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MECHANICS ASPECTS OF MICROCRACK GROWTH IN INCONEL 718-IMPLICATIONS FOR ENGINE RETIREMENT FOR CAUSE ANALYSIS

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physically short cracks and often the trend is toward much higher crack
growth rates than expected.

A literature review led to the conclusion that this short-crack effect arose primarily because of crack tip plasticity, transients from initiation to microcracking, and incorrect or incomplete implementation of LEFM. However, the data did not discriminate between these possible causes to that it was not clear which were significant. An experimental program was undertaken to isolate or emphasize the factors thought to promote the short-crack effect. The material used in the study was Inconel 718 in a heat-treatment condition found in current advanced engines. This report presents the results of those experiments.

Two specimen geometries were used in the experiments--a center cracked panel and a center hole notched panel. For the center cracked panels the variation in the ratio of plastic zone size to crack length  $(r_p/a)$  that could be achieved was bounded below by the threshold and above by  $K_c$ , and was small (from .13 to .32). No difference in microcrack growth rate behavior was detected over this range of  $r_p/a$ . Because the crack tip plasticity is confined, only limited closure developed. This was verified using a wake removal technique. A short crack effect of at most a factor of 4 was observed for cracks less than 600  $\mu$ m long.

For the center notched panels, a number of experiments were conducted to study free surface effects and initiation transients, three-dimensional crack geometry transient effects, and notch field effects. Natural initiation influenced results significantly because of free surface effects and crack geometry transients. Crack-growth rates more than an order of magnitude higher than long crack trends were observed in some cases. The influence of natural initiation 's observed to be accentuated by nearly elastic notch root deformation be vior. Elevated crack-growth rates were also observed when the crack was embedded in the plastic zone at a notch root.

The report provides details of the experimental procedures used and a discussion of the experimental results including tabulations of the data. There is also a discussion of the implications of our findings relative to retirement for cause.

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### SUMMARY

This report presents results of an experimental program directed at assessment of the important aspects of the short-crack effect with regard to engine RFC analysis. Results of a first phase--a critical appraisal of the literature [4]--showed many factors have been viewed as possible sources of the short-crack effect. The purpose of the experiments was to identify and characterize key factors controlling the growth of small (short) cracks in engine applications. The desire was to make this assessment relative to LEFM--a deterministic continuum mechanics concept that assumes the existance of a dominant singularity. Accordingly, the study was also restricted to crack sizes that can be addressed as a dominant singularity in a continuum sense. Thus, the scope may be restricted by an implicit lower bound crack size on the order of 3- to 10-grain diameters.

The results of the literature survey indicated an absence of data that isolate or emphasize factors thought to promote a short-crack effect. This experimental study, therefore, set out to develop such information. Specifically, experiments were performed to isolate or emphasize  $r_p/a$ , closure, free surface effects and initiation transients, notch-field effects, stress-state effects, and 3D-crack geometry (transient) effects.

Analyses based on a pseudo plastic extension of LEFM have been developed to deal with values of  $r_p/a$  that exceed the LEFM confined flow situation (Appendix C). Analyses have also been developed to assess growth rate dependence on stress state and normalized stress level (Appendix A). The influence of 3D crack geometry effects have been addressed in a survey of available K solutions (Appendix B) and via experiments. The need for geometry specific K solutions that reflect the dependence of K on the near field (notch gradient) and the far-field boundaries has been demonstrated analytically (Appendix F). Also the fact that single term K expressions develop near infinite values of d(K/S)/dc approaching the notch boundary has been analytically demonstrated. In this same context, the utility of K as a measure of crack driving force as  $c \rightarrow 0$  has been questioned (Appendix F).

Exploratory experiments were performed to assess each of the abovenoted factors in the finite growth-rate regime. The range of variations in  $r_p/a$  that could be achieved were bounded below by the threshold and above by  $K_c$ , and were small. As expected, in view of the apparent effect of  $r_p/a$  in the literature, growth rates at small cracks were reasonably characterized by LEFM and long-crack data. Higher crack-growth rates of about a factor of 4 were observed for plane-fronted cracks growing from micro-preflaws. No applicable difference in microcrack-growth rate behavior was detected over the range of  $r_p/a$  considered. Finally, because plasticity was confined, only limited closure was expected to develop. This assertion was supported by results developed using the wake removal concept, over the range of  $r_p/a$  studied for net wakes as small as 40  $\mu$ m.

A number of experiments were also committed to the study of free surface effects and initiation transients, 3D crack geometry transient effects, and notch-field effects. Results of these studies showed a significant influence of natural initiation developed, apparently through free surface effects and crack geometry transients. Short-crack effects of more than an order of magnitude were observed. The influence of natural initiation was observed to be accentuated by elastic (or nearly so) notch-root deformation behavior. A significant short-crack effect was also observed as a result of inelastic action at notch roots.

Given that specimen, notch, and crack geometry appear to control the mechanics factors noted as key drivers for a short-crack effect, it was emphasized that the incidence and extent of the short-crack effect observed depends on both the application of interest and the material. It was also noted that results generated to screen materials for a short-crack effect will depend on the test specimen geometry. Finally, it was emphasized that a lower bound exists below which deterministic continuum fracture mechanics cannot be applied. The implications of these considerations to polycrystalline DS and to SC materials of various strength levels were discussed for engine RFC analysis. Categories of behavior were identified based on the continuum limitation and  $r_p/a$ , and the specimen or component geometry regarding notch fields and crack shape.

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### FOREWORD

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Drs. M. F. Kanninen and B. N. Leis served as coprincipal investigators for this study. Dr. A. T. Hopper was the program manager.

Special acknowledgement is made to Mr. D. P. Goetz whose careful attention to detail was responsible for the successes in the laboratory. We would also like to acknowledge the substantial contributions of Mr. T. P. Forte and Mr. Dennis Rider of Battelle's Columbus Laboratories.

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### INTRODUCTION

Fatigue crack growth rate predictions based on linear elastic fracture mechanics (LEFM) have been widely and successfully used for many years. The electric utility industry is but one example of an industry that is relying increasingly on LEFM for run, retire, repair decisions on major components. Damage tolerance analyses have been developed by the Air Force and used in many Special Projects Offices to allow rational decisions to be made concerning inspectability and continued use of cracked components until the cracks are of near critical size. The success of LEFM in these and other applications has led to research to develop the technology to track the growth of defects in engine components. This work is part of the effort to ensure the integrity of expensive engine components undertaken by the Air Force Wright Aeronautical Laboratories.

There are sound reasons for not blindly applying damage tolerance analyses to engine components. A growing body of experimental observations support the conclusions that LEFM does not always consolidate crack-growthrate data. Frost, Pook, and Denton [1], Ohuchida, Nishioka, and Usami [2], and Kitigawa and Takahaski [3] were among the first researchers to present data that did not conform to LEFM predictions at low- and near-threshold crack-growth rate conditions. Similar results have since been observed in many materials; the difficulties are particularly acute for physically short cracks. Data not consolidated by LEFM often indicate higher growth rates than expected thus implying <u>some</u> degree of nonconservatism in certain applications.

The Air Force (AFWAL/MLLN) undertook a study which had two ambitious objectives: identify the parameters that cause short cracks to behave differently than long cracks and develop a predictive model for short crack growth which included the effects of the governing parameters. The first undertaking of the program was a critical literature review which addressed the question of why small cracks apparently grow at rates that cannot be predicted using LEFM-based analysis methods that are successful for long cracks. The results were published in a report titled "A Critical Review of the Short-Crack Problem in Fatigue" [4]. It was concluded there that the reported short-crack

effect arose primarily because of crack tip plasticity, transients from initiation to microcracking, and incorrect or incomplete implementation of LEFM. Because the phenomenological data did not discriminate between the possible sources, it was not clear which were significant. Descriminating experiments were needed.

This report is concerned with the resulting test program. To provide continuity and background for the experiments, a summary of the findings of the literature review follows. It was from this data, that the test plan was devised.

### Summary of the Literature Review

Considerable data was found that does not correlate when growth rate is plotted against the stress intensity factor [4]. It was observed that such failures may be due to the way LEFM has been implemented rather than to some inherent deficiency in the theory. For example, K has been used for short cracks where closure is a factor, even though it is well accepted that  $\Delta K_{eff}$ is needed to account for stress ratio and closure effects for long cracks. There are also examples of data for which the underlying assumptions of LEFM were violated, making LEFM inapplicable.

Numerous miocro- and macro-mechanics of the flow and cracking processes which influence crack growth rate were identified in the literature. They include multiple growth modes, combinations of modes, and the threedimensional nature of the fracture process; the length and configuration of the crack front involving dimensions of both the specimen and the microstructure; free surface effects on slip character including effects of surface treatment and crystallographic growth; multiple cracking processes including possible environmental effects; and transient effects due to inclusions, grain boundaries, and grain-to-grain misorientation. In addition to these materials-related factors, a number of mechanics-related factors were identified. These included the influence of the plastic zone to crack length ratio on LFM, anisotropic effects, surface residual stress and local closure effects due to plane stress surface flow confined by a plane strain field, crack

bifurcation and ill-defined crack fronts, stress redistribution due to notch root yielding and to material transient deformation behavior, and macroscopic closure due to residual stresses and deformations. All of these factors interrelate and need to be considered together.

The process of going from a situation in which there is not a crack on a scale on the order of the microstructure to a situation in which a crack exists is transient. The crack tends to a steady state condition, the limit of which is the long crack condition. The mechanism of initiation (brittle to ductile) will control the length that the crack will attain before a steady state develops at its tip.

Brittle initiation tends to form a crack which grows stably from the beginning, with limited flow at the crack tip. In contrast, ductile initiation would initially tend to violate the plastic zone to crack length limitation of LEFM. Ohuchida, Nishioka, and Usami [2] have presented results for several steels in which the active plastic zones in ductile cases are as large as 0.3 mm while those for brittle cases approach  $10^{-3}$  mm. In this respect, a brittle steady state exists soon after inclusions crack, at crack lengths as small as can be consistently resolved using even highly sophisticated measurement systems. Ductile steady state, by contrast, develops only after extensive cracking. Significantly, LEFM criteria are satisfied for the lower extreme of brittle initiation at a crack length of about 10 µm--about the lower limit of detection. In contrast, LEFM criteria are violated at the upper limit of ductile initiation for cracks nearly 3 mm long.

Micromechanics is also a factor for short cracks for which the confined plasticity requirements of LEFM are met. In this case, local closure occurs due to plane stress flow on the surface that is contained within an unyielding plane strain field. For this reason, it is expected that cracks initiate naturally, in the absence of an overshadcwing notch plastic field, will show a short-crack effect. Artificially induced cracks, such as those initiating at the end of a starter notch, will demonstrate it to a much lesser degree, or not at all. In the case of ductile initiation, both small and laryer cracks may initially violate the LEFM confined plasticity requirement. Regardless of the reason for the existance of the plastic zone at the

initiation site which causes this violation, the crack cannot behave as a long crack until it has grown beyond the initiation zone and has developed its own steady state field. Again, both micromechanics and metallurgical features are important considerations in regard to the transient growth process. Equally important are multiple initiation and branching. Because artificial flaws would tend to concentrate deformation and tend to cause a more brittle initiation, natural cracks are expected to show the short crack effect much more than samples with starter notches. When the plastic zone is due to notch inelastic action, not only may the contained plasticity requirement be violated, but the K solution is inappropriate unless inelastic action in the notch field is taken into account.

Based on this information, experiments were designed to try to do two things:

- Isolate conditions under which physically small cracks exhibit anomalous growth when properly analyzed via LEFM.
- Define those factors which control such growth in both smooth and notched specimens.

The study has been performed on Inconel 718 in a heat-treatment condition found in current advanced engines. Nearly all of the tests were conducted at room temperature.

The experiments led to three major conclusions. These are:

- In the absence of elevated temperature, corner cracking, and inelastic notch fields, LEFM analysis is appropriate for small cracks in Inconel 718 under engine service conditions.
- 2. Inability to measure and analyze corner-initiating cracks can cause LEFM to become practically invalid for short cracks of that type.
- Notch root plasticity can elevate crack growth rates above those predicted by LEFM.

### EXPERIMENTAL DETAILS

Experimental results which isolate or emphasize four factors are useful to identify mechanics factors controlling the growth of short cracks in fine-grained Inconel 718. These factors are (1) the transient behavior from initiation to the formation of a dominant singularity, (2) three-dimensional crack geometry and stress state effects, (3) the extent of plasticity, and (4) microcrack closure. The experiments performed to develop these results are explained in the following section.

### <u>Test Plan</u>

### Initiation Transients

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The existence of a planar dominant singularity has been assumed in all analyses. Experiments with natural initiation (causing the associated transient initiation to microcrack), as well as experiments with flaw-induced initiation (which tends to minimize the microcrack transient), have been performed to explore the implications of this assumption.

From a fracture mechanics viewpoint, planar cracks longer or deeper than about 10 grains may be reasonably argued to be dominant singularities. Nonplanar (bifurcated) cracks greater than 10 grains long (in view of the LEFM analysis of Suresh [5]) can be expected to have lower stress intensities for the same effective length. Earlier experimental results of Schijve [6] also indirectly indicated a reduced stress intensity in that growth rates were reduced as compared to their planar counterparts as the same K level.

### **Three-Dimensional Effects**

Three-dimensional effects due to crack geometry were investigated by comparing the results of tests using initial flaws to start cracks and tests in which cracks were initiated "naturally". Tests with initial flaws tend to minimize 3D crack-geometry effects, whereas those with natural initiation tend

to emphasize the 3D nature of the crack in that part-through-thickness cracks develop.

Tests in plates with holes were conducted. This introduces the added complexity of a 3D-stress-state effect at the notch root, which ranges from plane stress for geometries with thickness, t, to diameter, 2r, ratios approaching zero, to plane strain for geometries where t/2r exceeds about 2. (In this study all tests of plates with holes had t/2r = 0.18.) Plane stress tends to cause corner crack initiation; plane strain tends to cause midthickness initiation [7]. Both lead to the just noted 3D crack-geometry effects, particularly for the case of natural initiation. Also, notch root stress biaxiality may alter the rate of crack propagation versus that for the long crack stressed uniaxially in Mode I. Results in the literature suggest this subject remains a major research area with a wide variety of effects on growth rate depending on the material [8]. Results of a recent major symposium dealing with this subject, however, suggest that the varied dependence of growth rate on biaxial stress ratio,  $\mu$ , could be correlated in terms of the ratio of maximum stress,  $S_{mx}$ , to the flow stress of the material, Y. The significance of this dependence for short cracks is alluded to in Appendix A along with free surface effects, and is discussed in more detail in the references cited there. The effect of biaxiality due to corner crack geometry is examined in the section on stress intensity factor solutions in the context of our experiments, as detailed in Appendix B.

### Extent of Plasticity

Prior analysis [2,9] suggested that the confined-plasticity limitation of LEFM could be removed, at least in part, through the use of strip yield models. Discussion of this effort is presented in Appendix 2. Experiments which emphasize this factor were performed by varying the ratio of the crack tip plastic zone size to crack length  $r_p/a$ ; also, cracks were grown in both elastic and plastic notch zones.

### Crack Closure

Discriminating experiments to sort out the role of plasticity induced closure were considered as the first priority, in view of the results of the review of the literature which formed the first phase of this program.

Analysis independently performed by Newman [10] during the course of the present study indicates that microcrack closure can simulate some of the crack growth tendencies referred to as short crack effects. To date, no conclusive studies have been performed to isolate the role of microcrack closure, although clear-cut evidence of macrocrack closure exists. For this reason experiments have been performed to isolate microcrack closure effects. The wake removal concept was used, as will be discussed later.

It should be remembered that closure can occur due to causes other than plasticity. Closure due to contacting asperities on nonplanar cracks and to oxide particles on planar or nonplanar cracks may be expected to reduce the effective stress intensity according to the work of Ritchie, et al [11,12]. This lowered  $\Delta K_{eff}$  would reduce the growth rate. In general, nonplanar cracks are not expected to develop differently as a function of crack length for a given stress state and level of stress intensity factor. Thus, nonplanar cracks would be expected to have the same relative effect on growth rate independent of crack length for the same local stress intensity factor range. Oxide-induced closure, however, may vary according to crack length if the rate of oxide deposition relative to  $\Delta$ CTOD differs as a function of crack length. In any event, if environmental accessibility controls the rate of oxide deposition, oxide-induced closure is expected to be greatest when the crack tip is most accessible to the environment. In this case, in the absence of very high deposition rates in systems developing hard oxides, the formation of a significant oxide layer would depress rates for short cracks more so than for long cracks.\* However, if deposition rates were high and hard oxides

<sup>\*</sup> It was noted in our earlier report that short cracks have been observed to grow at rates lower than LEFM long crack data would suggest. While academically of interest, this is not a safety problem in applications of RFC and thus is not of practical signifiance in the present study.

formed, the wedging action of the oxide would increase  $K_{mx}$  and da/dN and counteract any closure effect that tends to decrease  $\Delta K_{eff}$  and da/dN. In the latter case, growth rate could either increase or decrease with increasing length depending on many factors, the study of which is beyond the present effort.

Plasticity-induced closure develops as a wake of plasticity forms behind the advancing crack. This crack closure decreases the range of the effective stress intensity factor, thus decreasing the crack-growth rate. Therefore, the role of closure should be evident by an increase in growth rate as wake is removed. This is illustrated schematically in Figure 1. This figure shows the results of a hypothetical test run with loading such that the stress intensity factor range  $\Delta K$  is kept constant. First, a crack is nucleated from an electrical-discharge-machined (EDM) starter notch. As the microcrack grows to a length such that a steady-state wake of plasticity forms, a steady-state amount of closure also develops, and the crack growth rate takes on a constant value lower than the initial "short crack" rate. This constant rate is the long crack LEFM behavior. The wake is then removed by the EDM process, but the crack tip is left undisturbed. The crack tip now is affected by a minimum amount of wake. Although the crack has grown during the test, the situation is essentially the same as just after crack nucleation. The resumption of fatigue loading causes crack growth at an accelerated rate until a steady-state wake (and thus steady-state closure and effective  $\Delta K$ ) is developed again.

What is the upper bound on the increment of crack growth after wake removal for which the transient behavior can be seen? It is the crack length when the microcrack first grows at the long-crack rate. Unfortunately, data documenting the growth of short cracks in Inconel 718 are sparse. In the absence of such data, estimates of the length of crack below which a short crack effect can be expected follow from the threshold and endurance characteristics of the material [2,3,13,14]. But published data for Inconel 718 documenting threshold crack growth behavior and fatigue endurance behavior for the fine-grained microstructure of interest in this study are also sparse. In the absence of such results, estimates of these variables can



FIGURE 1. SCHEMATIC DESCRIBING A DISCRIMINATING TEST OF CRACK CLOSURE EFFECTS BASED ON THE WAKE REMOVAL CONCEPT

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be made from very limited unpublished data made available by General Electric Co., Aircraft Engine Group, late in 1982. These estimates are plotted in Figure 2, reproduced from Reference 4. They indicate that aberrant growth trends based on LEFM will develop only at very small crack lengths. Depending on grain size, this figure indicates the short crack effect will be confined to semicrack lengths less than 0.25-0.5 mm at 540 C. Therefore wake removal experiments with the material used in this study require measurement of very short crack lengths.

Other factors also suggest that difficulties may be met in successfully determining the role of closure using the wake removal concept. First, it should be noted that, prior to wake removal, the closure forces are distributed over some crack face area. Removal of that wake may simply decrease this area thus increasing the closure stress, unless sufficient material is removed to cause compression yield over the crack region remaining in contact. Secondly and alternatively, if closure is confined to the near-tip region (say 25  $\mu$ m), then wake removal becomes practically impossible because short cracks are seldom straight within 25  $\mu$ m over their entire front. Thirdly, the scale of plasticity also has practical implications. The larger the plastic zone, the larger the region of closure. In order to keep the test conditions similar to the service conditions of interest (i.e., typical engine conditions), only stress levels representative of service were used in testing.

