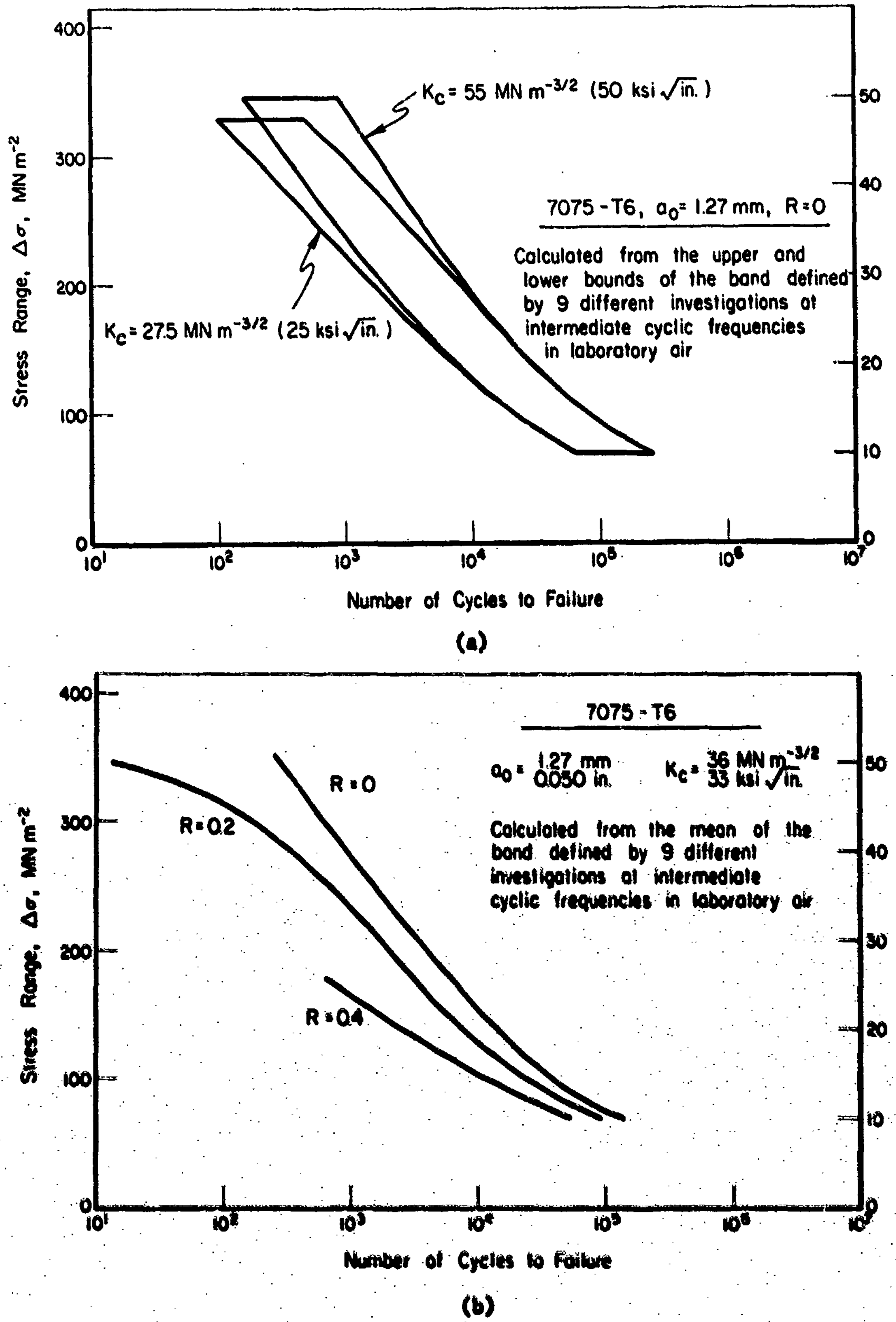

FIGURE 7. INFLUENCE OF: (a) K_c and, (b) the stress ratio, R, on the calculated "S-N" curves of precracked 7075-T6 panels (a_0 = 1.27 mm).

