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Ship Materials Engineering Department

Research and Development Report

## FATIGUE CRACK GROWTH OF 5456-H116 ALUMINUM AND HSLA-80 WELDMENTS

by

L. R. Link

DTRC/SME-88-39 Fatigue Crack Growth of 5456-H116 Aluminum and HSLA-80 Weldments



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Fatigue crack growth rate experiments were performed on 4W-type compact tension specimens of baseplate and weldments of 5556-H116 Al and of baseplate and HAZ of HSLA-80 steel. Stress ratios for the tests were 0.1 for both materials with the Al weld also being tested at R=0.5. Crack opening levels were determined for both the weld and baseplate in the aluminum material and for the A710 material in the as-welded and as-stress relieved conditions. The fatigue crack growth rates, when using the total applied load, of the welds and HAZ were significantly less than those of plate for both materials. Using the effective stress intensity, which represents the actual stress intensity at the crack tip, results in a shift of the da/dN versus ΔK curves to a faster growth rate. Comparison of the curves shows that the fatigue crack growth rates of the aluminum material fall in the same scatter band of data for baseplate, and for the HSLA-80 material the growth rate of the HAZ is shifted to faster growth rates than the baseplate. This shift of data leads to more conservative estimates on fatigue life.


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## ABSTRACT

Fatigue crack growth rate experiments were performed on 4W-type compact tension specimens of baseplate and weldments of 5556-H116 Al and of baseplate and HAZ of HSLA-80 steel. Stress ratios for the tests were 0.1 for both materials with the Al weld also being tested at R=0.5. Crack opening levels were determined for both the weld and baseplate in the aluminum material and for the A710 material in the as-welded and as-stress relieved conditions. The fatigue crack growth rates, when using the total applied load, of the welds and HAZ were significantly less than those of plate for both materials. Using the effective stress intensity, which represents the actual stress intensity at the crack tip, results in a shift of the da/dN versus $\Delta K$ curves to a faster growth rate. Comparison of the curves show that the fatigue crack growth rates of the aluminum material fall in the same scatter band of data for baseplate, and for the HSLA-80 material the growth rate of the HAZ is shifted to faster growth rates than the baseplate. This shift of data leads to more conservative estimates on fatigue life.

## ADMINISTRATIVE INFORMATION

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## INTRODUCTION

Since discontinuities leading to fatigue cracks generally occur in welds, it is important to understand and characterize the particular features of welds that affect fatigue properties. For example, when fatigue life is characterized by stress versus cycles to failure, the weld reinforcement geometry is a major parameter. However, in fatigue crack growth rate testing, where specimens have carefully controlled geometries, other factors can significantly affect observed properties. Factors such as residual stresses, corrosion debris, surface roughness, specimen size, and crack tip plasticity can influence the crack growth rate observed during fatigue testing by altering the effective stress intensity of the crack tip. Little is known about how residual stress fields are affected by crack growth, and how these altered stress fields affect crack growth. For instance, residual stresses at surface stress concentrations may be released by local yielding due to service loads, but the re-equilibrated distribution in depth may still have a significant influence on subsequent fatigue crack growth[1].

In the past, fatigue crack growth rates of welded materials have been reported to be slower than baseplate[2-5]. Davis and Czyryca also reported that the weld residual stress effects were more significant than environmental effects on the crack growth behavior[2,3]. This slower growth rate behavior has raised several questions because conventional fatigue (S-N) behavior indicates a lower fatigue limit for the weldments as compared to the baseplate. A recent explanation for this includes the presence of residual stresses from welding[6]. Residual stresses are produced in welded structures by thermal expansion, plastic deformation, and shrinkage during cooling. The amount of constraint determines the amount of residual stress. Some researchers estimate that tensile residual stresses from welding reach a maximum of 60 to 75% of the material's tensile yield strength. Others estimate that welding produces yield strength level residual stresses. Bucci reported that the residual stress distribution was largely responsible for the different propagation rates observed when crack starter notches were located in different regions of identically fabricated extruded rods[7]. Since the effect of tensile residual stresses on a real structure is dependent on their magnitude, the conservative design assumption must be that yield level residual stresses exist.

Preparing a specimen notch by removing metal which is under residual weld tensile stresses can induce compressive residual stresses in welded materials. These stresses act to oppose the applied testing loads, and keep the crack tip closed even under an applied tensile load. This phenomenon is known as crack closure and can occur at loads significantly above the minimum applied test load. Elber described the concept of an effective stress intensity range, $\Delta K_{eff}$, which assumes that crack propagation is controlled by the stress intensity only if the crack tip is opened[8]. When the closure load, $P_{cl}$ is greater than the minimum applied load, the stress intensity calculated using applied loads will be greater than that actually present at the crack tip. Thus, the effects of the crack tip closure must be considered to achieve a more accurate estimate of crack growth response to the stress intensity range.

Crack tip closure can be readily detected by monitoring the trace of load versus crack opening displacement (P-COD) on an oscilloscope. Figure 1a shows the P-COD response of an ideal specimen loaded elastically, where the slope of the curve is related to specimen compliance. With closure the curve's slope changes as shown in Figure 1b. The lower slope is the response of the specimen to the load necessary to overcome any residual stress, and open the crack. The upper slope corresponds to the compliance of the specimen with the crack open and is similar to the ideal specimen of Figure 1a. The closure load has been measured by several methods including the lowest tangent point of the upper slope, the intersection of the tangents of the two slopes[9,10] a compliance differential method[11,12,13], and a point of predefined deviation from the upper slope[14].

This study compared the fatigue crack growth rate of an aluminum 5456-H116, an aluminum 5086 and an HSLA-80 steel in the weld conditions to their respective baseplate growth rates. A load ratio effect was determined for the aluminum weld and the effects of stress relief of the steel was examined with respect to applied and effective stress intensities.

## MATERIAL AND EXPERIMENTAL PROCEDURE

The material used for this study included 3/8-in thick 5456-H116 aluminum baseplate and gas metal arc weld (GMAW) with a 5555 Al electrode, 1-in thick 5086 aluminum, welded with the same electrode, and a 5/8-in thick HSLA-80 steel baseplate and submerged arc weld (SAW). Baseplate specimens were notched through the longitudinal direction and welded specimens were notched parallel to the welding direction, through the weld metal deposit for the aluminum and in the HAZ for the steel. Nominal compositions and typical mechanical properties of both materials are listed in Table 1 and Table 2. The specimens were tested using the constant load-amplitude method as outlined in ASTM Standard E-647 on "Measurement of Fatigue Crack Growth Rates." Fatigue crack growth tests were performed in air using compact tension (CT) specimens under sinusoidal loading at a test frequency of 10 Hz for the aluminum and 5 Hz for the steel. The steel specimens were side grooved 10% of the specimen thickness on each side to help establish a straight crack front. Applied load ratios of 0.1 and 0.5 were used for the aluminum and 0.1 for the steel. Crack length was estimated from specimen compliance using the expression for an edge line compact tension specimen:[15]

$$a = W(1.001 - 4.6695u + 18.46u^2 - 236.82u^3 + 1214.9u^4 - 2143.6u^5)$$

where $u = \dfrac{1}{\sqrt{EvB_e/P} + 1}$

and
- $P$ = Load
- $v$ = Crack opening displacement
- $E$ = Modulus of Elasticity
- $B_e$ = Effective specimen thickness, $B_{max} - (B_{max} - B_{min})^2 / B_{max}$

Compliance measurements were based on the upper linear portion of the P-COD traces, and were stored, with the cycle count, at crack length intervals of 0.02 in. (5.08cm). Applied stress intensity was calculated using the expression in ASTM E-647 for CT type specimens. Crack closure levels were determined both visually and non-subjectively[14] by measuring the deviation from linearity of P-COD traces.