Two factors can be expected to help in conducting the wake removal experiments. The behavior of short cracks related to closure may be accentuated by the dominance of plane stress behavior (e.g., [10,15]). To this end, the study focused on thin sheet behavior. (However, difficulties are to be anticipated regarding the rotation of Mode I cracks from preflaws to stable Mode II cracks, as is often observed in thin sheets, e.g., [15-17].) Closure effects are also expected to be accentuated at low values of stress ratio, R. Given the range of behavior of concern in engines, the scope of the study embraced  $-1 \le R \le 0.1$ .



- Log Flaw Size, a
- a. schematic, after Staehle [12]
- FIGURE 2. BEHAVIOR OF STRESS AMPLITUDE AS A FUNCTION OF SEMICRACK SIZE

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b. results for Inconel 718 at 540 C, based on GE/AEG data

FIGURE 2. (Concluded)

### Test Plan Summary

The test plan and parameters of interest are set forth in Table 1. Thirty-three specimens have been employed to characterize the microcrack growth rate process embracing the effects of closure, initiation transients, notch stress fields, 3D crack geometry, stress level and R, net wake, and temperature. Cross correlation to isolate or emphasize these effects follows the plan laid out in Table 2 and includes useful results from completely successful tests on 18 specimens.

### Crack Tracking--Techniques and Practical Implications

Obtaining crack growth behavior for cracks *s*0.5 mm long (deep) requires tracking procedures other than typically used methods. ASTM standards require a minimum increment of crack growth between measurements of 0.25 mm or 10 times the crack length measurement precision, whichever is greater. The precision of the measurement techinque is defined as the standard deviation on the mean value of crack length determined for a set of replicate measurements. Obviously, the requirement of 0.25 mm growth cannot be satisfied. Therefore, the ASTM standard cannot be applied to the study of cracks of lengths of interest to the present study. But guidance can be taken from the requirement that the minimum increment be 10 times the standard deviation,  $\bar{\sigma}$ . Insight as to the required tracking scheme also follows from the desire to obtain multiple readings during the anticipated interval of the short crack behaviv Adopting a minimum increment of  $\Delta a = 50 \ \mu m$  meets this need and in turn counces a standard deviation (i.e., measurement precision) of 5 µm to meet the alternative ASTM requirement. (The effect of using  $1\overline{\sigma}$  or  $2\overline{\sigma}$  versus  $10\overline{\sigma}$  on the analysis of data for short cracks is examined later in this report.)

Study of available tracking schemes such as traveling microscope and KRAK gages indicates these may not provide the required precision. But more importantly--most provide only a voltage analog rather than a direct image. Data generated using a photographic technique developed in earlier studies

# SUMMARY OF TEST PARAMETERS (Center Cracked Panels) TABLE 1.

								:		
Svec imen	Temp. C	Freq. (Hz)	æ	Smx (MPa)	Smx (a)	r <sub>p/a</sub> (b)	Lrack Len Before Remov Side 1	gth, mm Wake Val Side 2	Average Net Wake, mm	Comments
cc-1	20		0.01	676	0.56	0.21				entire crack cut out in attempt to remove wake
cc-2	20	-1	0.01	676	0.56	0.21				film record of poor quality
CC-5	20	1	0.1	630	0.56	0.19				film record of poor quality
6-33	20	**	0.1	690	0.57	0.22				film record of poor quality
CC-7	20	1	0.01	690	0.57	0.22				non-cylindrical hole; corner cracks
CC-4	20	S	0.01	690	0.57	0.22				crack too long after precracking
6C-6	20	S	0.01	069	0.57	0.22				crack too long after precracking
6-JJ	20	S	10.0	690	0.57	0.22	0.434	0.465	0.076	
CC-10	20	S	0.01	820	0.68	0.31	0.381	0.363	0.041	
CC-11	20	ŝ	0.01	740	0.61	0.26	0.389	0.523	0.102	
CC-12	20	2	0.01	820	0.68	0.31	0.417	0.389	0.117	
CC-13	20	2	0.01	820	0.68	0.31	0.452	0.478	0.041	
CC-14	20	10	0.01	580	0.48	0.16	0.411	0.376	0.071	
CC-15	20	2	-1.0	522	0.43	0.13	0.579	0.566	0.061	
CC-17	643	S	0.01	820	0.84	0.23	2.957	2.27	:	gross section yielding; test abandoned
cc-3	643	ŝ	0.01	662	0.55	0.32	0.744	0.729	0.010	
CC-18	20	S	-1.0	524	0.43	0.13	0.457	0.478	0.058	
CC-19	20	5	-0.6	814	0.67	0.31	0.569	0.897	0.213	
(a) Flow str (b) Plane st	e_s v = (t ress value	ultimate e calcul	stress ated at	+ yield wake rem	stress)/2 oval.					

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$\frac{S_{mx}(1)}{r_{y}} r_{y/a}(2) x_{m}^{p}(c) x_{m}^{(c)} + \frac{Crack length c Ber}{Net Wake after Wa$	Static (MPG)         San(1) T $r_{p/a}(z)$ $\chi_{p}(c)$ $\chi_{p}(c)$ $r_{ayte arterNet Wayke arterNet Wayke arterSide 1         Crack length c BefNet Wayke arterSide 1         Crack length c BefNaterSide 1$	R $\frac{5_{mX}}{14}$ $\frac{5_{mX}}{1}$ \frac{5_{mX}}{1} <th>Freq. (142)         R         Sax(1) (3) (4)         <math>r_p/a(2)</math> <math>x_p(c)</math> (c) (14)         <math>r_{p/a}(1)</math> <math>r_p/a(2)</math> <math>r_{p/a}(c)</math> (crack lient rent (and line)         <math>r_{p/a}(1)</math> <math>r_{p/a}(2)</math> <math>r_{p/a}(c)</math> <math>r_{p/a}(c)</math></th> <th>AETERS (S) ore Wake Removal (mm) fre Cutting (mm) fre Cutting (mm) fre Cutting (mm) fre Cutting (mm) fre Cutting (mm)</th> <th>-validation tes strip yield mo</th> <th>-benchmark: i1 crack efect 5<del>25</del></th> <th>-ĉilm record '··· processing</th> <th>-film record `:: processing</th> <th>-film record ?::- processing</th> <th>-film record ':: processing</th> <th>-film record las- processing</th> <th>-film record less processing</th> <th>1.971 0.0 curner cracking <sup>4</sup> 1.041 0.0 crack 2</th> <th>0.0 0.0 *wire cut notch 0.0 0.0 than surface crait</th> <th>0.231 1.171 *wire cut notch 0.094 0.356 than surface cra:</th> <th>accidentially evented not complete</th> <th>0.391 0.074 0.081 0.036</th> <th>no wake remova</th> <th>no wake removal</th>	Freq. (142)         R         Sax(1) (3) (4) $r_p/a(2)$ $x_p(c)$ (c) (14) $r_{p/a}(1)$ $r_p/a(2)$ $r_{p/a}(c)$ (crack lient rent (and line) $r_{p/a}(1)$ $r_{p/a}(2)$ $r_{p/a}(c)$	AETERS (S) ore Wake Removal (mm) fre Cutting (mm) fre Cutting (mm) fre Cutting (mm) fre Cutting (mm) fre Cutting (mm)	-validation tes strip yield mo	-benchmark: i1 crack efect 5 <del>25</del>	-ĉilm record '··· processing	-film record `:: processing	-film record ?::- processing	-film record ':: processing	-film record las- processing	-film record less processing	1.971 0.0 curner cracking <sup>4</sup> 1.041 0.0 crack 2	0.0 0.0 *wire cut notch 0.0 0.0 than surface crait	0.231 1.171 *wire cut notch 0.094 0.356 than surface cra:	accidentially evented not complete	0.391 0.074 0.081 0.036	no wake remova	no wake removal
$\frac{5m\chi(1)}{\gamma} r_{p/a}(2) \chi_{p}(c) \chi_{m}(c) \frac{Crack lem}{Ret Watt}$ $\frac{5m\chi(1)}{r} r_{p/a}(2) \chi_{p}(c) \chi_{m}(c) \frac{Crack lem}{Ret Vatt}$ $0.44 1.41 2.0$ $0.24 0.31 0.0$ $0.40 0.85 0.46$ $0.40 0.85 0.46$ $0.40 0.85 0.46$ $0.38 0.73 0.20$ $0.40 0.85 0.46$ $0.40 0.85 0.46$ $0.40 0.85 0.46$ $0.40 0.85 0.46$ $0.40 0.85 0.46$ $0.00$ $0.40 0.85 0.46$ $0.00$ $0.40 0.85 0.46$ $0.00$ $0.40 0.85 0.46$ $0.00$ $0.40 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00$ $0.00 0.85 0.46$ $0.00 0.00 0.00 0.00$ $0.00 0.00 0.00 0.00 0.00$ $0.00 0.00 0.00 0.00 0.00$ $0.00 0.00 0.00 0.00 0.00 0.00$ $0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.0$		R         Smx(1) VHPa3         Smx(1) Fp/a(2)         Xp(c) Fm(c)         Crack Lenn Net Matic Teck Lenn Net Matic Frack I           0.01         186         0.44         1.41         2.0           -1.0         293         0.24         0.31         0.0           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46           0.01         352         0.38         0.73         0.20           0.10         352         0.36         0.46         0.032           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.30         0.160           -1.0         483         0.40         0.46         0.033           -1.0         483	Freq. (Hz)         R         Sax(1) V $r_{p/a}(z)$ Xp(c) red k lent Maxiv (mm)         Crack lent crack lent (mm)           0.5         0.01         186         0.44         1.41         2.0           1.0         -1.0         293         0.24         0.31         0.0           1.1.0         -1.0         293         0.40         0.85         0.46           1.1.5         -1.0         483         0.40         0.85         0.46           0.5         -1.0         483         0.40         0.85         0.46           0.5         -1.0         483         0.40         0.85         0.46           2/.5         -1.0         483         0.40         0.85         0.46           0.33         0.01         352         0.38         0.73         0.20           0.33         0.01         352         0.36         0.46         0.102           1.0         -1.0         483         0.40         0.85         0.46         0.102           1.0         -1.0         483         0.40         0.85         0.46         0.103           1.0         -1.0         483         0.40         0.85         0.46	PARAM Pane Pane ath c Bef after 4 Crack 2									0.0	0.411 0.142	0.871 *		0.104 0.069		
$\begin{array}{llllllllllllllllllllllllllllllllllll$	Sax, (1) (MPa)         Sax, (1) Tp/a(2)         Xp, (c) (mm)           186         0.44         1.41         2.0           293         0.24         0.31         0.0           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           483         0.40         0.85         0.46           48	R $\frac{\sqrt{3}}{\sqrt{4}}$ $\frac{\sqrt{3}}{\sqrt{4}}$ $\frac{\sqrt{3}}{\sqrt{4}}$ $\frac{\sqrt{3}}{\sqrt{4}}$ $\frac{\sqrt{3}}{\sqrt{4}}$ $\frac{\sqrt{3}}{\sqrt{4}}$ 0.01         186         0.44         1.41         2.0           -1.0         293         0.24         0.31         0.0           -1.0         293         0.24         0.31         0.0           -1.0         293         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46           0.01         352         0.38         0.73         0.20           0.10         352         0.38         0.746         0.46           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46           -1.0         483         0.40         0.85         0.46	Freq. (Hz)R $\frac{S_{mx}(1)}{(M_m^3)}$ $\frac{S_{mx}(1)}{T}$ $\frac{S_{mx}(1)}{T_p/a}(2)$ $\frac{N_p(c)}{(mn)}$ 0.50.011860.441.412.01.0-1.02930.240.310.01.1.1-1.02930.400.850.461.1.2-1.04830.400.850.461.1.5-1.04830.400.850.460.5-1.04830.400.850.462/.5-1.04830.400.850.462/.5-1.04830.400.850.461.0-1.03520.380.730.201.0-1.04830.400.850.461.0-1.04830.400.850.461.0-1.04830.400.850.461.0-1.04830.400.850.461.0-1.04830.400.850.461.0-1.04830.400.850.461.0-1.04830.400.850.461.0-1.04830.400.850.461.0-1.04830.400.850.461.0-1.04830.400.850.461.0-1.04830.400.850.461.0-1.04830.400.850.461.0-1.03100.260.350.46 <t< td=""><td>Notched Crack Lenc Net Wake Crack 1</br></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>1.039 0.102</td><td>0.032</td><td>0.160 *</td><td></td><td>0.373 0.058</td><td></td><td></td></t<>	Notched Crack Lenc Net Wake 									1.039 0.102	0.032	0.160 *		0.373 0.058		
Snx(1)     rp/a(2)       0.44     1.41       0.44     1.41       0.24     0.31       0.40     0.85       0.40     0.35	Smx (1) μ(μ)         Smx (1) γ         r <sub>p</sub> /a(2)           186         0.44         1.41           293         0.24         0.31           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           483         0.40         0.85           310         3.26         0.35	R         Smx (1) Y         rp/a(2)           0.01         186         0.44         1.41           -1.0         293         0.24         0.31           -1.0         483         0.40         0.85           -1.0         483         0.40         0.85           -1.0         483         0.40         0.85           -1.0         483         0.40         0.85           -1.0         483         0.40         0.85           -1.0         483         0.40         0.85           -1.0         483         0.40         0.85           -1.0         352         0.38         0.73           0.01         352         0.38         0.73           0.10         352         0.38         0.73           -1.0         483         0.40         0.85           -1.0         483         0.40         0.85           -1.0         483         0.40         0.85           -1.0         483         0.40         0.85           -1.0         483         0.40         0.85           -1.0         310         326         0.35           -1.0         310<	Fred.         R         Smx(1) Y         Fp/a(2)           (HZ)         R         Smx(1) Y         Fp/a(2)           0.5         0.01         186         0.44         1.41           1.0         -1.0         293         0.24         0.31           1.0         -1.0         483         0.40         0.85           1.1.5         -1.0         483         0.40         0.85           0.5         -1.0         483         0.40         0.85           0.33         0.01         362         0.38         0.73           0.33         0.01         362         0.38         0.73           0.33         0.01         352         0.38         0.73           1.0         -1.0         483         0.40         0.85           1.0         -1.0         483         0.40         0.85           1.0         -1.0         483         0.40         0.85           1.0         -1.0         483         0.40         0.85           1.0         -1.0         483         0.40         0.85           1.0         -1.0         483         0.40         0.85           1.0	(center x <sub>(mm)</sub>	2.0	0.0	0.46	0.46	0.46	0.46	0.20	0.20	0.46	0.46	0.46	0.46	0.46	0.0	0.0
Sax(1) 5ax(1) 0.44 0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.40 0.26 0.26	Smx (MPa)     Smx(1) Y       186     0.44       186     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.40       483     0.26       310     0.26       310     0.26	R         Sax(1) MPa)         Sax(1) Sax(1)           0.01         186         0.44           -1.0         293         0.24           -1.0         483         0.40           -1.0         483         0.40           -1.0         483         0.40           -1.0         483         0.40           -1.0         483         0.40           -1.0         352         0.38           0.01         352         0.38           0.01         352         0.40           -1.0         483         0.40           -1.0         483         0.40           -1.0         483         0.40           -1.0         483         0.40           -1.0         483         0.40           -1.0         483         0.40           -1.0         483         0.40           -1.0         483         0.40           -1.0         483         0.40           -1.0         310         326           -1.0         310         326           -1.0         310         326	Fred.         R         Sax(1) (HZ)         R         Sax(1) (MPA3)         Sax(1) (HZ)           0.55         0.01         186         0.44           1.0         -1.0         293         0.24           1/.5         -1.0         483         0.40           1/.5         -1.0         483         0.40           0.5         -1.0         483         0.40           0.5         -1.0         483         0.40           2/.5         -1.0         483         0.40           1.0         -1.0         483         0.40           0.33         0.01         352         0.38           1.0         -1.0         483         0.40           1.0         -1.0         483         0.40           1.0         -1.0         483         0.40           1.0         -1.0         483         0.40           1.0         -1.0         483         0.40           1.0         -1.0         483         0.40           1.0         -1.0         483         0.40           1.0         -1.0         483         0.40           1.0         -1.0         483	r <sub>p</sub> /a(2)	1.41	0.31	0.85	0.85	0.85	0.85	0.73	0.73	0.85	0.85	0.85	0.85	0.85	0.35	0.21
	C C C C C C C C C C C C C C C C C C C	R (MPa) R (MPa) -1.0 186 -1.0 293 -1.0 483 -1.0 231 231 -1.0 231 -1.0 231 -1.0 231 -1.0 231 -1.0 232 -1.0 232 -1.	Freq.         R         Same           (HZ)         R         Same           (HZ)         R         Same           0.5         0.01         186           1.0         -1.0         293           1/.5         -1.0         483           0.5         -1.0         483           0.5         -1.0         483           0.5         -1.0         483           0.33         0.01         362           0.33         0.01         362           1.0         -1.0         483           1.0         -1.0         483           1.0         -1.0         483           1.0         -1.0         483           1.0         -1.0         483           1.0         -1.0         483           1.0         -1.0         483           1.0         -1.0         483           1.0         -1.0         483           1.0         -1.0         483           1.0         -1.0         483           1.0         -1.0         483           1.0         -1.0         483           1.0         -1.0	$\frac{S_{mx}(1)}{\gamma}$	0.44	0.24	0.40	0.40	0.40	0.40	0.38	0.38	0*0	0.40	0.40	0.40	0.40	0.26	0.2
Temp.         Freq. (Hz)         R           Z0         0.5         0.01           20         0.5         0.01           20         1.0         -1.0           20         1/.5         -1.0           20         1/.5         -1.0           20         0.5         -1.0           20         0.5         -1.0           20         0.5         -1.0           20         0.5         -1.0           20         0.33         0.01           643         0.33         0.01           20         1.0         -1.0           20         1.0         -1.0           20         1.0         -1.0           20         1.0         -1.0           20         1.0         -1.0           20         1.0         -1.0           20         1.0         -1.0           20         1.0         -1.0           20         1.0         -1.0           20         1.0         -1.0           20         1.0         -1.0           20         2.0         1.0         -1.0           20         2.	Temp. Freq. C (Hz) C (Hz) 20 0.5 20 1.0 20 1/.5 20 1/.5 643 0.33 643 0.33 643 0.33 643 0.33 20 1.0 20 1.0 20 1.0 20 1.0 20 2.0 20 2.0	Temp., C C 20 20 20 20 20 20 20 20 20 20 20 20 20 2		pec imen	2024 T351 A1	СН-2	СН-10	СН-14	СН-9	CH-15	CH-8	СН-12	СН-1	СН-16	CH-4	СН-5	СН-3	CH-20	СН-6

# TABLE 2. COMPARISONS USED TO ISOLATE OR EMPHASIZE SPECIFIC PARAMETERS

Parameter	Specimens to be Compared
Unnotched	l Specimens (intended initial K <sub>max</sub> = 193 MPa/m)
● net wake	CC12 (long) vs. CC10 (short)
• stress level	CC13 (high) vs. CC11 (mod.) vs. CC9 (modlow) vs. CC14 (low)
• stress ratio .	CC19 (R=6) vs. CC12 (R=.01) vs. CC15, CC18 (R=-1)
• temperature	CC3 (643 C) vs. CC12 (20 C)
	Notched Specimens
short cracks	CH2, preliminary test - does the material show a short crack effect
<ul> <li>initiation transients, corner vs. plane fronted cracking</li> </ul>	CH1, CH16 (natural, corner) vs. CH3, CH4 (preflawed)
● stress level	CH3, CH4 (high) vs. CH2O (mod.) vs. CH6 (low)
<pre>• notch field</pre>	CH3, CH4, CH2O, CH6 (notched) vs. CC15, CC18 (unnotched)
• temperature	CH3 (643 C) vs. CH2O (20 C)

[18] indicated that precisions on the order of that required could be achieved. And, a photographic procedure would develop a permanent record of the crack (at least as it appears on the surface). Refinement of the photographic technique via increased magnification and changes in triggering the shutter produced precisions on the order of 5  $\mu$ m as summarized in Appendix D. Because the permanent record and the precision of the photographic technique suited the needs of this study, it was adopted with adaptations of the scheme used in Reference 18, as follows.