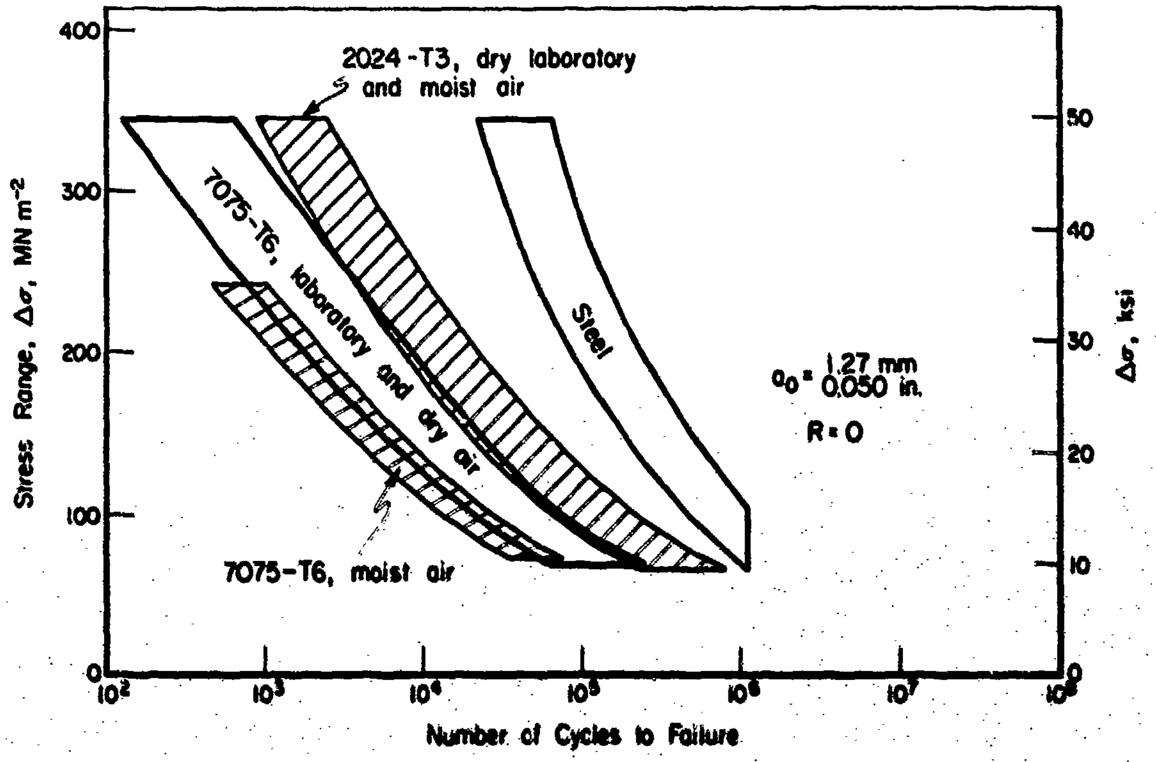

FIGURE 8. COMPARISON OF CALCULATED "S-N" CURVES FOR PRECRACKED 2024-T3 (K_c = 66 MNm$^{3/2}$) AND 7075-T6 (K_c = 36 MNm$^{-3/2}$ PANELS, AND HIGH STRENGTH STEEL PLATES. The band represents results reported for the HY-80, HY-130, a 10 Ni and 12 Ni yield strengths from grades reported by Barsom[29]. Calculations for the steel assumed K_c = 165 MNm$^{-3/2}$.

Figures 7a and 7b illustrate the influence of stress ratio and K_c on the S-N curves for 7075-T6. Larger values of K_c require that the crack attain a greater length by cyclic growth before it becomes unstable, and imply longer cyclic lives. However, the life added involves the upper extremities of the growth rate curves where $\Delta K \rightarrow K_c$ and the per cycle growth is large. Consequently, even a doubling of K_c, illustrated in Figure 7b, adds only hundreds of cycles to the total life.