## RESULTS

### ALUMINUM

Figure 2 shows the fatigue crack growth rates of the aluminum alloy for baseplate and weld at a stress ratio R=0.1 and weld at R=0.5. The stress intensity factor range, plotted on the abscissa, is calculated using the applied load. The figure shows that based on the applied stress intensity range, cracks appear to propagate more slowly in welds than in plate at the same load ratio. Also the crack growth rates of weldments appear to increase with increasing R. This finding is consistent with other reports[4,16,17].

Results of the crack closure measurements made on the specimens are plotted as best fit lines of percent closure versus crack extension in Figure 3. It can be seen that near the beginning of the test (zero crack extension) the closure loads are maximum, and they decrease as the crack grows. Initial closure loads for the welds are greater than 80 percent of maximum applied load ($P_{max}$) and for plate are about 30 percent of $P_{max}$. The initial closure values are nearly uniform within each group. These findings are consistent with the explanation that crack closure in welds results from the redistribution of weldment residual stresses due to machining of the specimen notch, and through crack propagation[3,18,19], that is stress relief with crack extension. Although residual stresses in welds are typically very high (approaching yield strength), those in plate usually are considered insignificant. However, the H116 temper of the alloy tested does incorporate a strain hardening operation that induces a significant residual stress (although not as high as that from welding).

Taking crack closure into account results in the fatigue crack growth rate curves for the three test conditions as plotted in Figure 4. In this figure $\Delta K_{app}$ is replaced by $\Delta K_{eff}$ as the independent variable. Because closure load rather than minimum load is considered, $\Delta K_{eff}$ represents the fatigue response to the actual stress state at the crack tip. The most visible effect of using $\Delta K_{eff}$ is the extreme shift of the weld data to the left (to higher growth rates) at lower $\Delta K$. When data from all conditions are superimposed, the close grouping indicates that $\Delta K_{eff}$ accounts for the differences in crack growth rate which was observed for plate, weld, and load ratio.

Figure 5 shows a comparison of the results of the 1-inch thick weld specimen with those of the 3/8-inch thick tests. The 1-inch specimen crack growth rates are shown as two curves, one plotted against $\Delta K_{app}$ and the other against $\Delta K_{eff}$. Examination of Figure 5 highlights the earlier observation of crack closure -- that is, the maximum effect is at lower $\Delta K$ (and lower growth rates). In addition, the $\Delta K_{eff}$-based curve for the thick weld lies on the lower side of the scatter band of the thin specimen results. These results show that, at least in this case, crack closure effects were similar for the thick and the thin welded specimens.

HSLA-80

Figure 6 shows the crack growth rates of the HSLA-80 material notched in the baseplate and the heat affected zone (HAZ) with respect to the applied stress intensity factor range. As for the aluminum weld, the growth rates for the HAZ are slower than the baseplate. The measured closure levels are shown in Figure 7 on several P-COD traces. As seen, the closure level, initially greater than 80 percent of the maximum applied load, decreases as the crack extends into the specimen to a level of about 40 percent of $P_{max}$. Further crack extension would result in additional reduction in the measured closure level to as low as the minimum applied load. Taking into account these closure measurements the crack growth rates were determined using $\Delta K_{eff}$, and are shown in Figure 8. Now, the growth rate has shifted to the left of the base plate data, that is, to faster growth rates.

To determine the extent the residual stress influenced the crack growth rates, two specimens were stress relieved at 1200 °F for 1 hr. before testing. Figure 9 shows the results based on $\Delta K_{app}$. Stress relieving resulted in the attainment of similar properties to that of the baseplate. However, closure levels were still detected, though not to as significant levels as the nonstress-relieved specimens, Figure 10. Initial closure levels were measured at only about 45 percent of the maximum load. Also, the maximum load necessary to obtain similar ranges in applied stress intensities was significantly lower than for the nonstress relieved test, 2100 lb. (9.3 kN) versus 6200 lb. (27.6 kN). So, taking into account these closure levels, the growth rates were re-evaluated based on $\Delta K_{eff}$. The combined results of baseplate, stress-relieved HAZ and nonstress-relieved HAZ tests are shown in Figure 11. Using $\Delta K_{eff}$ for all cases reveals that the stress-relieved data now falls into the same scatter band as the nonstress-relieved data, which falls at faster crack growth rates than the baseplate. Table 3 shows the Paris law constants for baseplate, nonstress relieved, and stress relieved HAZ based on both applied and effective stress intensity range. The slope (n) values of the HAZ applied are significantly higher than either the baseplate or stress relieved HAZ values, and especially the effective HAZ values.

## DISCUSSION

Accurate fracture property measurement requires caution so that the determined properties are not an artifact of residual stresses remaining in the test coupon. The problem develops in that stress-intensity factors are generally reproduced in fracture mechanics-type specimens with relatively small applied stresses and large cracks. In an engineering structure, however, the same stress intensity factor is often produced by large stresses and small cracks[7]. Therefore, residual stresses perceived to be small in the engineering sense can affect the growth rate measurement when the ratio of residual stress to applied stress in the test coupon is significant. Under this premise, fatigue crack growth rates at low $\Delta K$ levels represent the fracture mechanics property likely to be most seriously affected by residual stress influences. As seen from Figures 4, 5 and 11, the greatest shift in the growth rate curves occurs at the lower growth rates.

Raising the load ratio has the effect of reducing the effective stress intensity because the minimum applied load becomes closer to the actual minimum load at which the crack is opening. If the stress ratio is sufficiently raised to above the crack closure level, then no difference in crack growth should be detected. For the case of the aluminum, closure levels were measured to as high a level as 80 percent of the maximum load, so that the stress ratio applied ($R=0.5$) was not enough to overcome the actual stress at the crack tip until the crack had been extended significantly, Figure 3.

At relatively short crack lengths, the large initial closure level measured for the steel HAZ explains why the nonstress-relieved specimens required a much higher maximum load than in the stress-relieved specimens to propagate a crack at equivalent growth rates early in the test. In nonstress-relieved specimens the closure level decreased with stress relief during crack extension, and through residual stress redistribution. This explains the near equivalence of da/dN versus $\Delta K$ in both stress-relieved and nonstress-relieved specimens at high $\Delta K$ levels (long crack lengths)[19]. The closure levels observed in the stress relieved specimen indicate that complete stress relief may not have occurred in these specimens.

Some precautions need to be addressed when testing weldments. The initial fatigue precrack can sometimes be difficult to initiate and may require high initial $\Delta K$ values with subsequent load shedding before fatigue crack growth testing can begin. Once a precrack has initiated, some difficulty may arise in developing a straight crack path. The residual stresses that are present can cause the crack to initiate, and then propagate, from only one side of the blunt notch. Procedures that can eliminate this phenomenon include specimen side grooving, applying an initial compressive load, and using chevron notches to aid in crack initiation. However, even with specimen side grooving the steel specimens in this study still had significant difficulty in establishing straight crack fronts. Side grooving can also aid in planar crack propagation, that is crack propagation perpendicular to the applied load[20]. Seeley, et al,[20] reported a tendency for cracks deviating from the mid-plane of the specimen, perpendicular to the axis of load application. He also reported that those specimens where cracks deviated from mid plane resulted in higher crack growth rates. Because initial closure levels can be significant (greater than 80% of maximum load) when testing welds it is important to insure that only the portion of the P-COD trace where the crack is totally open, that is, the upper linear region, be used for compliance measurements for crack length determinations.