As is shown in Figure 3, the photographic method of crack tracking used standard 35 mm single lens reflex (SLR) cameras to monitor surface crack tips on both faces of the specimen. To maximize the region of the specimen inspected without too much loss of detail, the film record was made at about five times magnification at the film plane. Subsequent interpretation was performed at an additional 16 times magnification or more, a factor of two greater than used previously. The triggering was also changed. The prior study used peak load to trigger the shutter and flash. However, it was found that the camera's internal shutter triggering systems were not uniform enough to consistently catch the crack at maximum load when it is most open and the crack tip could most easily be located. This introduced scatter into the measurements. For this reason, shutters were triggered early in the rising portion of selected cycles. The film record was made by triggering flash units, mounted to produce incident (glare) lighting across the crack, at the peak load in that cycle. Counter devices were developed to trigger film advance, shutter, and flash at preset intervals.

The cameras were equipped with 250-exposure film backs. This was done to minimize changing rolls of film. Such long rolls of film required special processing, including drying in a warm forced air dryer built specially for these long rolls.

Although this crack tracking technique was desirable for the present study, the tremendous amount of film generated during testing was formidable. The main objective of the experiments involving wake removal was to record the crack growth just after initiation and again just before and after wake removal. Because the number of cycles to crack initiation could only be



6057-2

a. overview



6049-2

b. closeup

FIGURE 3. THE EXPERIMENTAL SETUP FOR CRACK TRACKING USING THE PHOTOGRAPHIC TECHNIQUE (AS USED AT 643 C)

estimated, much film was expended before it occurred. The period of crack growth over which elevated growth rates could be seen was expected to be small. This necessitated allowing a small number of cycles between photographs. Generally 1000-2000 exposures were taken per test. Fortunately, much of this film did not need to be reduced. It was only used to verify that a crack had not initiated.

At the beginning and end of each roll of film, pictures were taken of labels giving the specimen number, which camera, and the current number of cycles. This was essential in keeping track of all the film through processing and data reduction. A picture was also taken of a scale object. Because resolution is lost when the film is projected during crack measuring, a rule with scribed lines did not work. The end of a narrow strip of thin plastic was eventually found to work well. The distance between the corners was measured carefully using a microscope and micrometer-driven specimen table.

The processing of so much film would be prohibitive if prints were made of each frame. Instead, the negatives were projected onto a large (4' x 5') digitizing table using a standard film strip projector. The positions of the crack tips were entered by means of a cursor equipped with crosshairs; cartesian coordinates of the points were tored on magnetic tape. The scales of the reference axes were entered using measurements on the scale at the ends of each roll. Points giving crack tip positions were paired with their respective cycle counts by entering them on the magnetic tape when digitizing each point. A simple computer program translated the digitized data into crack lengths.

Projection greatly increased the magnification, but it also decreased the picture resolution somewhat. Small errors in focusing at 5X magnification were multiplied in the process. Thus, careful camera setup was essential.

Various flash unit arrangements were tried. It was found that the positioning of the flash units was very important. The most effective setup used one unit on each side of the specimen as shown in Figure 3.

Appendix D presents a study of the accuracy and precision of this measurement and data analysis procedure.

### Material and Specimens

The Inconel 718 material used in this investigation was 0.093 inch thick sheet with the following chemistry (in weight percent):

С	Mn	Ρ	S	Si	Cr	Cb/Ta	Cu
0.04	0.07	0.012	0.006	0.13	18.42	5.14	0.03
Mo	Fe	Со	Ti	A1	В	Ni	
3.07	18.14	0.3	1.06	0.48	0.004	bal.	

The as-received material was cut into specimen blanks and then heat treated in batches of 10 using a duplex heat treatment including:

Anneal in vacuum 954 C/Air Quench Heat 704 C/8 hours to 621 C/8 hours then air cool.

The heat-treated material exhibited a fine grain size (ASTM 10 to 10.6), as evident in Figure 4, a microstructure typical of this alloy for the indicated heat treatment. Metallographic study did not disclose any significant alloy depletion or any other undesirable surface condition as a result of any of these treatments. Grains were uniform, and there were no significant microstructural features on the order of the upper bound crack size associated with the short crack effect expected in view of Figure 2.

The grain size of this material is about 10  $\mu$ m. Thus, on the average, increments of crack advance measured on the surface separated by less than 5  $\mu$ m will represent growth steps within surface grains. However, the crack tip observed on the surface is tied to a subsurface front that on the average crosses about 225 grains. Therefore, while on the surface the crack tip may be tied up by grain and subgrain features, this tip will be dragged along by the subsurface crack front.



(Etch: 97 HCl, 3 HNO3 with  $\frac{1}{2}$  gm CuCl)





(Etch: 42 Glycol, 29 Hcl, 29 HNO<sub>3</sub>)

FIGURE 4. PHOTOMICROGRAPHS OF MICROSTRUCTURE TYPICAL OF THE MATERIAL INVESTIGATED

The material used in this study had room temperature mechanical properties as follows:

Ultimate tensile stress 1378.7 MPa 0.2 percent offset yield 1027.3 MPa 21.4 percent elongation, and a modulus of 194.6 GPa.

These properties were obtained from a single 5.1-cm-gage-length sheet, tensile coupon tested at 20 C at a displacement rate of 0.063 mm sec<sup>-1</sup>. The average hardness was measured to be about  $R_c42$ .

Two types of specimens have been used in this investigation. In both, the long axis of the specimen was aligned with the rolling direction of the sheet. For the study of microcrack closure, a center-crack panel (CCP) was used because (1) the stress field is symmetric and the K solution simple, and (2) both active surface crack tips on one side of the sample could be tracked with a single camera. Local access to numerically controlled EDM machining facilities meant suitable preflaws could be developed within the range of sizes anticipated to produce the short crack effect (see Figure 1). The specific CCP geometry used is shown in Figure 5(a). The remainder of the study has made use of the center-hole-notched panel (CNP) shown in Figure 5(b). A notched geometry was selected to achieve the program's plan to examine microcrack growth through notch fields. A center circular notch is preferred over other notch configurations because holes are commonly found in engine components. It is also preferred because a center notch facilitates tracking four surface cracks through the use of dioptric lenses which cut out the center of the camera's field of view to bring diametrically opposite cracks together; then they could be photographed at one time by the same camera.

### Apparatus and Procedure

All tests were performed in a commercially available servocontrolled test system under axial load control using a sinusoidal forcing





FIGURE 5. DETAILS OF THE CCP AND THE CNP SAMPLES USED

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č,

function. The load was measured via a load cell mounted in series with the specimen. The load cell was calibrated prior to the testing program to within  $\pm 1$  percent accuracy.

The camera system used was built using commercially available optics and flash units, adapted to present focal length and magnification requirements. (During the program, several unusual failures occurred in the photographic equipment because they were rapidly subjected to several lifetimes of service.) Shutter and flash triggering electronics were designed and built to match requirements of this and other similar studies. Cameras were mounted on X-Y slide translation mechanisms attached to the test frame to permit coarse focus and to center the camera with respect to the line of crack extension assuming symmetric growth.

Setup of each experiment involved the usual specimen installation and setting of the command function. Prior to testing, the anticipated area of crack advance was polished on each specimen with successively finer grades of paper and polishing compound, in some cases down to 0.5  $\mu$  diamond paste. (While this developed a near mirror image, the roughness of the surface and the presence of localized microstructural perturbations left randomly distributed dark spots on the otherwise polished surface.) Cycle interval and initial delay for the cameras were then programmed and the test initiated. For tests involving wake removal, crack position was monitored and growth was permitted until a preset increment of crack advance occurred. Judging the time to stop the test was often difficult. The surface crack tips were often at varying lengths. Thereafter specimens were removed and the surface crack lengths were measured at about 35X magnification using an optical microscope and a micrometer-driven translating specimen table. Decisions as to the amount of wake removal were then made based on the nature of the cracks and purpose of the test. Wake was removed using a numerically controlled wire cutting machine equipped with 50 µm wire. Specimens were then reinstalled in the loading frame and testing resumed. Experiments not involving wake removal followed this same procedure, except that the specimen was not removed for wake removal prior to separation.

Numerically controlled electrical discharge wire cutting was the key to using the wake removal concept. It was found that conventional electrical discharge machining was not sufficiently controllable to cut out a preexisting crack while leaving the tips untouched. Generally, the wire cutting process could be controlled as closely as  $\pm$  25-50 µm during wake removal. This is remarkable, given that the machinist had to relocate the starter notch and then remove a crack he could not see. Still, some risk was involved in wirecutting each specimen. The desired results were not always obtained. Perhaps the main complicating factors were the irregularities of the crack front, especially when the crack twisted through the thickness of the plate, and relating the crack measurements to a reference location on the specimen. A reference hole was EDMed near the grip area of each specimen. Using this, the orientation of the specimen could be determined very accurately.

10.50 S
#### DATA REDUCTION

### Nomenclature

The raw data generated in this study consist of surface crack length and the corresponding number of cycles, N, for a given crackt. For each specimen containing preflaws, as many as four crack tips may be active. However, for natural initiation, multiple cracks have been found to be active at a site anticipated to generate one crack. In these cases, many more than four crack tips could be active<sup>\*</sup>. For the sake of crack identification, each crack is labeled as follows: specimen number, specimen face, crack location, as detailed in Figure 6. CCP specimens are prefixed with CC while the CNP specimens are prefixed with CH. As an example, consider the crack identified as CH6, crack 1,2. The specimen number is CH6. The crack is located at the left-hand notch root, designated as 2, with respect to the front face, designated 1. Discussion of this crack in comparison to others in CH6 would refer to crack 1,2.

## Editing Procedure\*\*

Several factors made editing of the raw crack growth data necessary. The automatic measurement system used did not allow decisions to be made about the admissibility of each reading as the test was in progress. Therefore, such decisions had to be made after the complete crack length versus cycles record was produced. "Admissible" in this study means meeting the criterion

+ Raw data are tabulated in Appendix E.

<sup>\*</sup> In all but one case in which multiple initiations were observed, the crack growth data reported here is for the crack which eventually grew until specimen separation. Data for one crack which did not grow to cause failure is reported for specimen CH6.

<sup>\*\*</sup> Comments here apply to surface crack length measurements made for both CCP and CNP samples, although the nomenclature relates specifically to the CNP geometry.



Crack 1 is on the front face Crack 2 is on the rear face All cracks symmetric, to within a few percent

(a) CCP sample, denoted CC



(b) CNP sample, denoted CH

FIGURE 6. ILLUSTRATION OF SPECIMEN NUMBERING SCHEME AND CRACK NOMENCLATURE

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explained below. The purpose of this criterion is to ensure that the increment in crack extension between successive readings was greater than the precision of the measurement system used--enough so that unreasonable scatter would not present a problem. As described below, a criterion based on a multiple of the standard deviation in repeat measurements,  $\sigma$ , was chosen. As mentioned in a previous section, the ASTM standard requires a minimum crack growth increment of 0.25 mm or 10  $\sigma$ , whichever is larger. Guidance was taken from the second requirement. Still, because the editing criterion might have an effect on the data trends, a study was made on its effect.

To establish a reasonable value of  $\Delta c$  between successive readings, results from several specimens were edited using  $\Delta c = 1 \ \overline{\sigma}, 2 \ \overline{\sigma}$ , and  $10 \ \overline{\sigma}$ . Very little difference was observed in the resulting data trends for unedited data and the results for edits using  $\Delta c = 1 \ \overline{\sigma}, 2 \ \overline{\sigma}$ . But, in cases where data trends showed changing slopes on the c-N plots for small values of c, editing using  $\Delta c = 10 \ \overline{\sigma}$  significantly altered these trends. This is, of course, to be expected because such large values of  $\Delta c$  effectively skip the region of the short crack effect. Given the results of this survey,  $\Delta c = 2 \ \overline{\sigma}$  has been chosen as the standard editing increment. In all cases, editing began after the first data point. Comparison of different choices for  $\Delta c$  between readings is given in the next section as we consider calculation of crack growth rates.

## Evaluation of dc/dN\*\*

It remains to decide upon analysis procedures to translate raw c-N data into a format that admits comparison of data for long and short cracks and other stress levels and specimen geometries. To this end, dc/dN must be calculated as a function of the stress intensity factor, K.

Calculating the crack growth rate dc/dN is complicated by the nature of the short crack problem. Because dc/dN may vary significantly for only small changes in N, values of dc/dN for prior or successive cycles may bias the computed "average" value found in smoothing procedures. On the other

\*\*Ibid.

hand, simple slope calculations may lead to excessive scatter. With these considerations in mind, dc/dN has been calculated for a range of results using unedited data and data edited using  $A_{\rm C} = 1$   $\overline{\sigma}$  and 10  $\overline{\sigma}$ .

Results of one comparative study are presented in Figure 7, for the case of a plate with a central hole and plastic behavior at the notch root. Note from Figure 7(a) that simple slope analysis (SSA) for unedited data and data edited at  $\Delta c = 1 \overline{\sigma}$  produce comparable trends showing a large amount of scatter. The only difference between results edited at  $\Delta c = 1 \sigma$  and the unedited data is a reduction in scatter for smaller lengths. However, if  $\Delta c =$ 10  $\overline{\sigma}$  is used, the editing eliminated most of the detail for short crack lengths. Unedited results for a three-point-divided difference analysis (3PDDA)\* show essentially the same trend as observed for the corresponding simple slope calculation of dc/dN. Using 3PDDA, results for  $\Delta c = 1 \overline{\sigma}$  show a decreasing then increasing trend--i.e., an apparent "short crack effect". But when edited at  $\Delta c = 10 \ \overline{\sigma}$ , the initial slightly decreasing trend for SSA is now moderated to an increasing tendency by 3PDDA, as shown in Figure 7(b). When dc/dN is calculated using a seven-point incremental polynomial analysis (7PIPA)<sup>+</sup>, the unedited data and data edited at  $\Delta c = 1 \overline{\sigma}$  show an increasing, then decreasing, then increasing tendency, as shown in Figure 7(c). With still further smoothing of the data by editing at  $\Delta c = 10 \overline{\sigma}$ , this aberrant growth rate trend disappears.

The example trends presented in Figure 7 and other similar results show that the growth rate calculation procedure can accentuate or camouflage possible short crack effects. Experience with this analysis and the analyses of other short crack data suggests that SSA introduces the least analysis bias but is prone to high scatter. On the other hand, 7PIPA tends to reduce

\* The three-point-divided difference is a weighted average of crack growth rates:

$$\left(\frac{dc}{dN_{i}}\right) = \left(\frac{c_{i} - c_{i-1}}{N_{i} - N_{i-1}}\right) + \left(\frac{N_{i} - N_{i-1}}{N_{i+1} - N_{i-1}}\right) \left[\left(\frac{c_{i+1} - c_{i}}{N_{i+1} - N_{i}}\right) - \left(\frac{c_{i} - c_{i-1}}{N_{i} - N_{i-1}}\right)\right]$$

+This analysis is explained in ASTM Standard E647.



a. simple slope analysis





b. three-point-divided difference analysis

FIGURE 7. (Continued)



K

c. seven-point incremental polynomial

FIGURE 7. (Concluded)

SSA scatter but in so doing may smooth out what are real short crack effects. The 3PDDA lies between the extremes of SSA and 7PIPA and suffers (to a lesser extent) the same drawbacks of these extremes. But it provides a middle ground--more scatter (less smoothing) than 7PIPA (vice versa for SSA)--and thus seems best suited for present purposes. For this reason, the 3PDDA is used to calculate dc/dN throughout the remainder of this report, except for the long crack reference data, for which the 7PIPA was used.

## Stress Intensity Factor Solutions

Consider now measures of the driving force for cracking. Portions of this study have addressed analyses of the crack driving force when the crack tip plastic zone is large compared to the crack length. As alluded to in Appendix C and discussed in detail in References 9 and 19, this situation can be dealt with using  $\Delta$ CTOD calculated via pseudoplastic strip yield models (e.g., [20]) or elastic-plastic numerical analysis. For other situations where the plasticity is confined, LEFM is appropriate. However, the finite size of test specimens and the development of local biaxial stress states and corner cracking precludes the use of the simpler and therefore more popular stress intensity factor (K) solutions.

## Through Cracks

The K solution for the CCP (Figure 5(a)) of finite width, W, containing through cracks, subjected to axial tension with Mode I cracking used in this study is represented by the result for the infinite plate,

$$K = S \sqrt{\pi a} , \qquad (1)$$

where S is the far field stress and a is the surface semicrack length. The influence of the edge of the plate is provided in this study by the secant correction, so that

$$K = S \sqrt{\pi a} \quad \sec \frac{\pi a}{W} \quad . \tag{1a}$$

The K solution for the finite width CNP (Figure 5(b) with symmetric through cracks of length c has a comparable form to that for the CCP

$$K = S\sqrt{\pi c} F(\frac{C}{W}) , \qquad (2)$$

where c is the surface length of the crack measured from the edge of the notch.

Values of F(c/W) must include the influence of the notch root free surface, the notch gradient, and the finite width of the specimen. For physically very small cracks,  $\tilde{K}$  is reasonably approximated by

$$K = 1.12 K_{+} S_{N} \sqrt{\pi c}$$
 (2a)

Here  $K_t$  is the net section stress concentration factor, equal to the ratio of the maximum principal stress, denoted as  $\sigma$ , to the net section stress denoted as  $S_N$ .  $S_N$  is related to S by the ratio of far field (gross) section area. A, to net section area,  $A_N$ :

$$S_{N} = S(A/A_{N}) = S(W/(W-2r)) , \qquad (3)$$

and r denotes the radius of the hole.

For two physically short cracks in notched plates, if the  $K_{t's}$  are the same and the gradient in  $\sigma$  as a function of distance across each plate is geometrically similar, K will provide similitude in the crack driving force for the same degree of through thickness constraint (same t/2r). In the absence of the same constraint, K will not provide similitude based on numerical results generated for cracks in the absence of the notch gradient [21], for values of c measured on the plate's surface. Likewise, if the diameter of the hole is the same but the width varies, Equation (2a) indicates K will not provide similitude unless (F(c/W)) is geometry specific. That is, solutions for K (F(c/W)) that represent the geometry in Figure 5(b) are required. A number of different forms of F(c/W) have been considered for present purposes. Included are numerical solutions for similar geometries, solutions adapted to the geometry considered (e.g., [22-25]), and others (as outlined in Appendix B).

Because the interest here is in short cracks and Equation (2a) is exact in the limit as  $c \rightarrow 0$ , the suitability of the various functions F(c/W) have been judged by comparing them to the trend for Equation (2a) for crack sizes 25  $\mu$ m  $\leq c \leq 490 \mu$ m. These bounds are the limits of the validity and accuracy of Equation (2a) as developed in Appendix F. They have been chosen with regard to matching the peak stress and the stress gradient in the K solution adapted to that in the CNP of Figure 5(b). The upper bound has been chosen by consideration of related work done by Schijve [26], Novack and Barsom [27], Smith and Miller [28], Broek [29], Karlsson and Backlund [30], and others who developed analysis for or discussed control of the notch field on the crack driving force via LEFM analyses. Results catalogued by Tada, et al [25] have also been considered.