Figure 8 compares the S-N characteristics of the 2024-T3 and 7075-T6. For service in laboratory air or dry air at intermediate cyclic frequencies, the 2024-T3 displays cyclic lives ~ 3 times greater than the 7075-T6, consistent with the relative positions of the growth rate curves. The differential between 2024-T3 and 7075-T6 increases to ~ 5 times, if the comparison involves crack growth in humidified air, and to a differential of ~ 10 times if, in addition the cyclic stress range is in proportion to the yield strength of these two materials. A comparison of 2024-T3 with the band for high strength steels shows that the stress ranges associated with equivalent cyclic lives are roughly in proportion to the density of aluminum and steel. Steels with strength-to-weight ratios superior to the one for 2024-T3, would therefore tend to display shorter cyclic lives than 2024-T3 for comparable flaw sizes and stress ranges in proportion to strength.

IV MECHANISM OF CYCLIC CRACK GROWTH

Studies of the mechanism of cyclic crack growth offer additional insights to the underlying metallurgical factors. The mechanism proposed by Laird[41] and McClintock[42], which attributes c· .ck advance to irreversible plastic blunting of the crack tip has been discussed extensively[38,43] and serves as a starting point for this review. The blunting argument relates the crack advance per cycle to the COD^c, the crack-tip opening displacement under cyclic loading, which represents the maximum amount of blunting achieved during the loading cycle. Simplified treatments of the cyclic plastic zone[44] offer the following expression:

$$COD^c \approx \frac{\Delta K^2}{4E\sigma_Y} \tag{1}$$

where E is the elastic modulus and σ_Y the yield stress (more correctly, the average flow stress within the zone. Consistent with this, crack growth rates in aluminum, titanium, and steel have been correlated with the elastic modulus[17] but the dependence on σ_Y^{-1} is not observed[29,38]. As an example, growth rates are higher in the 7075-T6 alloy than in 2024-T3 in spite of its 40% greater yield strength.

This discrepancy does not seem to stem from the approximate nature of the formulations of the fatigue crack plastic zone. Recent studies by Bowles[45] and Hahn and coworkers[46] indicate that Equation (1) and analogous expressions for the cyclic plastic zone size are in reasonably good accord with actual measurements. The studies, which revealed the plastic zone of a fatigue crack in Fe-3Si steel,[46] provide an approximate description of the cyclic strain history experience by the material in advance of the crack including 3 distinct regions of cyclic deformation (see Figure 9).

Studies by Feltner and Laird[47] indicate that the pattern of straining in Figure 9 develops a cellular, fatigue-type dislocation substructure within the cyclic plastic zone. Such substructures have actually been observed by transmission microscopy by a number of workers.[48-51] Hahn and coworkers also suggested that the cell structure could be unraveled by the last 5 to 10 cycles which involve very high plastic strains because of their proximity to the crack tip. Thinned sections taken close to the fatigue fracture surface have been examined by Bowles and Broek[52] and these do show eivdence of dislocation-free bands having the periodicity of striations. Furthermore, the instabilities attending the "unraveling" could contribute to irreversible blunting and account for the fatigue striations on the fracture surface. This view of cyclic crack growth simply combines elements of the plastic blunting mechanism and the cumulative damage arguments developed by McClintock[42] and Liu and coworkers[53-54]. It derives strong support from the work of Miller and coworkers[55], and more recently, by Ishii and Weertman[56], who have demonstrated a direct connection between substructure and the cyclic growth rates in copper. These workers altered the substructure in two ways:

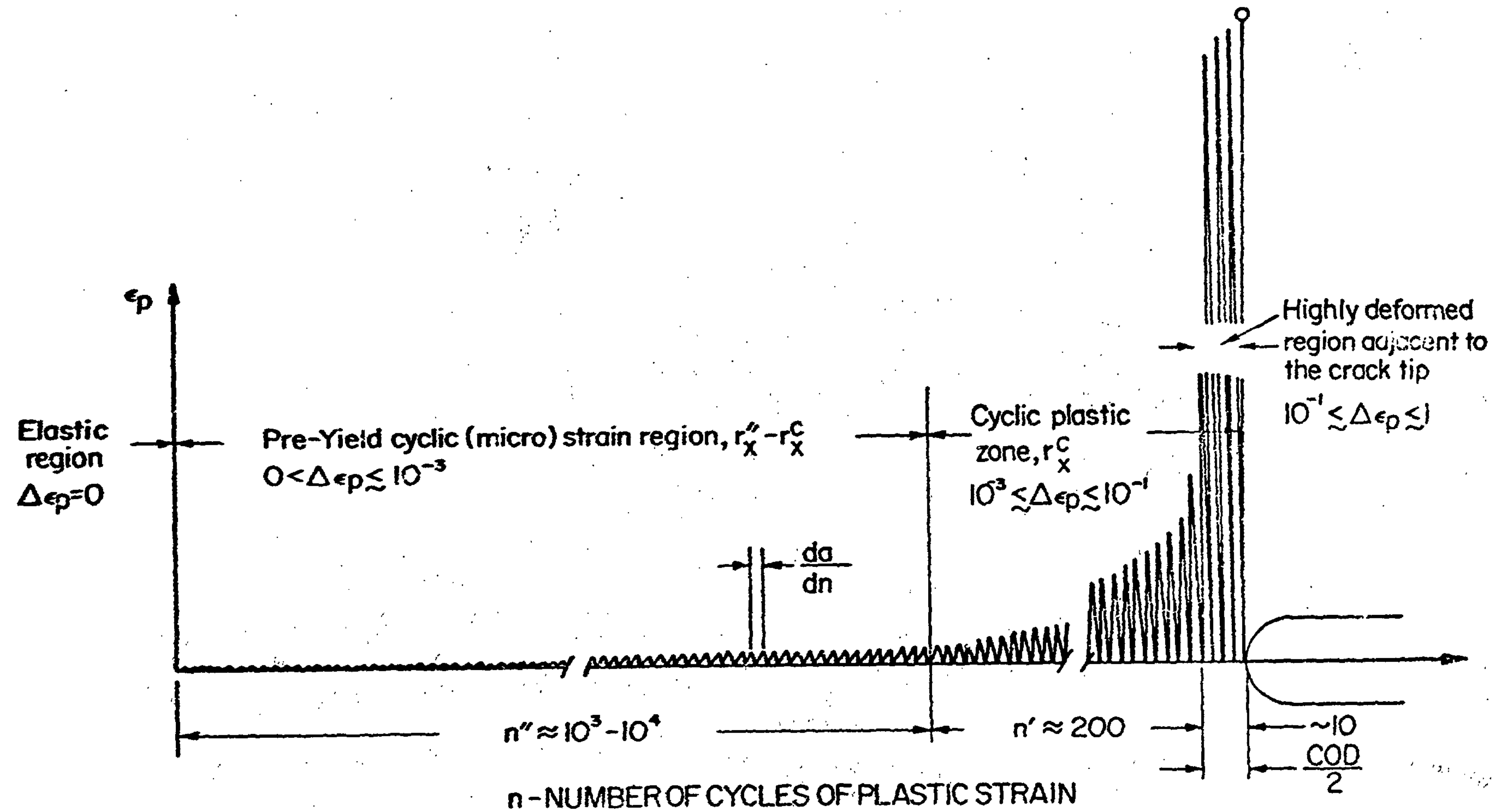

FIGURE 9. SCHEMATIC PRESENTATION OF THE CYCLIC STRAIN HISTORY WITHIN THE FATIGUE CRACK PLASTIC ZONE (38)

(1) Alloying with up to 13.5% aluminum, which reduces the SFE (stacking fault energy) from 40 ergs/cm^2 to 2.5 ergs/cm^2, and

(2) Lowering the test temperature from room temperature to -196°C; which probably reduces cross slip.