The effects of crack tip closure must be considered to achieve a more accurate estimate of crack growth response to the stress intensity range. The opening load is required to offset compression at the crack tip caused by the superposition of clamping forces attributed to residual stress in the bulk material and forces caused by wedging action of residual deformation left in the wake of the propagating crack[7]. ASTM Standard E-647 assumes internal stresses to be zero, and uses external loads only to compute the stress intensity. Hence, though growth rates from weldments are completely accurate and valid according to ASTM practice, the data should not represent the true material behavior. Means of taking into account crack closure include increasing the R ratio to above the level of crack closure or stress relief of the material to eliminate the effect of the internal stresses. Caution should be advised when stress relieving to ensure that no metallurgical changes take place that might effect the intrinsic fatigue crack growth response of the material.

## SUMMARY

Th~~e~~ results of this investigation lead to the following:

1. The crack growth rates of welded material can be significantly reduced in the presence of welding residual stresses due to the effects of crack closure.

2. Closure loads of up to 80% of maximum load have been measured in fatigue crack growth weldment specimens of both aluminum and steel alloys. These closure levels are predominantly an effect of the presence of weld residual stress.

3. Increasing the applied stress ratio can account for the closure effects in weldments by raising the minimum applied load closer to or above the opening load at the crack tip.

4. Stress relieving HSLA-80 weldments shifted the fatigue crack growth rates to equivalent rates of baseplate; however, closure levels up to 40% of maximum load still remained due to incomplete stress relief.

5. The shift of the fatigue crack growth rate data using effective stress intensity range shifts the growth rates of the welds to faster growth rates, resulting in more conservative estimates on fatigue life.

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Table I Chemical composition (wt%) and mechanical properties of aluminum alloys

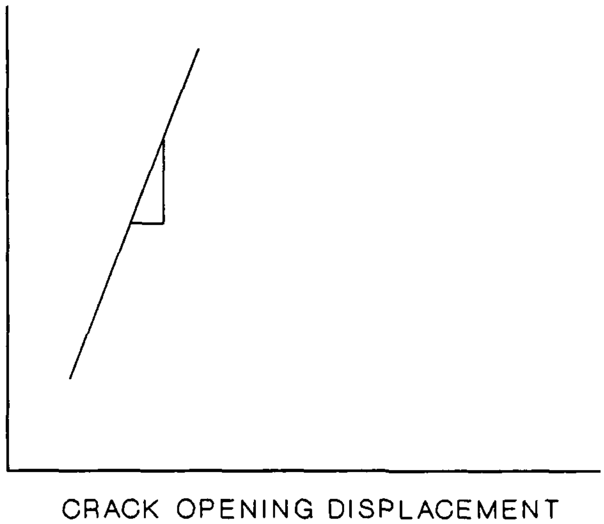
| MATERIAL | Yield Strength (ksi) | Ultimate Strength (ksi) | %EL | RA | Mg | Mn | Cr | Fe | Si | Zn | Ti | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plate 5086 | 29.4 | 45.4 | 26.6 | 38.5 | 4.00 | 0.04 | 0.14 | 0.31 | 0.08 | 0.06 | 0.00 | 0.09 |
| Plate 5456 | 42.0 | 56.0 | 13.0 | 11.0 | 4.90 | 0.68 | 0.10 | 0.30 | 0.05 | 0.12 | 0.03 | 0.14 |
| Weld Filler 5556 | - | 45.5 | - | - | 4.80 | 0 62 | 0.07 | 0.28 | 0.07 | 0.12 | 0.05 | 0.07 |

Table II Chemical composition (wt%) and mechanical properties of HSLA-80

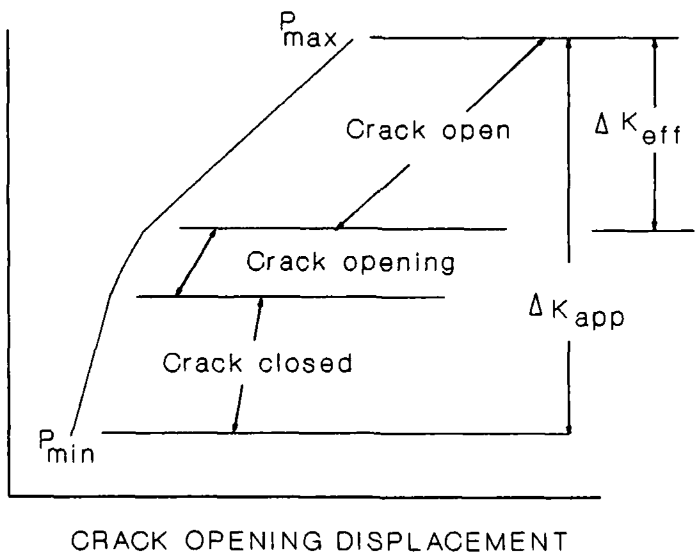
| MATERIAL | Yield Strength (ksi) | Ultimate Strength (ksi) | %EL | RA | C | Mn | Si | P | S | Ni | Mo | Cr | Cb | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HSLA-80 | 97.2 | 108 | 37 | 73 | 0.05 | 0.69 | -- | 0.01 | 0.004 | 0.92 | 0.19 | 0.83 | 0.04 | 1.20 |
| Weld Filler | 92.2 | 102 | 22 | 62 | 0.08 | 1.50 | -- | 0.01 | 0.01 | 1.75 | 0.4 | 0.3 | - | - |

Table III Paris law constants for HSLA-80 baseplate and HAZ

| | C in./cycle | n |
|---|---|---|
| HAZ ($\Delta K_{app}$) | 8.57E-14 | 4.96 |
| | 4.15E-14 | 4.95 |
| BASEPLATE | 2.03E-10 | 3.19 |
| STRESS RELIEVED HAZ ($\Delta K_{app}$) | 8.71E-10 | 2.86 |
| | 1.59E-10 | 3.40 |
| HAZ ($\Delta K_{eff}$) | 3.38E-8 | 1.99 |




a) Without Closure




b) With Closure

Figure 1 Load versus Crack Opening Displacement behavior a) without closure and b) with closure.