Note that, within the noted crack lengths, Equation (2a) estimates K within 5 percent (at  $c = 490 \mu m$ ). (Also, redistribution due to cracking is ignored.) Thus, it is expected that the optimum F(c/W) should match that for Equation (2a) at  $c = 490 \mu m$  within about 5 percent. Of the solutions considered, several do not approach the anticipated result as  $c \rightarrow 0$ . That of Newman [24] developed numerically for an almost identical plan form comes closest to the anticipated limit. It also matches closely the solution discussed by Karlsson and Backlund [30] which is similar to Equation (2a), but valid for somewhat longer cracks (see Appendix F). Therefore, this function, which is plotted in Figure 8, will be used in subsequent analysis of the CNP for symmetric cracking. Correction for asymmetric cracking follows from factors developed for infinite plates normalized with respect to crack length for the approximate degree of asymmetry developed. Such corrections are discussed in the work of Newman [31].

### Part Through Cracks

The K solutions discussed above are valid only for through cracks. If surface or corner cracks develop, the solutions must be modified to account



FIGURE 8. STRESS INTENSITY FACTOR SOLUTION ADOPTED FOR CNP SPECIMENS [24]

for the 3D effects of crack shape for both CCP and CNP--Equations (1) and (2)--and for the biaxial, through-thickness stress that develops as a function of t/2r in the CNP--Equation (2).

A number of stress intensity factor solutions now exist for part through cracks. Several good reviews present or compare these solutions (e.g., [31-35]. There is little agreement in the available solutions; this is illustrated, for example, by the wide range of solutions for surface cracks in Figure 9(a). The analyst has a broad range of K values to choose from for a given crack size and aspect ratio. Given the spread of K solutions available and no clear-cut basis by which to choose the correct result, uncertainty in the reduction of growth-rate data is almost unavoidable for physically short cracks that have not started the transition to through thickness. Once the through thickness transition begins, the choice of K and its implementation becomes even more complex because actual crack shapes are not always "part elliptical". However, once the transition is complete and a steady-state crack configuration develops, the uncertainty in K disappears in the absence of other factors.\* Crack growth trends, by definition, follow long-crack trends associated with through-thickness cracks, once a steady-state through crack develops.

There are many analyses of the corresponding problem for various cracked CNP specimens. These solutions range from somewhat general empirical equations to geometry specific trends generated via 3D finite element analyses. A broad range of K/S values are observed for quarter circular cracks, the extent to which is shown, for example, in Figure 9(b), reproduced from [36]. True 3D solutions (stress field and crack configuration) also exhibit a t/2r dependence. These trends are apparent in results presented in detailed summaries and reviews of 3D K solutions (e.g., [31-35,37]).

<sup>\*</sup> One complicating factor is the transition to a tongue-shaped long crack such as is typically observed in thin sheet prior to the transition from Mode I to stable Mode II cracking (e.g., 16, 65). The influence of the tongue shape and the ensuing Mode II growth has been ignored in the present study because their analysis is complex--and, more importantly, their influence on fatigue growth rates is small in an absolute sense (based on observations in an aluminum alloy [65]).



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(c) Predicted stress intensity (with respect to surface crack) normalized by the Bowie solution for an infinite plate of finite thickness with D/t = 1, after [37]

FIGURE 9. (CONCLUDED)

Newman [37] has compared results of numerical 3D solutions (near the hole) for otherwise infinite plates to the Bowie [38] result\*. Examination of this comparison reproduced in Figure 9(c) shows that the 3D value of K/S, for the same surface crack length, is less than that for a through crack the extent to which strongly depends on the aspect ratio, a/c. Values of a/c > 1 are of interest for the present analysis. In this case, Figure 9(c) indicates K<sub>3D</sub> (the 3D value of K) is bounded above by the through-crack value and below by about 0.7K, depending on a/t. Results considered in the process of the survey reported in Appendix B also showed that K<sub>3D</sub> is less than the corresponding through-crack value. In view of Figure 9(c) and the general trends in the literature, the driving force for growth of physically small cracks is reduced by as much as 30 percent (i.e., to about 0.7K) in the presence of circular corner cracks. As the crack propagates across the thickness, the aspect ratio tends toward a plane-fronted through crack, and the surface length increases so that K<sub>3D</sub> + K as evident in Figure 9(c).

It is apparent that 3D effects reduce the driving force for crack growth on the surface at crack sizes small as compared to the diameter of the hole. Further, they act to counter any short-crack effects that tend to increase growth rate. For typical crack-growth rate behavior, this could increase the apparent threshold K by as much as 30 percent (in the absence of correctly computed 3D values of K). These same considerations taken in the finite life regime indicate 3D crack-shape effects can suppress growth rates tracked on the surface by more than an order of magnitude. Likewise, during the formation of small cracks at near threshold stress intensity levels, the reduction in dc/dN due to 3D crack-shape effects may be significant. But once growing at finite rates, 3D crack-shape effect diminishes as the crack gets longer, and (in view of Figure 9(b)) disappear after break-through on the second face. Fortunately, for the most part, this study has used through preflawed CNP specimens and, as evident in Figure 10, these preflaws grew as

<sup>\*</sup> Tweed and Rooke [39] have been quite critical of the accuracy of the Bowie solution. Nevertheless, it remains popular (e.g., [35,37]) and is widely used in comparing results for infinite plates.



(a) Overview at low magnification (2X)



(b) Detail of the region in part (a), near the origin (10X;20X)

FIGURE 10. MACROFRACTOGRAPHIC VIEWS OF CRACK FRONTS IN PREFLAWED CNP SAMPLES

plane-fronted short cracks. Where corner cracks developed, the results presented in Figure 9(c) have been used to modify K/S in Figure 8, in accordance with the aspect ratios observed until transition. Thereafter, Equation (2) (Figure 8) has been used.

It should be noted that the K solution only embodies part of the mechanics of the 3D situation. However, it is established that crack growth rate also depends on stress state (e.g., [8]). Analysis performed to assess the significance of this aspect is alluded to in Appendix A and leads to the results reproduced in Figure 11. For the CNP geometry examined, the value of t/2r is 0.18. Three-dimensional elasticity analysis [40] indicates the local biaxiality ratio  $\mu \equiv \sigma_2/\sigma_1$ , corresponding to t/2r = 0.18, is  $\mu \doteq 0.012$ , for Poisson's ratio of 0.3. For fatigue crack initiation, the literature [7] indicates the influence of local biaxiality is significant. For the CNP used in this investigation, the literature suggests that local biaxiality results in a slightly decreased life to develop small cracks and indicates there is a preference to form corner cracks in the absence of artificial preflaws. Figure 11 indicates that the limited local biaxiality developed in the CNP used ( $\mu = 0.012$ ) causes an almost negligible decrease (<2%) in growth rate over the entire range of stress levels imposed in this study.

Consequently, when the preflawed samples tested in this study develop through plane-fronted cracks, it is concluded that the 3D stress state effect of the notch does not contribut to the observed growth rate behavior. Likewise, it can be concluded that no \_h induced stress state effects do not affect the growth rate of corner crach, as compared to that observed in the usual long crack uniaxial geometries, beyond the effect already embedded in K as function of crack geometry.

#### <u>Results</u>

Thirty-three crack growth specimens were tested in this study, as listed in Table 1. Results from several of these specimens have been used to develop a long-crack reference data base for this study. Specifically, raw data have been analyzed using the 7PIPA with a view to reduce data scatter as



FIGURE 11. DEPENDENCE OF CRACK-GROWTH RATE ON BIAXIALITY RATIO, AS A FUNCTION OF NORMALIZED STRESS (From Appendix A)

much as possible. Results representative of the long crack finite-crackgrowth rate behavior of this material have been developed from five separate cracks for R = 0.01, from two cracks for R = -0.6, and from three cracks for R = -1.0. Raw data typical of the scatter encountered are shown for the R = 0.01 case in Figure 12(a), on coordinates of dc/dN and K<sub>mX</sub>. Trends shown for R = 0.01 and R = -1.0 in Figure 12(b) form the long crack reference data base used in the next section titled "Discussion of the Results".

The long-crack trend for R = 0.01 of Figure 12(b) for the present material matches unpublished data independently developed by GE for a finegrained Inconel 718 under otherwise identical loading conditions (except T = 148 C). This match is evident in Figure 12(c), whereas Figure 12(d) contrasts results for coarse and fine grained material. Other GE data indicative of long crack trends at 538 C and 643 C are shown in Figures 12(e) and (f). Note that all GE data have been developed for surface-cracked geometries.

Results of 18 specimens provide information useful in the study of small cracks in Inconel 718. Crack length versus cycles data edited as detailed earlier are presented in Appendix E. Table 2 provided a matrix of these specimens and identified comparison results which serve to isolate or emphasize a particular parameter considered to cause short crack effects. Table 3 extracts the salient features of Table 2 and presents the various direct comparisons along with the appropriate figure numbers keyed to plots of data analyzed as just detailed. Generally, Part (a) of a given figure presents edited data points on coordinates of c and N for each specimen and Part (b) presents data on coordinates of log dc/dN and log  $K_{mx}$ . When helpful, relevant fractography is included. Where reference is made to the long crack trend, the results presented in Figure 12(b) for the appropriate stress ratio have been used for the 20 C comparisons. Finally note that many figures consist of several graphs that are compared to each other or to graphs in other figures. While there are obvious reasons to make all of the scales identical in such cases, it was felt that loss of detail was a more compelling consideration. Thus, scales have been chosen to retain detail, and caution must be exercised to avoid confusion in making comparisons for cases where the scales differ.



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FIGURE 12. (Continued)



2000 C

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FIGURE 12. (Concluded)

Parameter	Figure Number	Compare Results for Specimens
Center Cracked Panel Specimens		
• stress level	13	CC13 (high) vs. CC11 (mod.) vs. CC9 (modlow) vs. CC14 (low)
• net wake	14	CC12 (long) vs. CC10 (short)
• stress ratio	15	CC19 (R=6) vs. CC12 (R=.01) vs. CC15, CC18 (R=-1)
• temperature	16	CC3 (643 C) vs. CC12 (20 C)
Center Notched Panel Specimens		
short cracks	17	CH2, preliminary test - does the material show a short-crack effect
• stress level	18	CH3, CH4 (high) vs. CH2O (moderate) vs. CH6 (low)
• notch field	18	CH3, CH4, CH2O, CH6 (notched) vs. CC15, CC18 (unnotched)
<ul> <li>initiation transients, corner vs. plane fronted cracking</li> </ul>	19 (see also 18)	CH1, CH16 (natural corner) vs. CH3, CH4 (preflawed)
• temperature	20	CH8 (643 C) vs. CH2O, CH3 (20 C)

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# TABLE 3. KEY TO DATA INTERPRETATIONS

Figures 13, 14, 15, and 16 present results for CCP specimens, as laid out in Table 3. Figur: 13 includes results showing the influence of nominal stress. Since crack lengths are comparable, this figure also examines the influence of plastic zone size,  $r_p$ , normalized by crack length. In conjunction with data from Figures 13 and 15, Figure 14 shows the influence of closure and net wake. Figure 15, in conjunction with data for CC13 from Figure 13 presents the influence of R =  $S_{mn}/S_{mx}$  under conditions of high stress, or at different stress levels. With a backdrop from Figure 12 and taken with Figure 14, Figure 16 presents the effect of temperature for continuous cycling.

Table 3 indicates that results for notched specimens are plotted in Figures 17 through 20. Figure 17 presents the results of a preliminary test designed to verify that the fine-grained Inconel 718 did indeed show evidence of a short-crack effect. Figure 18 includes results that compare growth rates at different gross section stress levels and in elastic and plastic notch fields. Figure 18, using data from Figures 13 and 16, along with data from CH1 and CH16, also characterizes the influence of the notch stress field. Figure 19, using results from Figure 18, indicates the significance of the initiation transient and corner cracking. Finally, Figure 20 shows fractographs of room and elevated temperature fracture surfaces at comparable K.



IN CCP SAMPLES FOR R = 0.01 AT 20 C



**Service** 





















## a. crack length versus cycles

FIGURE 15. INFLUENCE OF STRESS RATIO ON CRACK-GROWTH BEHAVIOR OF CCP SPECIMENS AT 20 C



1.2.2







a. crack length versus cycles

FIGURE 16. CRACK-GROWTH DATA DEVELOPED FOR A CCP SPECIMEN FOR R = 0.01 AT 643 C AND 5.0 HZ







- a. crack-growth rate versus cycles
- FIGURE 17. PRELIMINARY TEST DEVELOPING CORNER CRACKS VIA NATURAL INITIATION IN AN ELASTIC NOTCH FIELD AT R = -1 AND 20 C



FIGURE 17. (Concludea)






a. (concluded)

FIGURE 18. (Continued)





FIGURE 18. (Continued)



FIGURE 18. (Continued)







CH1/crack 1





a. crack length versus cycles for corner cracks in an inelastic field

FIGURE 19. INFLUENCE OF NATURAL INITIATION (INITIATION TRANSIENT), FREE SURFACE, AND 3D CRACK CONFIGURATION ON CRACK GROWTH IN AN INELASTIC NOTCH FIELD AT R = -1 AND 20 C









N (kilunycles)

CH6/crack 2; corner vs plane preflawed, and inelastic versus elastic in Figure 19 because the preflaw was inadvertantly omitted at one notch root leading to major differences in initiation lives, and causing very asymmetric growth

a. (concluded)

FIGURE 19. (Continued)



FIGURE 19. (Continued)



FIGURE 19. (Continued)

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ex-x>





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FRACTOGRAPHS OF ROOM AND ELEVATED TEMPERATURE FRACTURE SURFACES AT COMPARABLE  $\Delta K$ FIGURE 20.

## **DISCUSSION OF THE RESULTS**

This section presents a discussion of the experiments designed to explore the short-crack effect in Inconel 718. These experiments have been performed with a view toward developing a predictive model for RFC analyses valid at crack sizes below the current capabilities of LEFM\*. Fractographic results are introduced as appropriate to aid in understanding the observed trends and their implications for Inconel 718 and other engine materials.

## Center-Cracked Panel Specimens

The literature suggests that large values of  $r_p/a$  tend to be associated with a short-crack effect. The results for the CCP specimens share a number of common features related to the value of  $r_p/a$ .

Table 1 listed normalized values of crack tip plasticity-- $r_p/a$ -based on plane stress LEFM calculations. Note that two tests had  $r_p/a$  ratios between 0.1 and 0.2, while two other specimens represented the interval 0.2 to 0.3. The remainder had values of  $r_p/a$  between 0.3 and 0.32. The values of  $r_p/a$  considered represent the practical limit of what can be achieved subject to two constraints: (1) the fracture toughness, and (2) the desire to examine somewhat realistic stress levels and stress intensities. The fracture toughness constraint is set by the stress level that can be applied before preexisting microstructural or microgeometric defects extend unstabily on the rising portion of a fatigue cycle. This bound leads to data generated for Inconel 718 at lower peak stresses (normalized to yield or flow stress) and much lower values of  $r_p/a$  as compared to the data generated for the lower strength materials which dominate the literature.

A value of  $r_p/a = 0.1$  generally is considered as an upper bound limit for valid applications of LEFM. The values of  $r_p/a$  from 0.1 to 0.32 addressed in this study do not satisfy this confined flow requirement. But,

<sup>\*</sup>It is to be emphasized that the short-crack effect is material-and applicationspecific (e.g., for discussion see [41]). Any analysis developed and demonstrated valid to a lower limit crack size for one material and application (load, geometry, etc.) is not general, and should not be applied indiscriminately.

neither are they indicative of large-scale plasticity relative to the crack length. (Values of  $r_p/a$  on the order of 100 have been found for short cracks in the absence of notch field effects [4].)

Because the conditions addressed by the CCP data at  $r_p/a$  near 0.1 meet or just exceed a usually accepted limit for confined flow, an LEFM characterization of the crack driving force is valid within usually accepted standards. For the remainder of the tests, values of K may be somewhat in error. But, as compared to cases in the literature where a short-crack effect is observed at very large values of  $r_p/a$  for finite growth-rate conditions, all cases considered represent very confined flow.

By most standards, this study deals with small  $r_p/a$ , whereas the literature tends to focus on large  $r_p/a$ . Therefore, analysis found appropriate for small  $r_p/a$  in this study are not sufficiently general to deal with large  $r_p/a$ . Likewise, because of the radical differences between brittle and ductile initiation, factors identified as being significant for large  $r_p/a$  in Reference 4 may not be keys to the behavior of data reported hereafter.

Relative differences in  $r_p/a$  may have led different authors to postulate very different models for the short-crack effect. Results where  $r_p/a$  is large all tend to be associated with plasticity, examples of which include  $\Delta J$  and  $\ell_0$  (e.g., [42]), and the effects of closure and notches (e.g., [10,43,44]). On the other hand, many argue that LEFM is valid for very small cracks where  $r_p/a$  is small (e.g., [45-47]). An obvious question arises in this context: can  $r_p/a$  be used as a criterion to assess whether or not to expect a short crack effect in engine RFC analysis? Certainly some data indicate the answer is yes. But an answer based on this study must await the following discussion of the experimental results generated.

Influence of Stress Level. The influence of absolute stress level on the growth of short cracks is presented for R = 0.01 and room temperature in Figure 13. Included are results for four stress levels (for comparable crack lengths) that represent values of  $r_p/a^*$  equal to 0.31, 0.26, 0.22, and

<sup>\*</sup> For all CCP specimens (CC prefixes),  $r_p/a$  is taken with respect to the crack length at wake removal, as listed in Table 1.

0.16, for CC13, CC11, CC9, and CC14, respectively. These develop at values of maximum stress divided by the flow stress\* denoted as  $\overline{S} = S_{mX}/Y$ , that range from 0.67 down to 0.48. Note that these values of  $\overline{S}$  are relatively large, but the corresponding values of  $r_p/a$  are rather small. As is evident from the figure, the crack growth patterns are similar for all four specimens. There are indications of initially higher growth rates over the first two to four data points.

Regarding the influence of closure as assessed by wake removal, this should be evident as a shift in growth rate following wake removal as shown schematically in Figure 1. On part (a) of Figure 13, this would appear as a change in slope in results just beyond the arrow\*\* which denotes the cycle at which removal occurred. Although they are not well defined, trends in the growth rate before removal and that for the first few points after removal tend to show an abrupt increase in rate for CC13, CC11, and CC14. Wake removal<sup>†</sup> to reduce closure causes an increase in  $\Delta K_{eff}$  for a given  $\Delta K$ . Thus an increase in growth rate is expected. But, the increase observed is at most only a factor of three for these data which cover values of  $r_p/a$  approaching the practical limit for this material.

<sup>\*</sup> Flow stress is a term relevant to analyses based on strip yield models and is usually defined as Y = (yield stress + ultimate stress)/2. For the present material, Y is larger than the 0.2 percent offset yield stress by a factor of 1.167.

<sup>\*\*</sup> An arrow is used to denote the cycle number for wake removal whenever the technique is employed. Likewise, on da/dN versus  $K_{mx}$  plots, the arrow denotes the level of K (or crack length at wake removal). These symbols are used throughout the remainder of this report. The short line on the abscissa denotes the initial crack size on this and all subsequent a-N plots.

<sup>†</sup> Wake removal is by low power, EDM wire cutting using 50 μm diameter wire. The system is numerically controlled to a reference position set when the starter flaws are cut. Results indicate that such wire cutting alters the microstructure to a depth less than 10 μm. Once the crack reinitiates and grows through this < 10 μm layer, the results generated represent the base material and heat treatment. The editing procedure coupled with the growth rate calculation procedure automatically skips this region, so that it is not a factor in data interpretation.