These changes, which are known to alter the fatigue substructure[47] produced as much as a 15-fold reduction in the fatigue crack growth rate.[56] The exploitation of a SFE-effect may be more difficult in aluminum because of the metal's higher SFE (~ 200 ergs/cm^2). However, other ways of altering the substructure should be explored.

Additional elements must be invoked to explain the crack growth in the presence of moisture. One of these is the clean surface generated by each loading cycle as a consequence of the large plastic crack-tip strains. The clean surface is a distinguishing feature of cyclic (as opposed to sustained) loading and can account for continuing corrosion activity during the loading (but not the unloading) portion of the cycle[57]. However, oxide films that form rapidly on aluminum are typically ~ 10^{-2} μm thick, and even their repeated formation does not, by itself, explain corrosion increments as large as ~ 1 μm/cycle. One possibility offered by Pelloux[58] is that the oxide film blocks the reversal of slip offsets, which are in the range of from 0.1 to 1 μm in high strength aluminum alloys. Sensitivity to moisture may, therefore, have some connection to the distribution of slip and the characteristics of slip offsets. Pelloux[58] also proposes "stress sorption cracking" as another explanation for the large corrosion increment which is supported by presence of brittle striations. Both possibilities offer further opportunities of metallurgical control.

V CONCLUSIONS

1. Existing crack growth rate measurements performed in different laboratories on the 7075-T6 and 2024-T3 aluminum alloys are in very good agreement provided the comparisons involve the same R-value, environment and cyclic frequency.

2. Both alloys can display widely different growth rates for the same ΔK-value when $\frac{da}{dn} < 1\,\mu m/cycle$. The highest growth rates are reported for tests in humidified air with intermediate cyclic frequencies; the lowest growth rates for tests in dehydrated air with high cyclic frequencies. These two extremes point to the involvement of a moisture assisted corrosion process capable of producing a 20-fold increase in the growth rate at low ΔK-levels.

3. Composition and microstructure also affect the growth rate. The 7075-T6 alloy displays higher growth rates than 2024-T3 for the same ΔK-values. Estimates of the cyclic life of center notched panels with a 2.54 mm flaw (0.10 in.) derived from the growth rate curves show that the cyclic life of 2024-T3 is ~ 3x that of 7075-T6 in laboratory air, 5x that of 7075-T6 in humidified air, and 10x that of 7075-T6 if ΔK is in proportion to the yield strength. The stress ranges for equivalent cyclic lives of 2024-T3 and high strength steel panels of this configuration are roughly in proportion to the densities of aluminum and steel.

4. A number of metallurgical factors exert a modest influence of crack growth rates. The cyclic life of 7-thousand series alloys in water is enhanced from 50 to 100% by overaging combined with a somewhat higher copper content and zinc magnesium ratio. Heat-to-heat variations in composition and processing, different heat treatment schedules, and small amounts of cold work can alter the cyclic life of 2024-T3 by 50 to 100%. Evidence based on the fatigue striation spacing indicates brittle particles and inclusions act to increase growth rates by ~ 100% when $\frac{da}{dn} > 1\,\mu m/cycle$. Finally, there is some evidence that grain boundaries in a number of alloys tend to retard crack growth.

5. Consideration of possible mechanisms of cyclic growth draw attention to the dislocation substructure generated by the cyclic plastic strains in advance of the crack tip. Alterations of the substructure in copper and copper alloys have produced as much as a 15-fold reduction in the crack growth rate. Ways of altering fatigue substructure in aluminum alloys should be explored. The character of slip offsets may be a factor contributing to the moisture assisted corrosion mechanism.

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