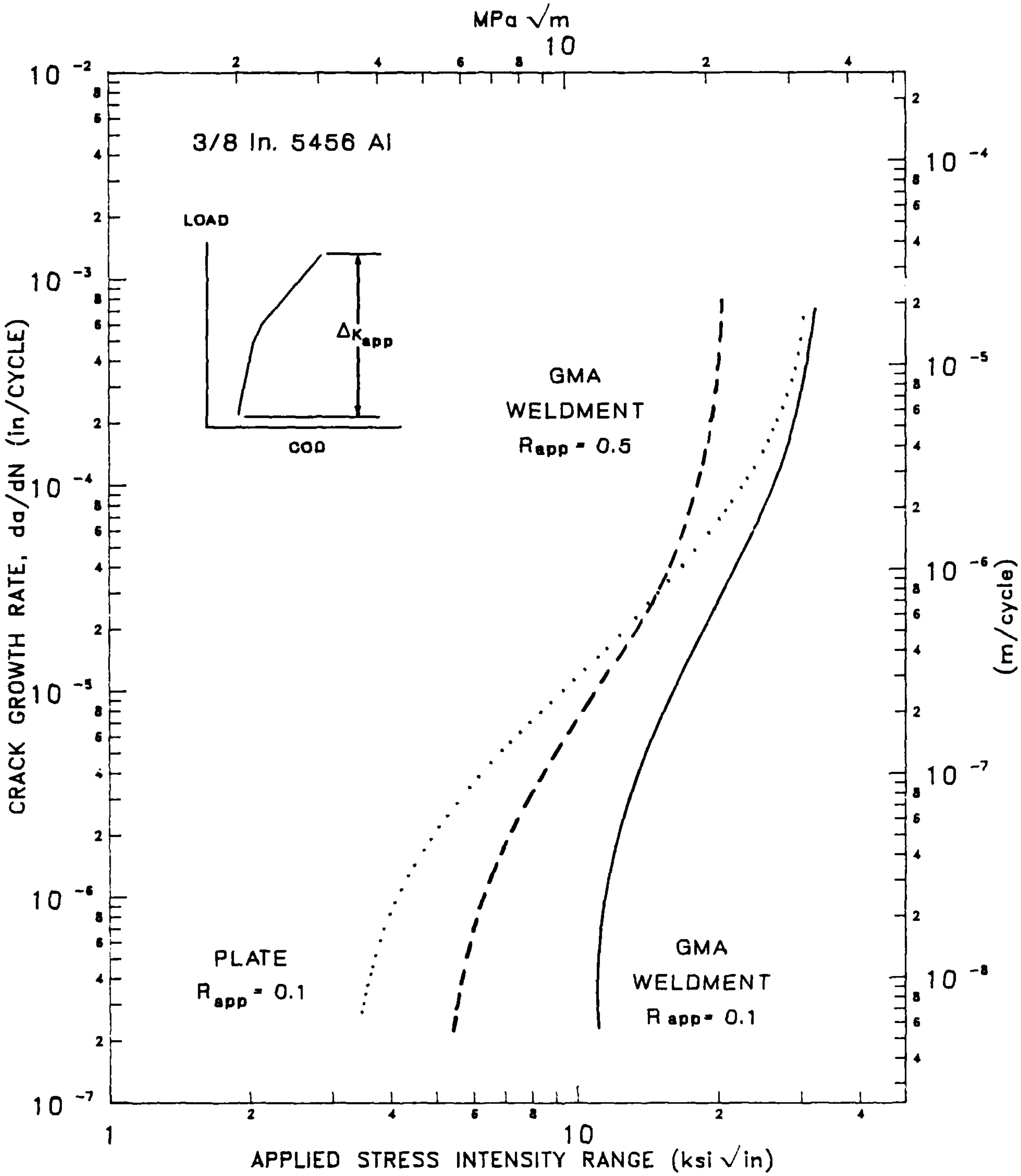



Figure 2 Mean curves of fatigue crack growth rate versus applied stress intensity range for Al 5456-H116 baseplate and weldment