The modest increase in growth rate due to wake removal is much less than the factors of 10 to 100 associated with the short-crack effects reported in the literature. But the values of  $r_p/a$  developed for this material are also orders of magnitude less than values typical for the ductile initiation materials that dominate the literature. The present data, therefore, are not incompatible with the literature; indeed, limited plasticity would be expected to generate limited closure. In the limit, as  $r_p/a \neq 0$ , inelastic action becomes so confined that the closure load approaches the lower load in the applied cycle. Under this condition,  $\Delta K_{eff} = \Delta K$  and wake removal can have no influence whatsoever.

For the highest value of  $r_p/a$  (CC13), only 40  $\mu$ m remained after wake removal. Evidently, even when wake is removed to within the limits of current wire EDM capabilities, closure does not appreciably alter crack-growth rates at the practical upper limit of  $r_p/a$  for this material. It may well be that this same trend would be observed for other materials at comparable levels of  $r_p/a$ .

Based on the available data in the literature and the results in Figure 13, the value of  $r_p/a$  may be a major factor controlling the incidence of a short-crack effect. For the Air Force, the implication is that microcrack growth via a reversed plasticity mechanism in high-strength, fine-grained engine materials may not be strongly dependent on closure.

Results for CC11/crack 2 presented in Figure 13(a) are replotted on coordinates of da/dN and  $K_{mx}$  in Figure 13(b) to illustrate the trends in part (a) as compared to so-called long-crack data. As expected in view of the a-N data, this plot shows that the growth rate for the first two points lies above the trend for the ensuing crack growth. Correspondence of the data for this specimen with those of the long-crack reference curve is good in that, except for the first two "short-crack" results, these data fall along the R = 0.01 trend line of Figure 12(b). While a few data points for the early growth of this crack do lie above the long-crack trend, the difference in rates is small in comparison to data for which  $r_p/a$  is large.

In summary, the results covering normalized stress levels from 0.48 to 0.67 and initial stress intensities as low as 15 MPa  $\sqrt{m}$  do not indicate

significant differences in the a-N trends observed. When plotted on da/dN-K<sub>mx</sub> coordinates, the results for all samples also show similar trends. Thus, it is concluded for this fine-grained, high-strength material that changes in absolute stress do not cause changes in microcrack-growth behavior correlated in terms of  $K_{mx}$ , over the range of stress and finite growth rates considered. This conclusion could be false at much lower stresses.

<u>Wake Removal</u>. Some insight as to the significance of closure can also be gained by exploring different amounts of net wake under otherwise identical conditions. To emphasize the effect, different wakes have been considered at the largest value of  $r_p/a$  found practical in this material  $(r_p/a = 0.31)$  at the shortest crack length possible using available EDM facilities.

Comparison results have been developed in CC10 and CC12, with average net wakes at 40  $\mu$ m and 115  $\mu$ m. The data plotted in Figures 14(a) and 14(b) show little difference between the respective trends. For CC10, the results show high growth rates\* when the cracks are small, after which the trends are similar to the data developed for CC12 as well as that generated using conventional long crack samples. With reference to Figure 14(a), an influence of wake removal cannot be seen for either specimen. This is contrary to the observations in Figure 13 for sample CC13, conditions for which are identical to CC12 (cf Table 1). As is evident in Figure 14(b), results for short crack growth in CC10 lie above the long-crack trend.

In summary, these results do not indicate that closure depends on the net wake as would be expected if extensive closure occurred. Since, with a few exceptions, applications of wake removal fall within the range of net wake considered in Figure 14, and since these represent the practical limit of  $r_p/a$  for this material, the results of Figure 14 imply that net wake is not a factor in this study. But, this does not mean that (in this study or in general) crack-growth rate and closure do not depend on the net wake.

<sup>\*</sup> The fact that symmetric crack growth does not occur may in part be responsible for this observation, particularly for the second crack.

First, for the present experiments, the largest value of  $r_p/a$  that can be achieved is relatively small. And, the extent to which closure develops depends on the extent of inelastic action local to the crack tip. Small levels of  $r_p/a$  (as in the present  $r_p/a \leq 0.32$ ), therefore, are expected to develop limited closure as compared to cases where  $r_p/a \, \cdot 10$  to 100 in the literature. For this reason, the absence of an influence of net wake may simply mean that plasticity-induced closure is not a controlling factor in this material. A second consideration relates to the fact that the effect of closure may be confined to a region very near the crack tip. This does not appear to be the case for the present study sincê ëvidence of increased growth rates after wake removal has already been discussed, and more will be introduced.<sup>†</sup>

Another approach for examining the influence of closure on the microcrack-growth process is to remove wake over a range of R. Varying R is useful because more negative values of R cause more compression yielding at the crack tip. In turn, this leaves the crack tip further open as compared to cases with more positive values of R, and thereby enhances the effect of closure on growth rate<sup>±</sup>. To emphasize closure, tests have been conducted at the largest value of  $r_p/a$  coupled with the most negative value of R possible. This has been achieved subject to the limitations of system stability using buckling restraints for samples CC12, CC19, CC15, and CC18. Results for these specimens, which represent values of R equal to 0.01, -0.6, -1, and -1, respectively, are plotted in Figure 15. Examination of the a-N data (Figure 15(a)) indicates their behavior is comparable to that already discussed. In some cases, the growth rate for the physically smaller cracks

<sup>†</sup> If closure had been confined to within 40  $\mu$ m of the crack tip in this study, the a-N data would fail to show a change in growth rate as a result of wake removal in all cases. The 40  $\mu$ m limitation is not inherent in the wake removal concept. Rather it is a constraint, imposed by the practical implementation of numerically controlled EDM using 50  $\mu$ m diameter wire, to avoid cutting away the crack tip along with the wake. Application of the wakeremoval concept, therefore, cannot be used to study closure effects if they are indeed confined this close to the tip.

<sup>\*</sup> If, as just discussed, closure is not a major factor controlling microcrack growth at low values of  $r_p/a$ , more negative values of R are expected to cause only modest changes in growth rate.

is greater than for subsequent growth. And, for CC15/crack 1, there is an abrupt increase in growth rate following wake removal. But, as with the other specimens, there is no marked pattern in these trends, either in the behavior for physically small cracks or after wake removal. As evident in Figure 15(b), growth rates for small cracks and after wake removal lie above the long-crack trend [Figure 12(b)].

In summary, the results presented failed to show a marked dependence of growth rate on R, for small cracks and after wake removal. This result is consistent with the previously discussed data.

Summary for CCP Specimens at 20 C. Overall, the data for the CCP specimens indicate small cracks may grow at rates slightly in excess of the long crack trend. But, the difference in rates was small and always less than a factor of 4. Wake removal was observed to cause an abrupt increase in growth rate about as frequently as physically small cracks were observed to grow at higher rates as compared to the long crack trend. When wake removal was observed to have an effect, the ensuing trend showed rates increased (coincidentally) by a factor less than 4. This suggests that the limited value of  $r_n/a$  possible in the high-strength, fine-grained material limits plasticity-induced closure and does not exceed the confined flow limitation of LEFM (in a practical sense). Its influence, if any, on growth from preflaws leads to increased crack-growth rates by a factor less than 4 for physically small cracks over the range of conditions examined. As indicated throughout, the absence of a short-crack effect causing increased growth rates for small  $r_{\rm p}/a$  is consistent with the literature where significant short-crack effects tend to be associated with  $r_{\rm p}/a$  on the order of 10 to 100.

The Effect of Cycling at 643 C on a CCP Specimen. Specimen CC3 has been used as a preliminary check of whether results developed for small cracks at 20 C carry over to temperatures more representative of service. Comparison data for otherwise matched mechanical conditions therefore have been developed at 20 and 643 C. Specifically, the crack geometry, R, and frequency\* match as closely as possible the conditions for CC12. The maximum stress also has been chosen to match CC12, with provision made to simulate  $r_p/a$  accounting for temperature-reduced flow resistance based on handbook properties.

As is evident in Figure 16(a), the crack growth versus cycles response looks similar to that developed at 20 C. Both cracks show that an initially higher rate develops for the first two points, but neither (data missed for one crack) show any evidence of a closure effect upon wake removal. As evident in Figure 16(b), the data for CC3 lie above the 148 C trend line, which is taken to approximately a 20 C long crack trend for the GE data. Also, they show a similar shift from 148 C to 643 C--including the  $\Delta K$ dependence--as do the long surface crack GE results shown in Figure 12(f). In this respect, whatever the source of the  $\Delta K$  dependence of growth rate shift with temperature, it seems to develop the same extent for small through cracks and long surface cracks.

The limited data developed at 643 C for the fine-grained Inconel 718 used in this investigation show trends similar to that generated at 20 C. The only major difference is that the fracture surface for the 643 C data shows Mode I cracking occurs to longer crack lengths, as compared to its 20 C counterpart, for results developed in this study. This difference in fractography can be seen in Figure 20. Also, the fracture surfaces developed at 643 C are smooth as compared to their long crack 20 C counterparts. The fractographic evidence thus shows a decreasing propensity for surface roughness (and therefore roughness-induced closure) as temperature goes from 20 C to 643 C. It follows that, as compared to 20 C data, the same imposed  $\Delta K$  and R may develop a larger effective stress intensity factor range at 643 C.

<sup>\*</sup> Lower frequencies probably would develop trends different than that observed in this preliminary study.

Results developed using CNP specimens, designated by the prefix CH, share the same material-related constraints discussed in regard to the CCP samples. One constraint is the limited peak stress imposed by the fracture brittle nature of the material studied. Accordingly, the normalized nominal stresses ranged from 0.40 to 0.20. These are lower than the 0.67 to 0.43 investigated for the CCP samples since the notch field serves to locally elevate the stress. Because the notch field is local, this geometry permits testing at higher local levels of the ratio at plastic zone size, rn, to surface crack length from the notch root, c. Values of this second constraint,  $r_{\rm D}/c$ , are tied to values of peak stress and to the depth of the notch plastic field along the transverse net section, denoted as  $x_p$ . At low levels of  $S_{mx}$ , because the notch field is elastic, the crack's plastic zone is the dominant (only) plastic zone. When this is the case (i.e.,  $x_p = 0$ ), values of  $r_p/c$  of 0.21, 0.35, and 0.31 have been developed in samples CH6, crack 1; CH20; and CH2; respectively. These values of  $r_{\rm D}/c$  are similar to values of  $r_p/a$  developed in the CCP samples. In all other cases, the crack grows (at least over part of its length) through an inelastic notch field. One depth of notch field has been successfully explored--460  $\mu$ m. The value of  $r_{\rm D}/c$ developed in this case is 0.85. This value of  $r_{\rm D}/c$  is much larger than the 0.1 generally associated with valid applications of LEFM, but are very small in comparison to values often associated with short crack effects\* as discussed for the CCP samples. Likewise, the depths of the notch plastic fields possible in this high-strength, fracture-brittle<sup>†</sup> material are small

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<sup>\*</sup> Recall that the present interpretation of this "short crack effect" terminglogy in an LEFM/RFC sense is a behavior that leads to nonconservative predictions-that is, a crack growth rate in excess of the LEFM long crack trend.

<sup>†</sup> The term fracture brittle herein denotes a material which exhibits limited plastic flow with cracking. Fatigue crack nucleation occurs with very localized and very little flow meaning only a limited wake of plasticity and very little propensity for closure. Crack growth occurs at relatively small values of rp/a, even for rather large nominal stresses. This term does not imply a low fracture toughness.

compared to those found associated with short crack effects in the literature. As with the CCP specimens, tests on CNP samples have been used to explore whether or not the initial growth of short cracks occurs at rates in excess of LEFM predictions. Also, as with the CCP samples. CNP specimens have been used to assess the role of closure via the wake removal concept. Reference to Table 3 indicates that the CNP samples also have been used to study the influence of natural initiation and 3D effects (Figures 17 and 19), absolute stress level (Figure 18), and notch stress field (also Figure 18). An attempt had also been made to examine the influence of temperature. (While fractography is possible for the test at 643 C, all growth rate data have been lost due to a film processing problem--see Table 1.) Results for through cracks in preflawed CNP samples are presented first. Then Figures 17 and 19, which involve natural initiation and corner cracks, are considered. Note that cracks in preflawed samples can be (and have been) considered as plane fronted while those for corner cracks have aspect ratios a/c, of about 1 for a/t up to 0.25 and between 1 and 3 at breakthrough. After breakthrough, the transition to a plane-fronted crack with nearly equal surface lengths occurs very quickly.

Influence of Stress Level and Notch Fields. Results for samples CH3, CH4, CH2O, and CH6 crack 1 can be used to examine the influence of absolute stress level on crack-growth rate behavior. But since the size of the notch plastic field and the value of  $r_p/c$  increase with increases in stress, both the stress level and the depth of the plastic field must be considered together.

Results for the CCP samples indicated that, by itself,  $r_p/a$  (note the nomenclature  $r_p/a$  for CCP means the same as  $r_p/c$  for CNP specimens) does not lead to differences in growth behavior over the range of values investigated. The extent to which this carries over to notches can be examined in the absence of notch plasticity effects using the results for CH6 crack 1 and

CH20. These data, plotted in Figure 18a on c-N+ coordinates are similar to results for CC14, CC9, CC11, and CC12.

The only difference evident in comparing CNP and CCP results on c-N coordinates is the absence of an initially higher growth rate in the CNP samples, such as that observed in many of the CCP specimens. But this difference is not surprising since, for the CCP case, K increases only with  $\sqrt{a}$  whereas the strain gradient due to the notch field in the CNP case causes K to increase very rapidly\*. Thus, the factor of less than 4 increase in da/dN observed in the CCP results occurs in a situation where subsequent growth is not overshadowed by the influence of the notch field. Trends for inelastic action at the notch, developed in CH3 and CH4, are similar to that just discussed for elastic behavior in regard to CH6 crack 1 and CH20. This is evident in comparing the results for these specimens, as shown in Figure 18. The only exception occurs for CH3, crack 1, which shows growth rates over the first few points slightly above those for the ensuing cycles.

The c-N data for the CNP samples do not indicate trends that could point to even a modest short crack effect, as did the data for CCP specimens. But because the influence of the notch field masks the trend evident when only  $\sqrt{a}$  drives K, the data must be examined on coordinates of dc/dN and K<sub>mx</sub> before conclusions can be drawn. Data showing growth rate as a function of K<sub>mx</sub> in the absence of inelastic notch action are plotted in Figure 18(b) for CH6 crack 1 and CH20. In comparison to the long crack trend, the results for CH6, crack 1,1 (the only results captured for small cracks) show growth rates for small cracks in excess of the long crack trend by more than an order of magnitude! Similar although less dramatic and somewhat scattered results develop for CH20 at crack 1,1, crack 1,2, and crack 2,2. This trend is not shown for crack 2,1 because data are not available for it at small crack sizes.

<sup>+</sup> The system of arrows to denote wake removal and a line to denote the initial crack length used for a-N plots is retained for c-N and  $dc/dN-K_{mx}$  plots.

<sup>\*</sup> This can be seen by comparing values of d(K/S)/dc per Appendix F, Eq. F.3 for small cracks with F(l)--the CNP case--and without F(l)--the CCP case--in the definition of K, Eq. A7.1.

The increased values of dc/dN just examined for growth through elastic fields becomes more complex for growth through an inelastic field, as evident in Figure 18(b) for CH3 and CH4. As with cracks in the elastic notch field, a decrease in growth rate with increasing crack length is evident particularly for CH3 crack 1,1 and CH4 crack 2,1. However, in contrast with the results for the elastic field, this decrease ceases at a trend which lies a factor of 5 to 10 above the long crack trend [Figure 12(b)]. The data for an elastic notch field quickly approaches the long crack trend; however, following initially high growth rates in CH3 and CH4, growth rates 5 to 10 times that of the long crack trend are evident so long as the cracks grow in the inelastic field. As apparent, at least for CH3 crack 2,1 and CH4 crack 1,2 and crack 2,2, growth continues at rates 5 to 10 times greater than the long crack trend at crack lengths greater than 575 µm and less than 1 mm. Beyond this, there is a decrease in growth rate evident toward the long crack trend. But, only for CH4, crack 1,2, is this decrease steep enough to indicate that the growth rate would actually meet the long crack results.\* This decrease in growth rate as the crack tip passes into the elastic field in CH3 and CH4 has also been observed in more ductile materials. References 18 and 43 present such trends for steels, whereas References 43 and 44 show such results for 2024 Aluminum. Plausible explanations for such behavior are considered in References 43 and 44.

For the situation just considered, approximate lower bound calculations indicate that  $x_p = 460 \ \mu m$  (Table 1). Given the accuracy of this approximation, it is reasonable to conclude that errors in the LEFM calculation of crack driving force due to local inelastic action are responsible for the 5 to 10 times increase in growth rates. Analysis for cases where cracks grow in an inelastic notch field have been presented in the literature. Several authors have discussed the use of detailed inelastic analysis for this problem (e.g., [48]). In the absence of such detailed solutions, engineering

<sup>\*</sup> Given the critical crack size operative at the stress level causing inelastic action, stable tearing is expected to intervene long before growth rates approaching the long crack trend could develop. Further testing beyond this exploratory study are necessary to confirm the apparent very significant short crack effect due to inelastic notch action.

methods based on the influence of local yielding on the crack driving force have proven useful [18,43], and may be appropriate for engine RFC analysis.

Influence of Natural Initiation (Free Surface/Initiation Transients) and 3D Crack Geometry. Consider now the results for CH2 presented in Figure 17. This test involves natural initiation under conditions bounded below and above by test conditions for preflawed samples CH6 and CH20, respectively (Figure 18). Observe from Figure 17(a) that two cracks developed on side 1 whereas only one crack was observed on side 2. Crack 1,1 was first to initiate followed by crack 1,2. Both initiated and grew as circular corner cracks based on stereo macrofractography (35X) until  $a/t \doteq 0.25$ . At this point, a/c began to increase from a value of 1 to about 3 at breakthrough. Growth of crack 1 to beyond the camera field occurred before 2,2 appeared. Growth of crack 1 outpaced that of crack 2 leading to separation well before crack 2 grew appreciably. Several points concerning the behavior evident in Figure 17(a) are noteworthy as follows.

First, there is an interplay between cracks on adjacent faces of the plate at the same notch root. Crack 1,1 initiated first and grew quickly as a corner crack. Then, because the driving force for c is decreasing as F'(c/W) takes the crack out of the dominance of the notch field (e.g., see Appendices B and F), growth across the transverse net section slows radically. Growth across the thickness is still in the dominance of the notch field so that, even though surface growth has slowed, the crack continues to propagate through thickness. As noted in Appendix B and discussed earlier in regard to Figure 9(c), continued growth in the thickness direction is toward increasing stress intensity factor (as  $\sqrt{a}$  increases) so that the through-thickness growth process accelerates as a increases. As a  $\rightarrow$  t, breakthrough occurs and the shorter "just initiated" crack, being tied to its longer counterpart on the other face, propagates rapidly. The now almost-plane-fronted through crack continues to grow as any other long crack.

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In view of the above, the rapid change in growth rate of crack 1,1 is due to the fact that crack initiation generates crack configurations that are not stable as the crack grows longer. Had the value of t/2r been larger,

the results of work cited in Reference 7 and noted in References discussed in Appendix A indicate corner crack initiation could occur along with multiple through thickness initiation. The nearly-plane-fronted through-thickness crack initiated would not exhibit the initial high growth rate and the ensuing transient evident for crack 1,1.

Another facet of the corner cracking process is that corner crack morphologies tend to involve extensive crystallographic cracking. While initially this leads to high rates (perhaps due to the absence of closure), the transition from a mixed Mode I/Mode II to Mode I cracking and the associated increased closure could lead to a continued reduction in rates with continued growth toward a stable crack geometry. In these respects, the result for crack 1,1 is interpreted as an initiation transient due to free surface effects admitted by natural initiation. It is due, for the most part, to the mechanics controlling crack initiation in gradients at a doubly free surface. For the case in point, this initiation transient influenced the first 800 µm of surface crack growth. However, the crack length over which this effect can occur is a function of the gradient, the peak stress, the notch geometry, the plate thickness, and other factors.

Another interesting feature evident in the data of Figure 17(a) is the stepped nature of the crack growth rate, even for longer cracks. Such steps are commonly observed in the growth of cracks during the transition from corner to plane-fronted cracks. To some extent, this can be ascribed to the interaction of separate cracks. But it is more likely attributed to the fact that c is growing in field where d(K/S)/dc is decreasing, whereas a is growing in a field where d(K/S)/da is increasing. This results in an unsteady balance wherein the growth along the crack front has to satisfy counteracting driving forces at the extreme tips of the crack front.

Whether or not the largely mechanics-controlled initiation transient is responsible for a significant portion of the short crack effects is not clear in the literature. But, it is certain that the shape of an initiateo crack often differs from that associated with its steady-state "long crack" geometry. Some data in the literature for another engine material [49], IN 100, attest to this fact. In that case, on coordinates of da/dN and  $\Delta K$ ,

the results indicated that the growth rate first decreased and then increased becoming nearly coincident with the long crack trend as crack length increased. This is exactly the tendency for crack 1,1--as shown in Figure 17(b). As evident in the figure, the first crack to initiate also shows initial growth rates in excess of the long crack trend based on LEFM analyses. Note that the effect is enhanced by the use of a corner crack versus (an inappropriate) through crack K solution. In summary, the results for this test show two features often observed in what are called short crack effects. These are initially higher growth rate and a decreasing, then increasing, growth rate.

Comparison of the results in Figure 17 with the corresponding c-N data in Figure 18 shows trends for natural initiation similar to those observed for preflawed specimens. However, there are several differences. First, the trend for natural initiation involves several data points over which the growth rate is very much higher than for subsequent growth while the trend for preflawed geometries (through cracks) does not. As just discussed, this behavior is rationalized in terms of the double free surface which leads to initia y high rates of cracking under locally large  $r_p/c$ . Decreases in growth rate to the long crack trend follow as a result of the 3D nature of the crack and the associated transient shapes leading to a stable value of a/c.

Another major difference is that natural cracks show significant scatter in initiation and consequent asymmetric crack growth, particularly at low stress levels. In some cases, multiple cracks initiate at the same notch root. Again this tendency is often accentuated at high stresses, as evident in the literature (e.g., [18]). Multiple cracking is evident in the results of CH6, crack 2. While planned for elastic local stress behavior, crack 1 initiated well before crack 2 in this specimen. Crack 1 therefore had grown well across the plate before crack 2 initiated. The asymmetric cracking and the related loss of section caused yield at the notch where crack 2 initiated. For this reason, this multiple initiation developed in an inelastic field. Yet another feature unique to corner cracks is the periods of dormancy, such as evident here in CH1, crack 1,1. Both multiple initiation and dormancy are

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evident in Figure 19. Also, corner cracks develop from corner to throughthickness cracks. For this reason, data for small cracks following breakthrough is strongly influenced by the plastic instability process in the ligament prior to breakthrough.

The final feature unique to natural initiation is the development of Mode II cracks, along with the Mode I cracks observed with preflaws. With reference to Figure 20, note that the fracture surface near the initiation site for the natural initiation, denoted N, is very stepped and coarse compared to its preflawed counterparts. Related roughness-induced closure is expected for natural initiation as compared to preflawed cracks, and may cause a significant reduction in growth rate for cracks grown beyond the effect of the doubly free surface (Appendix A). In contrast, the locally enhanced plasticity associated with the doubly-free surface and the presence of Mode II cracks for the natural initiation may lead to decreased closure, particularly for negative values of R. Natural initiation thus may represent a fine balance between competing mechanisms.

Results for CH2, crack 1,1, have already been discussed in terms of a 3D solution applied until near a = 0.5t, after which K has been evaluated as a through crack. Changes in aspect ratio have been accounted for in analysis according to Figure 9(c). Note that the essential difference between these data and the through-crack results that bound it (CH1 and CH6, crack 1) is the occurrence of much larger growth rates for the natural initiation case. Obviously then if the desire is to study the growth of small cracks or to screen for short crack effects, the natural initiation process is significant in the presence of a free surface. When double free surfaces occur, natural initiation transients may be even more important. Another major difference is the driving force for an initiated crack to find the equilibrium crack shape under mechanics conditions which differ as it grows away from the notch. As this process depends on component geometry, it is difficult to predict when it will be most significant. But, earlier discussion of results for CH2 suggest that changes in crack shape can have a major influence on the growth rate of a part-through crack.

The significance of initiation transients and 3D crack geometry effects on the behavior of small cracks growing in an inelastic notch field can be extracted by study of data for CH1, crack 1,2, CH6, crack 2, and CH16, crack 1,1. These three sets of data are representative of 3D crack effects and initiation transients; only these results are discussed. In contrast to the c-N data for corner crack growth in an elastic notch field, the data for samples CH1 and CH16 shown in Figure 19(a) do not show the initially high growth rate to the extent found for CH2.

Analysis of these corner crack data is presented in Figure 19(b) on  $dc/dN-K_{MX}$  coordinates. This analysis has been done in two ways. First, the cracks have been considered as through cracks with length equal to that measured on the surface. In the second analysis they have been treated as corner cracks. For this second analysis, the aspect ratio has been changed as a function of surface crack length based on fractographic results and surface crack length data. Values of corner crack K determined in this manner show that, for a given surface crack length, K is less than that for the through crack case up to about a/t = 0.5 (see Appendix B). That is, for the same surface crack length, the value of K is reduced for corner cracks as compared to through cracks (Appendix B). Since  $a/t \leq 0.5$  lies in the small crack domain these results suggest that an inappropriate through crack K underestimates the short crack effect that would be evident were a more appropriate corner crack K solution used for data analysis. Analyzed as corner cracks, the results are similar to the trend for CH2.

As has been noted for preflawed CNP data, the inelastic notch field operative in CH2 also is associated with growth rate trends in excess of the long crack data for growth through the notch field. Also, as was noted for preflawed data, the inelastic action of the notch seems to "wash out" the initially higher growth rates associated with small cracks in the CCP samples. Therefore, one could speculate that inelastic notch effects swamp the initiation transients and 3D effects observed to dominate the behavior for locally elastic conditions. In this respect, when local inelastic action occurs the value of  $r_p/a$  would appear to be the key driver for the short crack effect.

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<u>Summary of Results for CNP Samples</u>. Data developed for preflawed CNP samples showed only a limited short-crack effect, consistent with the results for the CCP samples. Notch inelastic action was observed to significantly elevate the crack-growth rate as compared to that expected based on LEFM analysis. Natural initiation was associated with initially high growth rates attributed to the doubly free surface at corner-crack initiation sites. Fracture surfaces developed in these corner initiations showed mixed growth modes, and were very stepped and coarse. Closure and the development of constraint were asserted as the cause for reductions in growth rate as the corner crack grew. Three-dimensional crack configuration was also noted to be a factor when the configuration at initiation changed with crack advance to some other steady-state configuration.

## Summary of Experimental Results for CCP and CNP Samples

The results developed for the precracked samples are not inconsistent with the use of  $r_p/a$  as a criterion to assess the possible extent of a short-crack effect. But results developed at nominally low values of  $r_p/a$  for both CCP and CNP geometries indicate the significance of free surfaces--a micromechanics contribution to  $r_p/a$  (or  $r_p/c$ ). The CNP samples also showed transients in crack geometry from initiation through the development of a stable configuration are important. Likewise the CNP samples showed inelastic action at a notch field may by itself be responsible for a short-crack effect.

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## COMMENTARY: IMPLICATIONS FOR ENGINE MATERIALS AND RFC ANALYSIS

One disturbing facet of LEFM (and fracture mechanics in general) as applied herein is the difference in the value of stress intensity factor\* that is encountered in the literature for, say, part-through cracks, for nearly the same geometry, cracking mode, etc. (See Appendix B for example.) Another disturbing facet of LEFM analysis (and fracture mechanics in general) is the need for geometry-specific analysis including the effect of boundaries on both peak stress and stress gradient. This tends to limit the utility of tabulated K solutions, at least in applications to cracks whose size is small compared to the dimensions of a component -- e.g., a notch radius. To date, these aspects have not presented a problem in airframe Aircraft Structural Integrity Programs (ASIP) since LEFM based damage tolerant design and RFC analysis assume initial flaw sizes large in comparison to the crack sizes that exhibit a short-crack effect. But, even if initial flaw sizes are not assumed to be large, the shear loaded fastened joints popular in airframe construction tend not to exhibit short-crack effects, at least at finite growth rates [50,51]. The absence of a short-crack effect is apparently traceable to typically small values of  $r_{\rm D}/c$  and the "propping" effect<sup>†</sup> that serves to reduce  $\Delta K_{\rm eff}$  but increases R [41]. Under these conditions, plasticity induced closure is virtually nonexistant, as is the inelastic action developed in open holes under otherwise identical conditions.

<sup>\*</sup> While this statement is made and supported only for LEFM, it is also valid for some nonlinear fracture mechanics methods in that K forms a part of the parameter evaluation.

<sup>+</sup> Fasteners in shear loaded joints, such as interference-fit-fasteners, by virtue of their design create a tensile hoop prestress. As the joint is stressed in tension, the behavior at the high stress site at the fastener hole is controlled by radial unloading of the fastener. As load on the joint is removed, the fastener reloads. For this reason the cyclic loading seen by a material element at the high stress site in the hole is reduced, while the stress ratio (R) is increased - an effect known as "propping". Because of the high value of R, crack closure is less likely as compared to the open hole case.

For RFC analysis of engines must break virgin ground. And they must do this in fracture brittle materials, some of which have very small critical flaw sizes under service stress conditions. It follows then that microcrack growth in engine applications requires extensive phenomenological study, well beyond this preliminary effort. Once the phenomenology is in hand, models capable cf characterizing key factors unique to microcracks can be formulated and tested.

This study has focused on identifying and characterizing factors that cause small cracks to grow differently than long cracks. Specifically, it was directed at cracks less than 1 mm long, and the objective was to develop and apply a framework valid for crack lengths less than 1 mm. Thereafter, the utility of this analysis was to be assessed, and consideration given to its use in engine RFC analysis. Based on the literature review [4], the key parameter controlling microcrack growth leading to nonconservative LEFM predictions was plasticity. Associated with plasticity were a host of related factors including inelastic notch fields, microfree surface effects, initiation transients and crack shape transients, and plasticity induced closure. Other factors were also noted such as the existance of a dominant singularity and microstructural features such as grain size, grain boundaries, etc.

The approach adopted to examine small crack growth in regard to engine RFC analysis recognized that deterministic applications of continuum fracture mechanics form the basis for most RFC analyses, as for example airframe ASIP [52]. Since deterministic fracture mechanics cannot deal with the variable crystallographic orientations at critical areas (at least polycrystalline materials), the study addresses cracking processes in an aggregate of material. Continuum mechanics likewise deals with an aggregate of material. The minimum volume of material to develop grain-to-grain compatibility is one criterion to judge the number of grains needed to develop the "bulk" response of an aggregate. Therefore, grain-to-grain compatibility can be used to set a lower bound to the crack sizes that can be dealt with if isotropic deterministic continuum mechanics descriptions of cracks are to be used. Discussions of single crystal, bicrystal, and surrounded bicrystal and

polycrystal deformation behavior (e.g., [53]) shed some light on this lower limit. Based on these results, the smallest crack addressed within such an analysis framework is one from 3- to 10-grain diameters along its least dimension. For the Inconel 718 studied, this lower limit crack dimension ranges from 30 to 100  $\mu$ m. But for other materials used in engine applications, this dimension may be quite large. This lower limit associated with the use of continuum fracture mechanics restricts the scope of this study to rather fine-grained materials since the desired upper bound on crack size was 1000  $\mu$ m. The lower limit crack dimension of 30 to 100  $\mu$ m also restricts applicability of the results and continuum fracture mechanics<sup>†</sup> analysis to certain directionally solidified (DS) materials. Likewise, it essentially precludes consideration of single crystal (SC) materials using deterministic fracture mechanics--unless directional properties are expressly factored into the analysis.

Results presented in the literature show a short crack effect tends to be associated with large values of  $r_p/a^*$  [4]. However, the material investigated admits only small values of  $r_p/a$  before brittle fracture intervenes, for both 20 C and temperatures typical of service. (This is attested to in the termination of CC17 at only  $r_p/a = 0.23$  because of stable tearing tending to unstable growth, for a test at 643 C.) Given that large values of  $r_p/a$  tend to be associated with short crack effects in the literature, the small values admitted by the material studied suggest LEFM analyses might correlate most of the data generated. Indeed, in the absence of free surface effects or a notch which lead to locally large values of  $r_p/a$  at globally low levels, the results fail to indicate a short crack effect. Also, at small values of  $r_p/a$  (confined plasticity), plasticity induced crack closure is not expected to be a major factor. This is supported in a preliminary sense by

<sup>+</sup> Continuum fracture mechanics in this context is taken as an isotropic solution for crack driving force, which assumes the existance of a dominant singularity.

<sup>\*</sup> The nomenclature relates specifically to CCP samples--but the discussion is general and  $r_p/a$  could be replaced by  $r_p/c$  used for CNP samples throughout this section.

the wake removal studies designed to isolate closure effects which showed only a limited effect of closure.

The peak value of  $r_p/a$  considered represents a value approaching the practical limit possible in the material studied. It is reasonable to expect that fine-grained high strength materials will also lead to similarly limited values of  $r_p/a$ , unless time-dependent flow or some other mechanism is involved. Thus, the results presented here may be indicative of the behavior of a broad class of engine materials. This assertion is supported to a limited extent by the literature for Rene 95 [45,54]. In that the largest practical values of  $r_p/a$  in these materials indicate flow is still confined, LEFM should be valid down to crack sizes associated with free surface effects (valid continuum fracture mechanics). This assertion is also supported in the literature, at least for Rene 95 [54]. That is, LEFM may provide a viable basis for RFC analysis for crack lengths (depths) down to about 100 µm in these materials, provided creep and oxidation (and oxidation-induced roughness) are kept in check through appropriate alloy selection.

For coarser-grained engine materials, larger values of  $r_p/a$  are possible. Also, microstructure may control growth to much larger crack lengths, since the lower bound crack length for the valid application of continuum fracture mechanics increases with grain size. These assertions are indirectly supported in the literature which shows that LEFM analysis does not achieve correlation in steels and aluminum alloys with coarser grain sizes, and noteably in a coarse-grained variant of a titanium alloy used in engines [55]. Adopting the titanium alloy as a vehicle for further discussion, results developed for that material show short crack effects at cracks a few mm long. Significantly, the short-crack effect can in that study [55] be ascribed to crack growth controlled by microstructure. But, it is also significant that this study involves conditions which violate the minimum crack length for valid application of deterministic continuum mechanics as noted earlier. The lesson to be learned is that continuum fracture mechanics must be applied with caution in dealing with coarse-grained high-strength materials. That is,  $r_p/a$ , based on bulk (continuum) calculations, is only valid if the crack is large compared to the microstructure. Therefore, care

must be taken in adopting a macroscopic value of  $r_p/a$  as an indicator of possible short crack effects, particularly in regard to DS and SC engine materials.

A general RFC analysis capability must address the limited viability of LEFM as  $r_p/a$  grows beyond values on the order of 0.1.  $\Delta$ CTOD has been advanced in References 9 and 19 as a basis to extend the applicability of LEFM type analysis to higher values of  $r_p/a$ .  $\Delta$ CTOD has the advantage of being related to physical parameters, but it may be difficult to calculate. Alternatively, analysis on  $\Delta J$  [56] based on adaptation of the J integral [57] to fatigue applications could be used. An important advantage of a J-based framework is its convenient calculation using J estimation procedures. Unfortunately, in the presence of a notch stress field and the notch's related influence on closure, determination of  $\Delta J$  requires detailed numerica? evaluation just as would  $\Delta$ CTOD.

Given that detailed analyses are required, the more general parameters such as  $\Delta$ CTOD and  $\Delta$ T [58] seem to offer the most promise. But it is desirable to use modifications of available LEFM analysis whenever possible in view of the complexity and cost associated with the evaluation of these parameters. As noted in Appendix C,  $\Delta$ CTOD can be evaluated in terms of a pseudo plastic strip yield formulation based on LEFM technology (e.g., [59,60]. Since such models can be adapted to account for closure (e.g., [61,62]), this class of models may provide an economical alternative to detailed inelastic analysis without great loss in accuracy.

Regarding the influence of notch plasticity, analyses in the literature [18,43] indicate that for confined notch plasticity, LEFM analysis can be adapted to this situation. The key in this adaptation is modification of the far field stress to reflect stress-strain conditions that operate in the inelastic notch field. Once the inelastic field is fully traversed by the crack, LEFM can be used. Obviously, the situation of cracking in notch fields is complicated by the influence of local biaxiality (t/2r) near the site of crack initiation and the initial crack shape [7,63]. Since crack geometries at initiation are not necessarily the equilibrium "long crack" geometry, 3D K solutions for finite width may be required. And K so developed must reflect
both the peak stress and the stress gradient [26]. Also, the apparent dependence of crack-growth rate on far field stress state and normalized stress level (Appendix A) must be accounted for once applied gross section stress becomes an appreciable fraction of yield.

In summary, much work remains to be done before RFC analysis comes of age in applications where concern is directed at physically small cracks. Throughout, differences in micro-free surface effects on  $r_p/a$  between fine-and coarse-grained materials must be remembered. Lower bound limits on crack size for the applicability of LEFM must be set not only in terms of violating the confined flow restriction ( $r_p/a$  less than about 0.1) but also the continuum restriction (crack length or depth greater than about 10 times the grain size). Experiments should focus on natural initiation in test geometries that reflect key geometric parameters over the range of service conditions expected. Situations examined should reflect potential service conditions to develop creep and oxidation to the extent they occur in service.

Finally some cautions regarding developing and interpreting screening tests to see if a "material shows a small crack effect" are appropriate. In such studies, it should be remembered that for "continuum valid" applications of fracture mechanics, mechanics parameters seem to control whether or not a short-crack effect develops. This is not to say that materials considerations such as grain size are not important. Rather the situation is that changes in microstructure affect mechanical properties, which in turn affect mechanics parameters. As an example, grain size influences flow response which in turn figures into  $r_p/a$ . Grain size also figures into the lower bound crack size for deterministic continuum mechanics analysis.

Unfortunately it is difficult to study a material to screen crack growth behavior for a short-crack effect without the use of some test specimen. As has been emphasized by the results developed herein, certain test geometries enhance or play down the role of specific mechanics parameters noted in this study as drivers of the short-crack effect. It follows then that screening materials for "short-crack effects" using a given geometry tends to emphasize particular mechanics or materials parameters and factors known to control the microcrack growth rate. Therefore, the extent to which

any material exhibits a short-crack effect depends on the geometry used. For this reason, the question of whether or not a "material shows a short-crack effect" is not of consequence--unless it is asked in regard to a specific 3D geometry and loading that reflect some eventual service application.

#### CONCLUSIONS

The major conclusions of the experimental phase of this study are summarized below.