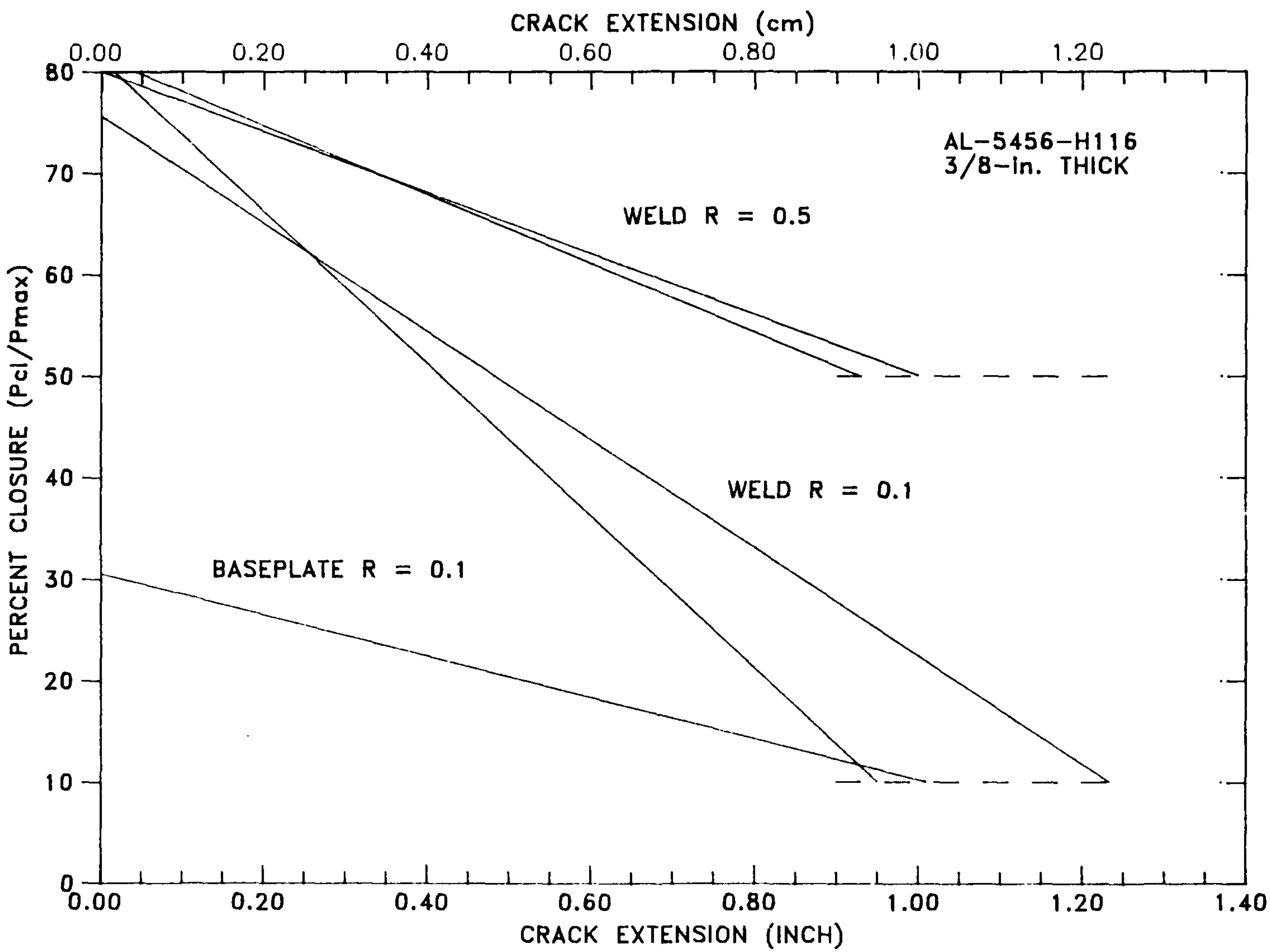



**Figure 3** Percent closure versus crack length for weld and baseplate Al 5456-H116

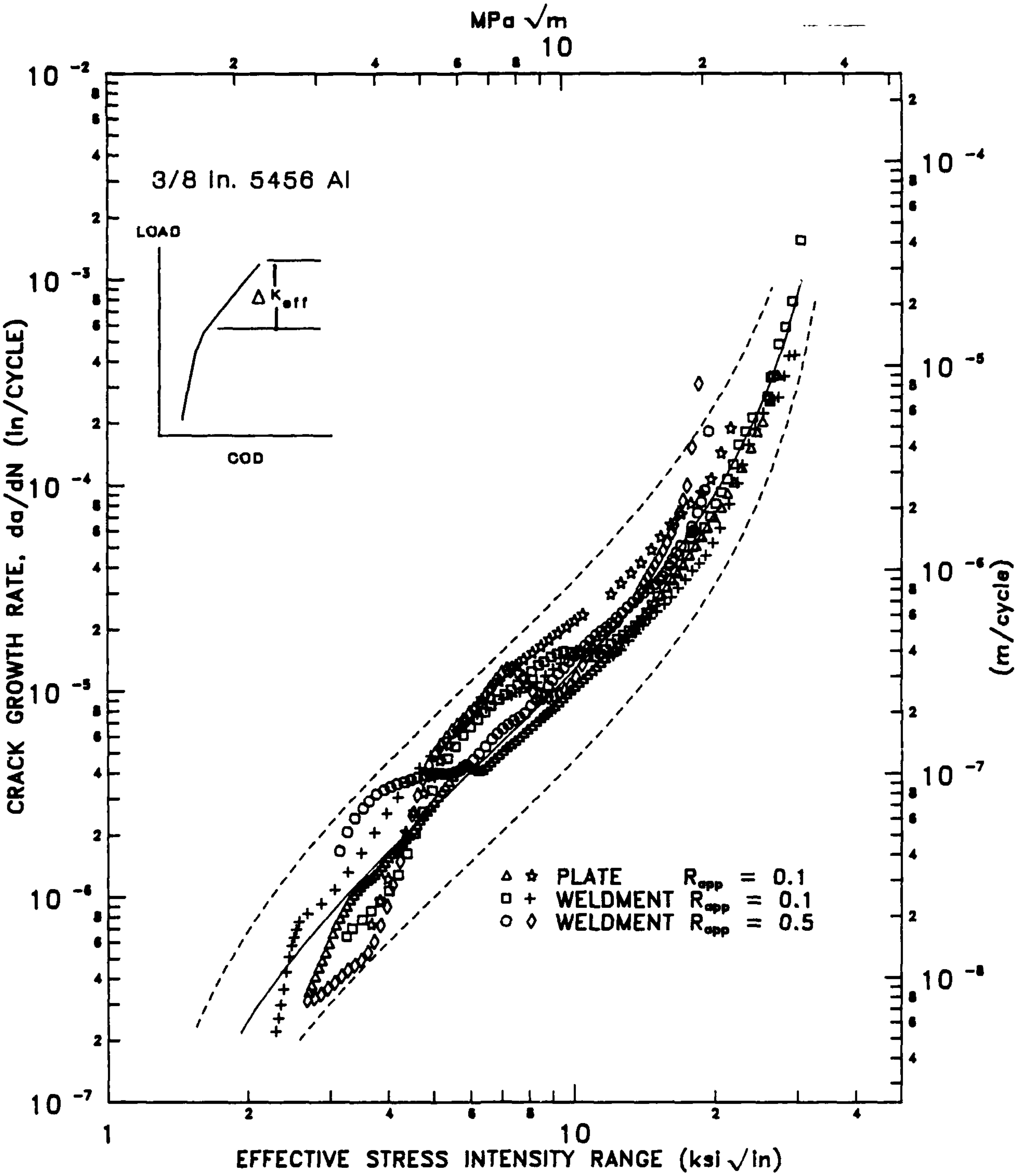



Figure 4 Fatigue crack growth rate versus effective stress intensity range for Al 5456 baseplate and weldment

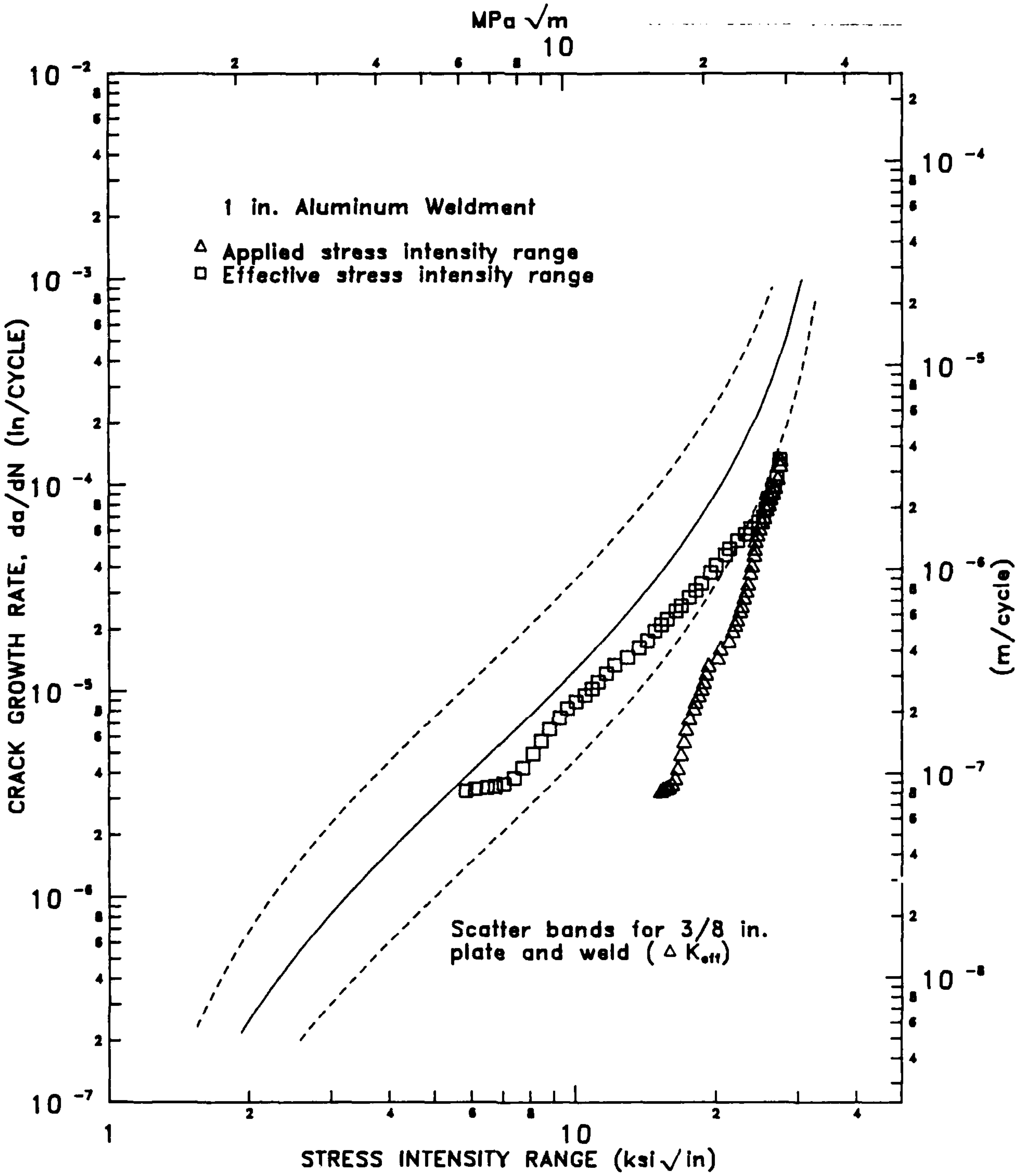



Figure 5 Comparison of fatigue crack growth rates of 3/8 in. and 1 in. thick Aluminum weldments