- In the absence of the elevated temperature, corner cracking, and inelastic notch fields, LEFM analysis is appropriate for small cracks in fine-grained Inconel 718 under engine conditions. Tests meant to simulate the mechanical service conditions showed an elevation of crack growth rate less than five times for short cracks. This increase operated over a very small crack growth increment.
- Inability to measure and/or analyze corner-initiating cracks can cause LEFM to become practically invalid for short cracks of that type. Consolidation of crack growth data by LEFM requires the accurate calculation of the stress intensity factor (SIF). The discussion of K solutions in this report establishes the widely varying solutions which are available in the literature. If the appropriate SIF cannot be determined or if the measurements needed to use the appropriate SIF cannot be made, then there is little hope that LEFM can consistently consolidate cornerinitiating short cracks. Corner initiation can lead to elevated growth behavior caused by stress-state and transient-crack geometry effects.
- Notch root plasticity can elevate crack growth rates above the those predicted by LEFM. Growth rates 5 to 10 times the rates expected from LEFM analysis have been observed in tests.

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### NOMENCLATURE

RFC		Retirement for cause
DTD	-	Damage tolerant design
LEFM	-	Linear-elastic fracture mechanics
∆CTOD	-	Crack-tip-opening displacement range
μ	-	Biaxial stress ratio
S <sub>mx</sub>	-	Maximum stress
S	-	Far-field stress
Y	-	Flow stress
t	-	Thickness
W	-	Width
r	-	Radius of hole
R	-	Stress ratio
К	-	Stress intensity factor
∆K <sub>eff</sub>	-	Effective stress intensity factor range
K <sub>mx</sub>	-	Maximum stress intensity factor
ССР	-	Center crack parel
CNP	-	Center hole notched
c, a	-	Surface crack length in CNP and CCP specimens, respectively
N	-	Number of cycles
da/dN, dc/dN	-	Crack growth rate
Kt	-	Net-section stress accentuation factor
a/c	-	Crack aspect ratio
rp	-	Plastic zone size
SC	-	Single crystal
DS	-	Directionally solidified
×p	-	Notch plastic field, measured along transverse net section

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#### APPENDICES

This section contains six appendices which report work done in support of this study, the results of which are used/referenced in summary or parametric form in main body of the report. Included are:

- A Influence of Stress Biaxiality on Fatigue Crack Propagation Rate, Including Free Surface Effects
- B Survey of Results of Stress Intensity Factor Solutions for Plates with Holes, Including Crack Configuration
- C Analytical Consideration of Crack Tip Plasticity--Pseudoplastic Extension of LEFM to Small Cracks
- D Accuracy and Precision in Crack Length Measurement
- E Data Tables

F Considerations in the Choice of Stress Intensity Factor Solution for Finite Width CNP Specimens.

Each appendix is introduced with the background that identified the need for the effort reported, and is self standing. Where references are used, they are listed in the List of References.

#### Appendix A. Influence of Stress Biaxiality on Fatigue Crack Propagation Rate

Thickness to diameter ratio in CNP specimens is known to control the biaxial stress field at the notch root [40]. In a mechanics sense, this biaxiality is embedded in the stress intensity factor--which represents Mode I cracking (not loading). But it is known that crack-growth rate depends on stress biaxiality,  $\mu$ . Note that the dependence of dc/dN on  $\mu$  is not accounted for in (Mode I) K. Note too that short-crack data for growth in biaxial fields are compared to uniaxial long-crack data. Therefore, it is necessary to account for the presence of stress biaxiality to complete consideration of 3D effects in the CNP specimen. Also, because the extent of the local plasticity varies, this dependence of dc/dN on  $\mu$  should be expressed as a function of 1 prmalized stress level.

Even after accounting for the macroscopic free surface effect in a mechanics sense [64] (via 1.122 applied to K for cracks at surfaces), and accounting for stress biaxiality as outlined in the following, there remains an unaccounted factor associated with surface cracks. As one passes from the surface to the interior of a body, there is an increase in the grain to grain compatibility. This develops since as compared to fully surrounded interior grains, those on the surface deform in the presence of fewer neighbours that limit flow in other directions. Furthermore this flow may occur on slip systems with an exterior normal component--which incurs no constraint at all at the free surface. The more slip systems, the more likely it is that slip systems are favorably oriented, therefore the greater the flow involved.

Without micromechanics analysis it is difficult to calculate the significance of this effect and the depth to which it may be a factor. However it can be inferred from consideration of differences in stress-strain (flow) behavior. Such data, presented as a function of the number and orientations of grains studied and the number of slip systems available (active) for various pure materials\* suggest this microscopic free surface

\* For a discussion of this subject, see for example [53].

effect is operative in a surface layer as few as 3, but up to 10 grains deep. For the present material, this means easier flow and therefore higher growth rates can be expected due to this microfree surface effect for cracks from 30  $\mu$ m to 100  $\mu$ m long.

It should be noted that the effect of free surface can create surface cracks that are "open" compared to their longer counterparts [63]. Moreover, its influence would be greatest when the crack is small, and would decrease with crack growth. In this sense, crack closure serves as a macroscopic vehicle to rationalize a process driven by a micromechanics phenomenon. Bulk flow properties, therefore, should not be used to develop closure models for short cracks. Finally, the length over which the effect is observed is indirectly tied to the material via grain size. For this reason, any associated short crack effect due to the micromechanics of free surface flow may be erroneously concluded to be "material" dependent. A more complete discussion of free surface effects and biaxiality is contained in Reference 63.

The issue of free surface aside, the dependence of dc/dN on  $\mu$  was formulated in terms of a colinear strip yield model following the lead in earlier analysis tasks (compare Appendix C). This effort was funded in part by the analysis appropriation and by Battelle. Results of this formulation are presented in J. Ahmad, B. N. Leis, and M. F. Kanninen, "Analysis of Fatigue Crack Propagation Under Biaxial Loading Using an Inclined Strip Yield Zone Representation of Crack Tip Plasticity", accepted for publication in Fatigue of Engineering Materials and Structures. Figure 11 presents a summary of the findings of this study. The related text discusses some of the implications.

#### Appendix B. Survey of Results of Solutions for Plates with Holes, Including Crack Configuration

Results of the review indicated the 3D crack configuration may be a factor in explaining the nonunique correlation of dc/dN on  $\Delta K$  or  $K_{mx}$ . Given that the first test performed using both the aluminum and the Inconel 718 indicated corner cracking developed for natural initiation, a survey of through thickness and part through thickness stress intensity factor solutions was initiated. The survey had a limited scope given that much of the experimental work utilized preflawed CCP or CNP samples anticipated to produce through cracks. The survey, performed and reported by Mr. T. P. Forte, was funded in part by Battelle and this contract out of the reporting appropriation and represented a small but significant fraction of that effort. A summary of the results of the survey follows.

Numerous stress intensity factor (SIF) solutions are available in the literature for cracks eminating from holes in plates. Unfortunately, however, there are significant differences between the results for the various solutions. Table B-1 contains a partial list of the references containing alternative SIF solutions for single and double through-thickness cracks as well as single and double corner cracks emanating from holes. This survey has been undertaken to compare some of the more popular stress intensity factors for the case of (: symmetric through cracks, and (2) single corner cracks. (Double corner cracks and single through cracks are not prevelant in this study and as such have not been considered.) The study was further limited to the case of uniaxial, uniform, remote stress loading, perpendicular to the crack plane; in finite width plates; at crack sizes small compared to the hole diameter. Lastly, only those SIF solutions that were readily programmable were considered.

The ultimate goal of the survey of SIF solutions was to select the solution most appropriate for the analysis of the short crack, crack growth rate data developed in the current study. For this reason, the focus was on solutions applicable to short cracks (less than one-tenth the hole diameter in length). Of the many solutions available, those geometrically similar to the CNP test specimen (Figure 5b) developed using finite element analysis

techniques were of interest. (Recall that the test specimen nominal dimensions were: width = 2.25 inches, hole diameter = 0.5 inch, and thickness = 0.09 inch.) In addition, solutions incorporating finite width corrections were desired. Note that the finite width corrections were sought not only to compensate for the increase in the SIF as a growing crack consumes the width of the plate, but more importantly to compensate for the differences in the near-hole stress fields between infinite and finite width plates. These differences are reflected by differences is stress concentrations and in the shape of the stress gradient.

#### TABLE B-1. SOURCES OF SIF SOLUTIONS FOR CRACKS EMANATING FROM CIRCULAR HOLES

#### THROUGH-THICKNESS CRACKS

#### One Crack

- Tweed, J. and Rooke, D. P., Int. J. Engr. Sci., V11, 1973 pp 1185-1193
- 2. Bowie, O.L., J. Math. Phys., V35, 1956, pp 60-71
- Shah, R. C., ASTM-STP-590, <u>Mechanics of Crack Growth</u>, 1976, pp 429-459
- Oladimeji, M. K., Engr. Fract. Mech., V15, No. 3-4, 1981, pp 391-405
- 5. Broek, D., <u>Elementary Engineering Fracture Mechanics</u>, Noordhoff International Publishing, Leyden, 1974.

#### Two Cracks

- 6. Bowie, O. L., (same as 2 above).
- 7. Shah, R. C., (same as 3 above).
- 8. Oladimeji, M. K., (same as 4 above).

TABLE B-1. (Continued)

- 9. Broek, D., (same as 5 above).
- Karlsson, A. and Backlund, J., Int. J. Fract. Mech. V14, No. 6, 1978, pp 585-596.
- 11. Newman, J. C., NASA TN D-6376, 1971.

#### CORNER CRACKS

#### One Crack

- 12. Shah, R. C., (same as 3 above).
- 13. Broek, D., (same as 5 above).
- 14. Newman, J. C., NASA TN D-8244, 1976.
- Newman, J. C. and Raju, I. S., ASTM-STP-791, <u>Fracture</u> <u>Mechanics, 14th Symposium, Volume 1, Theory and Analysis</u>, 1983, pp I 238-I 265.
- 16. Hall, L. R. and Finger, R. W., AFFDL TR 70-144, Edited by Wood, H. A., Et al, 1970, pp 235-262.
- 17. Liu, A. F., Engr. Fract. Mech. V4, 1972, pp 175-179.
- 18. Smith, S. H., WPAFB, ASD TR-18, 1974.

#### Two Cracks

18. Newman, J. C., NASA TN D-8244, 1976.

- 19. Newman, J. C. and Raju, I. S., (same as 15 above).
- 20. Shah, R. C., (same as 3 above).
- 21. Broek, D., (same as 5 above).

#### Comparison of SIF Solutions

The comparison of the various SIF solutions has been made graphically using computer generated plots. The normalized coordinates used for the abscissa and ordinate were the SIF divided by the applied remote stress, K/S, and the crack length (measured from the edge of the hole to the crack tip, in the width direction) divided by the hole diameter, c/D.

#### Symmetric Through Cracks

SIF solutions from References 7, .8, 16, and 17 were plotted on a single plot so that differences could be observed. As expected, each solution showed an increasing SIF with increasing crack length, but the large difference in the SIF for the solutions was somewhat unexpected. At a crack length to diameter ratio of 0.02 the values of K/S ranged from 0.38 to 0.62 with the lowest value being associated with Reference 6 and the largest with Reference 11\*. For the 0.5 inch diameter hole the ratio of c/D of 0.02 corresponds to a 0.010-inch crack. At a c/D ratio of U.10, a 0.050-inch length crack, the value of K/S ranged from 0.73 to 1.11, again the lowest value was associated with Reference 7 and the largest with Reference 17.

In each of the above two examples, for different c/D values the spread in K/S was largely due to the low values of K/S from Reference 7. Most likely this was because the solution from Reference 7 did not include a finite width correction. Comparing the other solutions, the variation in K/S at c/D = 0.02 was reduced to a range of 0.45 to 0.62 and at c/D = 0.10 to a range of 0.96 to 1.11. This result to some extent exhibits the influence of the finite width correction.

<sup>\*</sup> This SIF solution was developed for a diameter to plate width ratio of 0.25. The corresponding ratio for the test specimen was 0.222. To offset this difference two sets of calculations were made, one with a hole size of 0.5 inch and a width of 2.0 inches, and a second with a width of 2.25 inches and a 0.5625 inch diameter hole. These provided closely spaced bounds for the test specimen geometry.

The SIF solution selected for the analysis of the short crack growth rate data was taken from Reference 17. The choice was made because this solution was derived from a finite element analysis of a model most nearly matching the test specimen geometry, c/D = 0.25 for the model and 0.222 for the specimen. As noted in the report, this solution most closely matched the limiting value of K = 1.122 K<sub>t</sub> S  $\sqrt{\pi c}$  over the crack interval from 25 µm to 490 µm.

#### Single Corner Cracks

SIF solutions from References 5, 6, 11-13, and 18 were plotted on a series of three plots, one for each of the following ratios: a/c = 1, 2, and 2. As with the through-thickness cracks, c was the length of the crack measured from the hole's edge in the width direction; a, on the other hand, was the length of the crack in the depth (through thickness) direction. The variation in K/S as a function of c/D was similar to that of the through thickness SIF solutions. The variation tended to increase with increasing a/c. The closest agreement among the various solutions was for the case of a/c of 1 and c/D less than 0.04. In this regime the applicable SIF solutions (from References 5, 13, 14, and 18) exhibited only minor differences. For example, at c/D of 0.04, K/S ranged between 0.45 and 0.54.

An important criteria in the selection of a corner crack SIF solution for the analysis of the test data was that the corner crack solution reduce to a through-thickness crack as a/c approached infinity. This was taken as the upper limiting bound for candidate corner crack solutions. In the lower limit, i.e., for small quarter-circular with c/D less than 0.04, it was felt that the corner crack solution should be similar to the solutions given by References 5, 13, 14, and 18 since they were in such close agreement. Each of these conditions was satisfied through the use of the correction factor given in Figure 11 of Reference 13. This factor reflected the

relationship between the SIF for a corner crack and that of a throughthickness crack, each having the same value of normalized crack length c/D.\* A plot of the SIF solution adopted for the analysis of the test data is shown in Figure B-1. Note that part of the figure shows an expanded plot of c/D less than 0.10.

In adopting the SIF solution shown in Figure B-1 it was necessary to prescribe the relationship between a and c, for a corner crack that begins as a quarter-circular crack and gradually transitions into a through-thickness crack as c increases. Such a relationship was established from consideration of the observed crack growth behavior. In general, the crack started as quarter-circular and grew as quarter-circular until c/D = 0.05, at which length they began to transition into through-thickness cracks. At c/D = 0.07, the cracks were approximately 2/3 through the thickness and at c/D = 0.075, the cracks were all but completely plane fronted through-thickness cracks. Using this information, and the correction factor given in Figure 11 of Reference 13, it was possible to define a smooth, continuous relationship between c/D and K/S for cracks that begin as corner cracks, transition to through-thickness cracks, and grow to failure as through-thickness cracks. The correction for corner cracks shown in Figure B-1 was used in analysis throughout the text discussing figures designated as "analyzed as a corner crack".

<sup>\*</sup> Combining a SIF solution for a single corner crack and a double throughthickness crack was considered reasonable for two reasons. First, because of the close agreement between the single corner crack solution and the double through-thickness crack solution, as modified using the data in Figure 11 of Reference 13, for short cracks, and because the difference in SIF solutions betweeen single and double corner cracks, for the crack sizes of interest, was less than 3 percent.



a. corner-crack domain - expanded scale

À.S



b. full range of normalized crack length

#### FIGURE B-1. NORMALIZED STRESS INTENSITY FACTOR VERSUS NORMALIZED CRACK LENGTH FOR CRACKS EMINATING FROM CIRCULAR HOLES, CENTRALLY LOCATED IN FINITE WIDTH PLATES

#### <u>Appendix C. Analytical Consideration of Crack Tip Plasticity--</u> <u>Pseudoplastic Extension of LEFM to Small Cracks</u>

This appendix reports on a task whose purpose was to analytically examine the influence of crack tip plasticity as a function of crack length. The desire was to find a simple and inexpensive method to extend the applicability of LEFM to smaller crack sizes with significant crack tip plasticity.

The effort pressed forward in four subtasks and is so reported. These subtasks were: (1) review the relevant literature, (2) develop a simple analysis framework to account for crack tip plasticity, (3) evaluate an economical procedure to generate solutions for a variety of geometries within the analysis framework of Subtask 2 and (4) develop a means to account for microcrack closure. Commitments to these efforts involved an almost equal split of about 80% of the analysis appropriation, a portion of the appropriation for the literature review, and a small but significant portion of the experimental appropriation for model verification for Subtask 2. Results of these subtasks follow.

#### Literature Review

Results of this effort are presented in our earlier report [4].

#### Analysis Framework for Crack Tip Plasticity--Pseudoplastic Model and Application/Evaluation

Results of this effort are reported in two papers [9,19] that present and summarize the framework and outline its application and verification in terms of results for the aluminum CNP sample noted in Table 1.

#### Exploratory Evaluation of an Economical Solution Generation Procedure

As detailed in References 9 and 19, our analysis framework makes use of a pseudoplastic characterization of crack driving force. It uses the usual LEFM K solution in conjunction with a singularity canceling relationship that also follows from LEFM considerations. The boundary point least squares (BPLS) solution procedure offers a very economical means to develop this information. For this reason a study of the utility and accuracy of BPLS was undertaken for an edge cracked panel and a symmetrically cracked CNP. Unfortunately, problems with the solution procedure developed as the crack length decreased. After a persistant attempt by Dr. L. E. Hulbert in cooperation with Ms. V. Papaspyropoulus, the BPLS effort was abandoned leaving only the finite element approach detailed in Reference 19 as the basis to make the required LEFM analysis.

#### Crack Closure

This is the last of the analytical tasks initiated in regard to crack tip plasticity. Need for this task was identified as a result of the literature review which showed closure to be a key factor in some explanations of short-crack effects. The effort focused on an extension of earlier work by Kanninen et al [20] based on an inclined strip yield formulation, following the lead of others [59], who had applied strip yield models to this type of analyses. The advantages of such a framework were (1) it is a direct extension of the colinear strip formulation already in use, (2) it has the potential to be implemented in the absence of detailed inelastic analysis and (3) the concept already had been used in Europe and later the U.S. to account for closure for long cracks [59,61,62]. The work was terminated in view of funding limitations, awaiting definitive results showing a significant closure effect for Inconel 718. Subsequent to our critical review and concurrent to our feasibility study, Newman [10] independently demonstrated with appropriate calibration of his model that closure could simulate short crack trends observed in the literature.

#### Appendix D. Accuracy and Precision in Crack Length Measurement

Measurement of physically small cracks involves problems and techniques not always encountered with physically long cracks. Accuracy and precision are important considerations in choosing editing and analysis procedures and in data interpretation for short cracks. For this reason details concerning accuracy and precision, and also the threshold for detection, have been summarized under funding from the reporting appropriation. This summary is presented in this appendix.

Accuracy of a measurement technique is a measure of the agreement between the absolute measurements obtained using the technique with those obtained using some other technique which serves as a standard. The photographic method used in this study does not allow simultaneous measurement of the crack length by another suitable measurement technique. Therefore, in the strictest sense one cannot establish the accuracy of the present method; however, information is available to give a rough estimate of expected accuracy. Specimens which were to undergo wake removal were removed from the load frame after initiating and growing the crack to some specified length. The cracks were then measured using a monocular microscope equipped with a micrometer-driven X-Y table. The micrometer accuracy was  $\pm$  0.00025 inch\*. These measurements were used to guide the machinist carrying out wake removal. Comparison between these lengths and those obtained using the photographic method gives a one point check of accuracy (see Table D-1).

Two things should be noted. First, the number of load cycles experienced by the specimen at the time of measurement is reported in Table D-1. Often the last picture prior to wake removal was taken a number of cycles before load cycling was stopped. Thus, a small increment of crack growth could occur before microscopic measurement. Second, this one point check of agreement is not a true measure of accuracy. A proper determination

<sup>\*</sup> As inch units form the basis for this study, the results are reported in that units system. Summary results and conclusions are presented with SI equivalents.