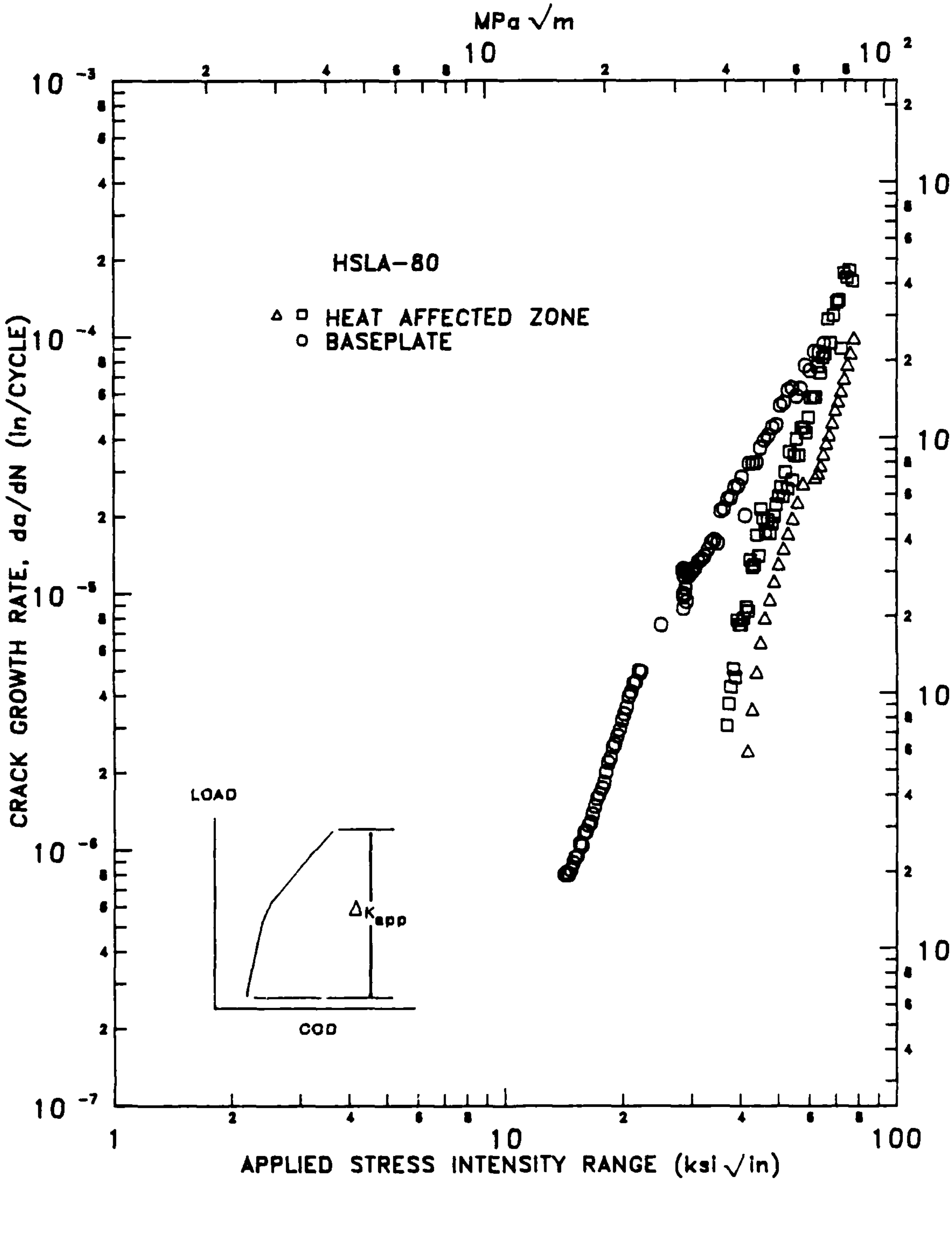



Figure 6 Fatigue crack growth rate versus applied stress intensity range for HSLA-80 baseplate and HAZ

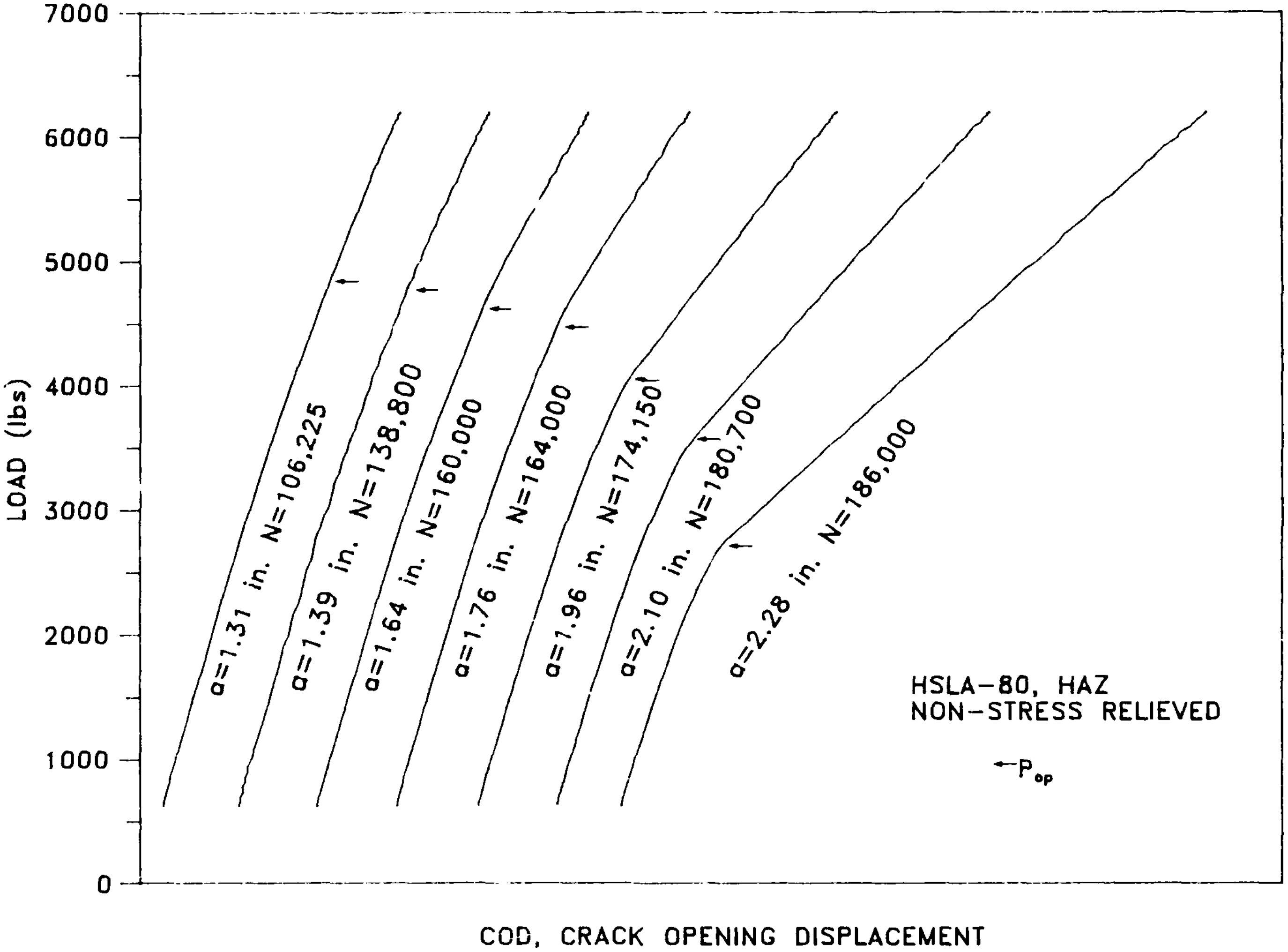



Figure 7 P-COD traces showing closure levels of non-stress relieved HSLA-80 HAZ

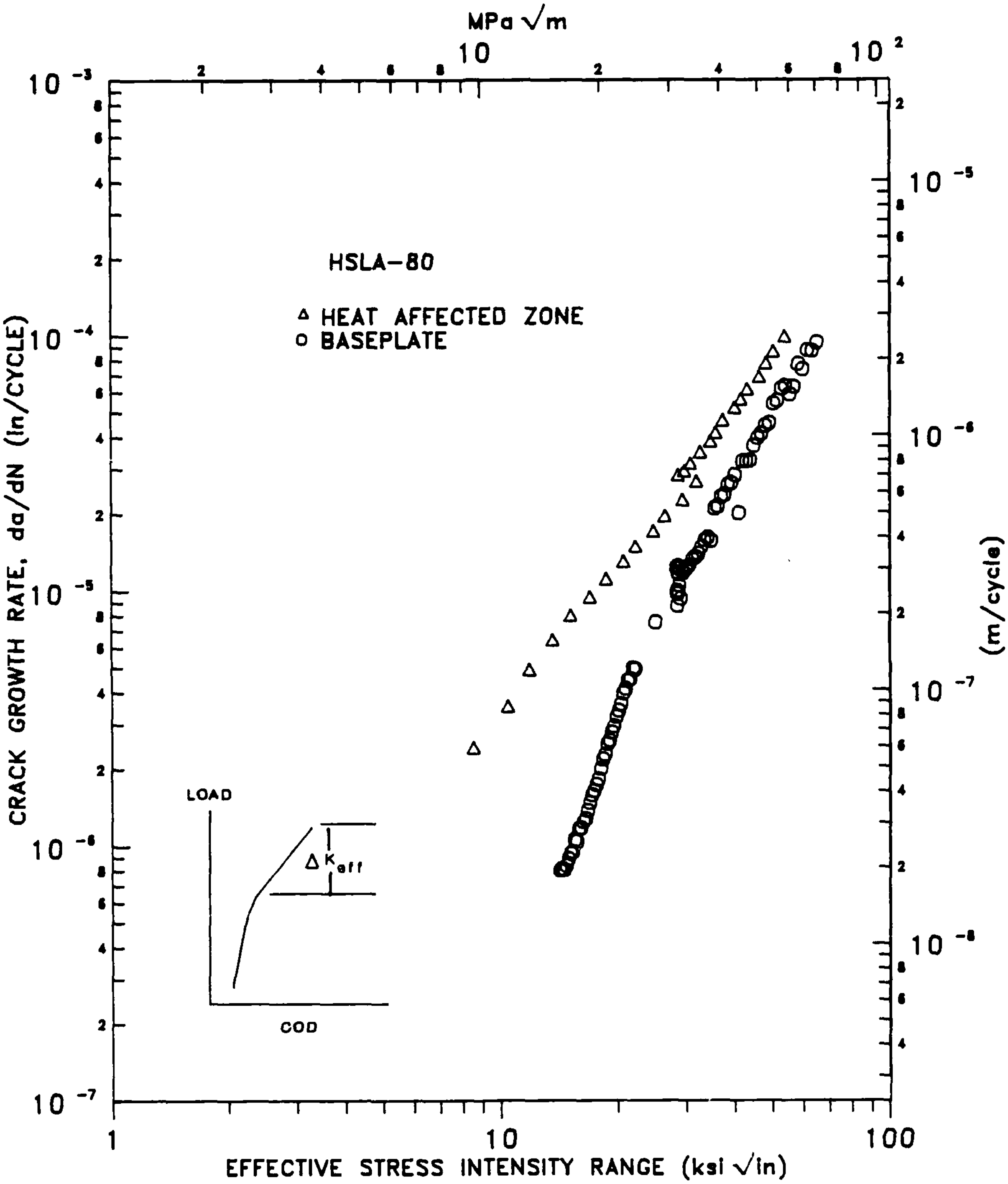



Figure 8 Fatigue crack growth rate versus effective stress intensity range for HSLA-80 HAZ

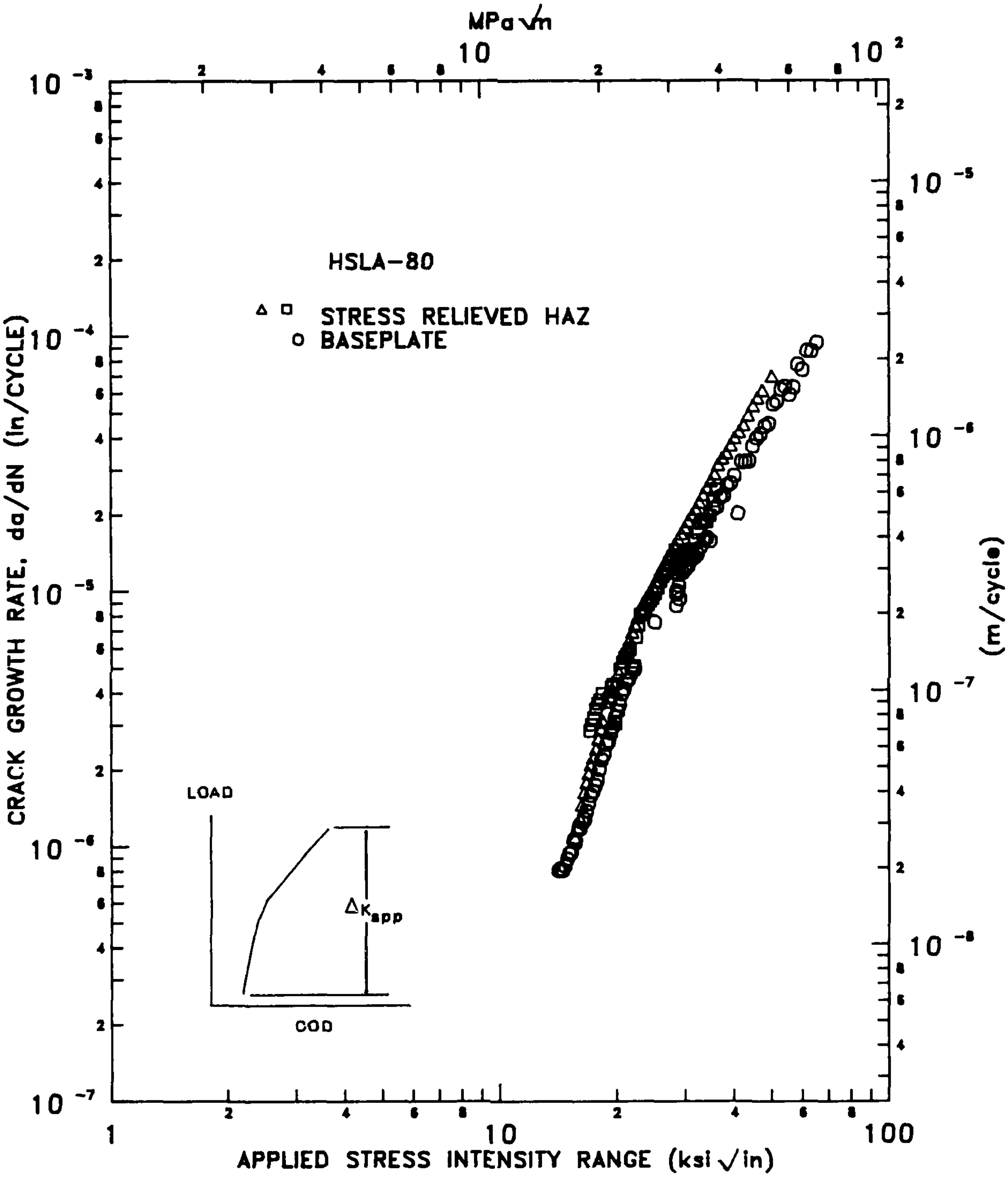



Figure 9 Fatigue crack growth rate versus applied stress intensity range for stress relieved HSLA-80 HAZ

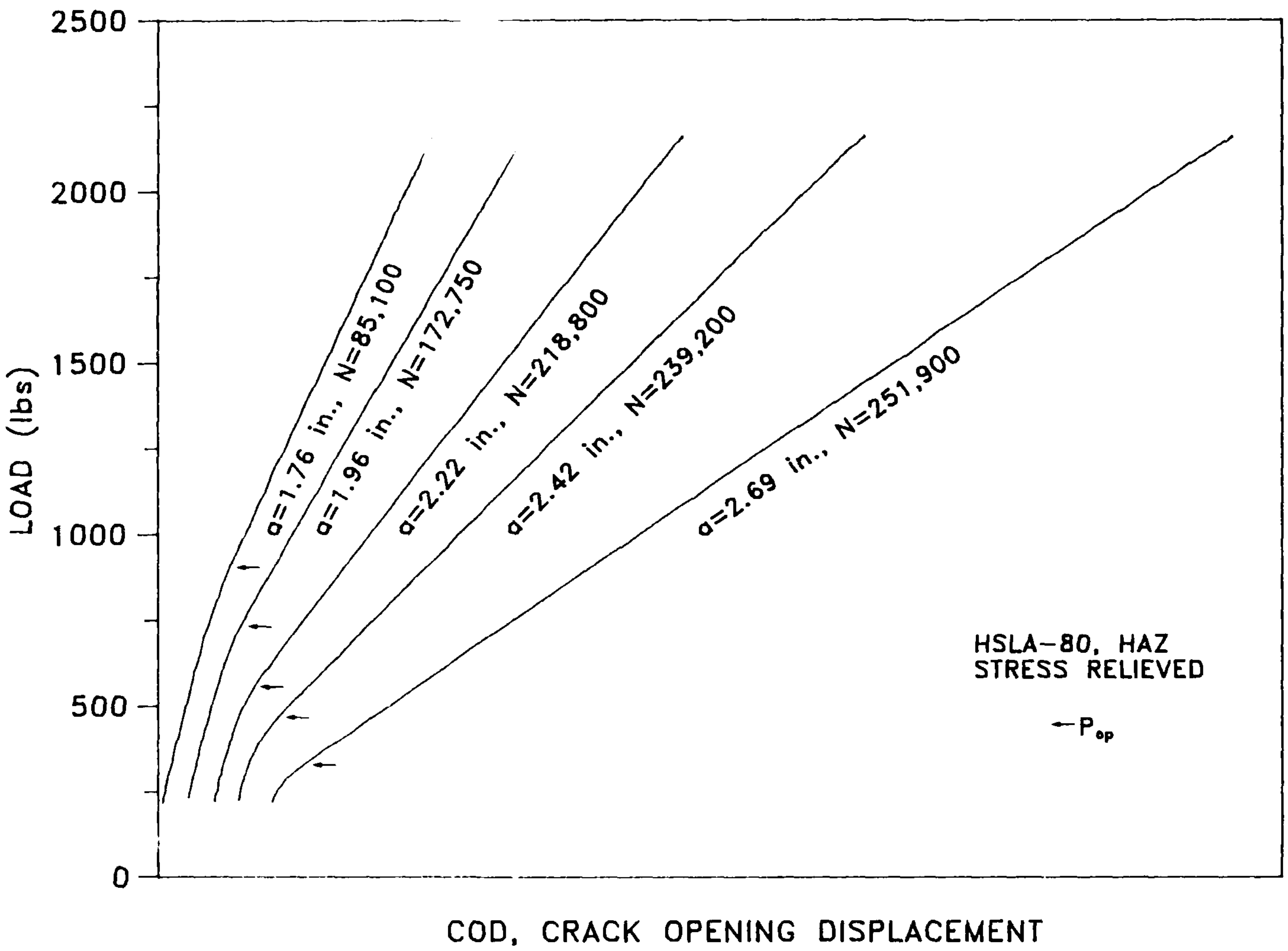



Figure 10 P-COD traces showing closure levels of stress relieved HSLA-80 HAZ

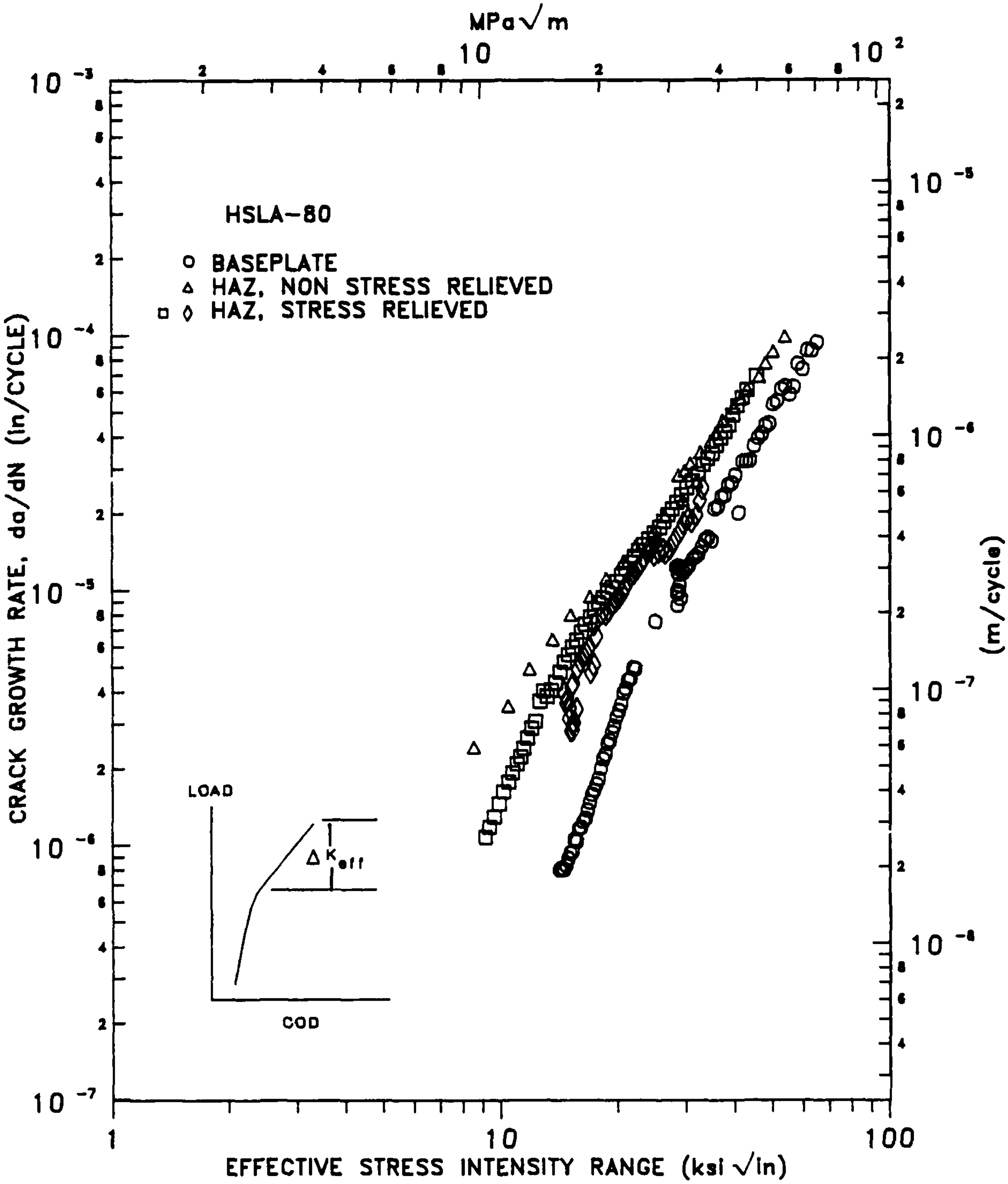



Figure 11 Fatigue crack growth rate versus effective stress intensity range for HSLA-80 baseplate, non-stress relieved, and stress relieved HAZ

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