TABLE D-1a. COMPARISON OF CRACK LENGTHS AT WAKE REMOVAL MEASURED BY MICROSCOPE AND THE PHOTOGRAPHIC METHOD\*

inches) Side 2 -.0009 -.0009 -.0005 .0006 .0002 .0102 .0020 .0002 -.0041 .0000 Absol.te Side 1 0.0 .00.5 00.22 .00.08 .0004 -.00.38 1000. .0127 .00.01 0001 Side Error 2.8 10.9 68.5 9.6 1.6 -22.0 -6.4 4.0 -2.4  $\sim$ -3.1 Relative (%) ide 1 Side 0.0 6.5 -4.8 4.3 1.2 10.3 <u>د</u> S. 3 84.7 Side Cyc le 1980 8490 4490 13300 7400 2580 7500 8430 3720 4350 Side Photographic Method .0139 0278 .0183 .0230 0185 .0226 .0155 .0232 Length .0241 .0147 Cyc le 4490 1980 9270 13300 7400 2580 7500 8480 3720 4350 Side .0169 .0165 .0190 .0154 .0229 0299 .0188 .0357 Length .0277 .0171 Cycle 4510 2590 7600 8500 3750 13400 7500 1980 8430 4350 Microscope .0148 .0188 .0183 .0143 .0206 .0223 .0188 Length .0153 0287 .0224 Side Length 0228 0298 .0353 .0150 .0153 .0164 0178 .0162 .0180 .0171 Side Spec imen CC-15 CC--19 CC-10 CC-13 CC-14 CC-18 CC-12 CC-11 6-00 CC-3 ×

= 1 mm) lengths are in inches, which formed the basis for measurement (.03937 inches microscopic measurements are  $\pm$ .00025 inches. All **LIA** 

TABLE D-1b. COMPARISON OF CRACK LENGTHS AT WAKE REMOVAL MEASURED BY MICROSCOPE AND THE PHOTOGRAPHIC METHOD (CONT'D)\*

		Side Crac	ч Ч Ч	Error	Side Cracl	1 <sup>0</sup>	Error	Sid Crac	ie 2 ck 1	Error	Side Crac	2 0 7	Error
0)	specimen	M'scope Cycle	Photo. Cycle	% Absolute	M'scope Cycle	Photo, Cycle	% Absolute	M'scope Cycle	Photo. Cycle	% Absolute	M'scope Cycle	Photo. Cycle	% Absolute
l	CH-1	.0409 3082	.0302 3074	-26.2 0107	0 3082	0 3082		.0776 .3082	.0707 3074	-8.9 0069	0 3082	0 3082	
	CH-3	.0147 211	.0146 205	0001	.0041 211	.0057 211	39.0 .0016	.0154 211	.0149 205	-3.2 0005	.0029 211	.0016 246	-44.8 0013
	CH-4	.0063 370	.0071 367	12.7	.0343 370	.0300 367	-12.5 0043	.0091 370	.0054 367	-40.7 0037	.0461 370	.0429 367	-6.9 0032
121	СН-16	.0316 3131	.0332 3131	5.0 .0016	.0162 3131	.0140 3131	-13.5 0022	0 3131	0 3131		0 3131	0 3131	
*	All leng <sup>1</sup> All micro	ths are in oscopic mea	inches, v isurements	which formed s are ±.0002	l the basi: 5 inches.	s for me	asurement	(.03937	inches =	1 mm).			

of accuracy would involve a number of comparisons of mean values obtained by making repeat measurements of crack length at various stages in its growth.

For the 32 sets of data listed in Table D-1, the mean absolute error is - 0.00002 inch (.5  $\mu$ m) and the standard deviation on the mean is 0.0041 inch (104  $\mu$ m). These numbers suggest a high variability in the accuracy of the method, but a very good agreement in the mean. Note that error bands for K derived from applying  $\pm$  0.004 inch to crack length would be on the order of the width of the symbols used in the da/dN -K<sub>max</sub> plots in this report. It can be expected that some of the variability observed arises from the procedure being used to estimate accuracy. Estimates of relative error are also reported. For cracks 0.014-0.017 inches in length, the average relative error is 13.7%, with values ranging from -0.7% to 84.7%.

Precision indicates the inherent variability of the measurement technique. In this study measurement precision is defined as the standard deviation on the mean value of crack length determined for a set of replicate measurements. Because of variations in film quality from roll to roll, the precision was determined for each roll by averaging the standard deviations found for 3 sets of 15 replicate readings made on 3 film images chosen at random. These average values are reported in Table D-2. For the 45 values shown, the mean value is 0.0002 inch (5  $\mu$ m) with a standard deviation of 0.0002 inch (5 $\mu$ m). Error bands for this precision would be smaller than the height of the symbols used on the plots in this report.

Editing of the crack length record was done by requiring a  $2\bar{\sigma}$  increase in successive readings, applying the appropriate standard deviation determined for each roll of film to the raw data for that roll. Determination of precision was not made for specimens CC-10, 11, 12, and 13. They were edited with an assumed value of  $\sigma$  equal to 0.0002 inch. The resulting data sets were satisfactory.

The threshold for crack detection is significant because it limits the amount of information obtainable in the range of crack lengths over which anomolous growth behavior is expected. Table D-3 summarizes the smallest crack lengths detected for each test. Initial EDM flaw length, natural crack length, and total crack length are included. The three factors most affecting

Specimen	Side	Ro11	ơavg	Specimen	Side	Ro11	σ <sub>avg</sub>
CC-9	1	1	.000100	CH-1	1	1	.000204
•••	-	2	.000138	0	-	2	.000164
	2	ī	.000155		2	ī	.000271
	-	2	.000365		-	2	.000335
		3	.000067			-	
		•	•••••	CH-3	1	1	.000344
CC-15	1	1	.000146	••••••		Ž	.000344
••		2	.000189		2	ī	.000529
	2	1	.000243		-	2	.000481
		2	.000126			-	
		-		CH-4	1	1	.000224
CC-3	1	1	.000173		-	2	.000806
•• •	_	2	.000509		2	1	.000211
	2	ī	.000107		-	2	.000510
		-				_	
CC-18	1	1	.000131	CH-16	1	1	.000240
-		2	.000389			2	.000221
	2	1	.000072		2	1	.000256
		2	.000079				
				CH-20	1	1	.000154
CC-19	1	1	.000106	-	2	1	.000172
		2	.000092			_	
	2	1	.000097	CH-6	1	1	.000122
		2	.000133	••••••	-	2	.000144
					2	ī	.000658
CC-14	1	1	.000099			2	.000221
	2	1	.000164				
		2	.000062				
		3	.000081				
			_				

### TABLE D-2 SUMMARY OF MEASUREMENT PRECISIONS\*

\* All  $\sigma$  are expressed in inches, which formed the basis for measurement (.03937 in = 1 mm).

		Cracks Starting	from Small EDM Flaws	
Specimen	Side	Initial EDM Half Flaw Length	Average Half Crack Length Measured from Initial EDM Flaw	Total Half Crack Length, a
CC-9	1	.0105	.0028	.0133
	2	.0092	.0009	.0101
CC-10	1	.0106	.0091	.0197
	2	.0083	.0084	.0167
CC-11	1	.0153	.0016	.0169
	2	.0097	.0049	.0146
CC-12	1	.0096	.0019	.0115
	2	.0087	.0023	.0110
CC-13	1	.0093	.0012	.0105
	2	.0138	.0009	.0147
CC-14	1	.0096	.0011	.0107
	2	.0094	.0023	.0117
CC-15	1	.0088	.0023	.0111
	2	.0090	.0011	.0101
CC-3	1	.0085	.0011	.0096
	2	.0073	.0024	.0097
CC-18	1	.0076	.0009	.0085
	2	.0087	.0022	.0109
CC-19	1	.0103	.0012	.0115
	2	.0110	.0020	.0130

### TABLE D-3a. THRESHOLD FOR CRACK DETECTION\*

\* All lengths are in inches, which formed the basis for measurement. (.03937 inches = 1 mm) All measurements are  $\pm$ .00025 inches.

	C	racks Sta	arting from .5 in	nch Diameter Holes	
Specimen	Side	Crack	Depth of EDM Starter Notch	Crack Length Measured from EDM Starter Notch	Total Crack Length c
CH-1	1	1	0	.0080	.0080
	2	2 1	0 0	.0097 .0197	.0097 .0197
CH-2	1	1	0	.0154	.0154
		2	0	. 0027	.0027
	2	1	0	.0010	.0010
CH-3	1	1	.0028	.0009	.0037
		2	.0018	.0044	.0062
	2	1	.0029	.0035	.0064
		2	.0020	.0005	.0025
CH-4	1	1	.0014	.0032	.0046
	_	2	.0017	.0024	.0041
	2	1	.0014	.0044	.0058
		2	.0018	.0024	.0042
CH-16	1	1	0	.0064	.0064
		2	Ō	.0051	.0051
CH-20	1	1	.002		.0049
		2	.002		.0027
	2	1	.002		.0123
		2	.002		.0059
CH-6	1	1	.001		.0021
		2a	0		.0019
	-	2b	0		.0043
	2	1	.001		.0122
		2	0		.0064

## TABLE D-3b. THRESHOLD FOR CRACK DETECTION (CONT'D)

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the threshold for detection were film image quality, the presence of surface irregularities such as pits, and the tightness of the crack. Including the preflaws (about 0.01 inch), the mean crack length, a, for earliest detection is 0.0123 inches (312  $\mu$ m) with a standard deviation of 0.0029 inches (74  $\mu$ m) for the center cracked panels. For the plates with holes, the mean crack length, c, including the preflaws (about 0.001 inch), at earliest detection was 0.0063 inches (160  $\mu$ m) with a standard deviation of 0.0045 inches (110  $\mu$ m). Corresponding means and standard deviations of thresholds for detection in the absence of the preflaws were 0.0025 ± 0.0023 inch (63.3 ± 57.5  $\mu$ m) in CCP samples and 0.0055 ± 0.0053 inch (137 ± 132  $\mu$ m) in CNP samples.

In summary, the results reported here suggest that the photographic method used in this study is capable of highly accurate measurements but is also subject to variability in accuracy for crack lengths on the order of those of interest to this study. Further study of the system is required to make a categorical statement of its measurement accuracy. The precision of the digitizing method was found to be generally on the order of 0.0002 inches (5  $\mu$ m). Therefore data trends for small increments of crack growth could be easily studied. The threshold for crack detection varied from specimen to specimen. Generally the threshold beyond the preflaw was on the order of 0.05 to 0.15 mm.

### APPENDIX E. DATA TABLES

The following tables list the data generated in this study and presented in graphical form in this report. All data has been edited and labeled as detailed in the section on data reduction. Test conditions are given in Table 1, and the specimen geometries are shown in Figure 5.

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## <u>Side 2</u>

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15240. 15120. 14960. 14840.

14720. 14600. 14480.

14320. 14200. 14080.

13960. 13840. 13720.

13520. 13360. 13120.

13000. 12280. 12080.

11960. 11680. 11560. 11560. 11440. 11320. 10900. 10620. 8400. 8200.

8100. 7800. 7600.

7500. 7400. 7200. 7120.

a	<u>N</u>	<u>a</u>
	45080	• • • • • •
0.10658	15280.	0.10034
0.10044	13100.	0.09425
0.05233	14000.	0.08722
0.05931	13900.	0.08257
0.05089	13040.	0.07785
0.05430	13/20.	0.07341
0.05223	13000.	0.05965
	13760.	0.06493
0.04709	13300.	0.06170
0.04572	13120	0.05932
0.04398	13000	0.05061
0.04319	12880	0.05357
0.04070	12760.	0.05106
0.03968	12640.	0.04777
0.03849	12520.	0.04363
0.03704	12400.	0.03202
0.03613	12280.	0.03323
0.03528	12160.	0.03165
0.03502	12040.	0.03119
0.03340	11920.	0.02901
0.03192	11800.	0.02859
0.03112	11680.	0.02708
0.03057	11560.	0.02618
0.02999	11440.	0.02564
0.02930	11320.	0.02427
0.02856	11200.	0.01688
0.02825	10900.	0.01622
0.02760	10780.	0.01601
0.02714	10660.	0.01477
0.02594	10540.	0.01454
0.02566	10420.	0.01428
0.02483	10300.	0.01391
0.02436	10180.	0.01381
0.02152	9500.	0.01331
0.02099	9340.	
0.02069	9260.	
0.02013	9180.	
0.01944	<b>910</b> 0.	
0.01679	8780.	
0.01845	8480.	
0.01753	8280.	
0.01712	8180.	
0.01668	7980.	
0.01607	7680.	
0.01536	7480.	
0.01466	6720.	
0.01289	6400.	
C.01154	5700.	
0.01108	5300.	
0.01009	5100.	

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<u>Side 2</u>

<u>a</u>	<u>N</u>	<u>a</u>	<u>N</u>
0.12413	7080.	0.16138	7310
0.1151	7010.	0.14703	7260
0.10858	6950.	0.13513	7210
0.09843	6860.	0.12756	7160
0.08815	6710.	· 0.11869	7110
0.07492	5550.	0.11092	7050
0.06892	6410	0.0000	7010.
0.06335	6310.	0.09329	5950.
0.05919	6210.	0.09032	69 IU.
0.05498	6110.	0.08446	6810
0.05221	6010.	0.08067	6760
0.05022	<b>596</b> 0.	0.07683	6710.
0.04757	5910.	0.07408	6660.
0.04889	5810	0.07181	6610.
0.04074	5560	0.06837	<b>656</b> 0.
0.03804	5460.	0.00305	6510.
0.03755	5360.	0.06083	6410
0.03538	5310.	0.05968	6360
0.03485	5160.	0.05867	6310.
0.03339	<b>505</b> 0.	0.05606	5260.
0.03231	5010.	0.05413	6210.
0.02953	4910.	0.05148	6160.
0.02793	4280	0.04859	6110.
0.02560	4210.	0.04504	<b>6060</b> .
0.02372	4060.	0.06348	6010. 6080
0.02334	4010.	0.04109	5900.
0.02758	3720.	0.04084	5860
0.02523	3500.	0.03960	5760.
0.02518	3470.	0.03974	5710.
0.02453	3320	0.03837	5660.
0.02381	3130.	0.03749	5610.
0.02312	3040.	0.03568	3350. 5540.
0.02199	2930.	0.03509	5480
0.02140	2900.	0.03443	5360
0.02089	2840.	0.03267	5260.
0.01967	2810.	0.03160	5210.
		0.03100	5110.
		0.02928	5080.
		0.02875	5010.
		0.02896	4910.
•		0.02646	4660
		0.02595	4610.
		0.02546	4460
		0.02483	4410.
		0.02409	3720.
		0.02243	3630.
		0.02170	3600.
		0.02041	3450.
		0.01858	3330.
		0.01674	3270

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<u>Side 1</u>

## Side 2

<u>a</u>	N	<u>a</u>	<u>N</u>
0.09944	12810.	0.11619	12990.
0.09321	12750.	0.11165	12930.
0.08920	12690.	0.10622	12870.
0.08533	12630.	0.09768	12750
0.08140	12570.	0.09511	12690.
0.07555	12390.	0.09132	12630.
0.07116	12330.	0.08842	12570.
0.06859	12270.	0.08430	12510.
0.06433	12210.	0.08194 0.07945	12450.
0.06176	12150.	0.07586	12380.
0.05977	12090.	0.07417	12270
0.05638	11970	0.07125	12210.
0.05369	11910.	0.06927	12150.
0.05282	11850.	0.06724	12090.
0.05039	11790.	0.06612	12030.
0.04747	11730.	0 06448	11970.
0.04705	11670.	0.06033	11850
0.04511	11550.	0.05929	11790.
0.04403	11490.	0.05793	11730.
0.04091	11370	0.05639	11670.
0.03926	11310.	0.05408	11550.
0.03758	11250.	0.05178	11490.
0.03670	11190.	0.05062	11430.
0.03534	11130.	0.04679	11250
0.03326	11010.	0.04580	11190.
0.03258	10890.	0.04526	11130.
0.03178	10770.	0.04403	11070.
0.03034	10530	0.04292	11010.
0.02637	10470.	0.04204	10950.
0.02573	10410.	0.04012	10830.
0.02496	10230.	0.03896	10710
0.02422	10170.	0.03787	10590.
0.02375	10050.	0.03669	10530.
0.02084	9930	0.03594	10470.
0.01984	9810.	0.03534	10410.
0.01912	9750.	0.03304	10350.
0.01846	9390.	0.03219	9930.
0.01688	9270.	0.03130	9810.
		0.02951	9750.
		0.02876	9630.
		0.02819	9330.
		0.02/71	9270.
		0.02461	8790
		0.02419	8730
		0.02247	7400.
		0.02154	6680.
		0.02058	6560.
		0.01634	6440.
		0.01458	6290.

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a	<u>N</u>	<u>a</u>	<u>N</u>
0.09645	7590.	0.11347	7610
0.08878	7530.	0.10359	7550
0.08179	7470.	0.09497	7490
0.07724	7410.	0.08327	7430
0.07286	7350.	0.08159	7370
0.06752	7290.	0.07614	7310
0.06435	7230	0.07095	7250
0.06111	7170.	0.05690	7190
0.05749	7110.	0.06349	7130
0.05517	7050	0.05918	7070
0.05267	6990.	0.05557	7010
0.04982	6930	0.05396	6950
0.04840	6870	0.05075	6890
0.04577	6810	0.04836	6830
0.04492	6750	0.04598	8770
0.04281	6690	0.04446	6710
0.04152	6570	0.04299	6850
0.03859	8510	0.04088	8590
0.03712	6450	0.03983	6530
0.03562	6390	0.0303	6330
0.03463	6320	0.03801	04/0
0.00400	6270	0.03031	0410
0.03265	6210.	0.03533	6350
0.02122	6160	0.03368	6290.
0.03122	613U. 8090	0.03262	6230.
0.03010	6030.	0.03177	6170.
0.02833 A 02880	5030.	0.03090	6110.
0.02005	337U. 5010	0.02991	6050.
0.02019	381U. E8E0	0.02903	5990.
0.02592	363V. 567A	0.02819	5930.
0.02503	3070. EEEO	0.02728	5870.
0.02004	5420	0.02618	5810.
02260	3430.	0.02561	5850.
02211	5370.	0.02493	5790.
02126	5310.	0.02441	5730.
02075	318U. 5070	0.02363	5670.
01949	5070.	0.02279	5550.
01995	4830.	0.02222	5490.
01922	4880.	0.02159	5430.
01797	4770.	0.02082	5310.
01707	4710.	0.02001	5190.
01730	4350.	0.01918	5070.
0.01048	4330,	0.01837	4950
0.0138/	4230.	0.01787	4890.
01493	41/Q.	0.01726	4770.
0.01435	3750.	0.01656	4650
0.01300	3570.	0.01610	4470
0.01281	3450.	0.01554	4350
9.01153	2730.	0.01491	4230
		0.01404	3990
		0.01291	3480
		0.01103	2540

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# <u>Side 2</u>

a	N
0.10786	7230.
0.09492	7170.
0.08175	7050.
0.07726	6990. 8530.
0.06757	6870.
0.06185	6750.
0.05592	6690.
0.05072	<b>657</b> 0.
0.04845	6510. 6450
0.04553	6390.
0.04427	6330. 6270.
0.03861	6050.
0.03785	5990. 5930.
0.03342	5870.
0.03241	5750.
0.03172	5690. 5570
0.02829	5510.
0.02776	5450. 5330.
0.02499	5150.
0.02408	5090. 4790.
0.02163	4730.
0.01969	4550.
0.01895	4490. 4430
C.C1694	4290.
0.01 <b>594</b> 0.01502	3990. 3870.
0.01353	3510.
0.01380	3450. 3330.
0.01250	3150.
0.01208	3090. 2850.
0.01051	2790.

<u>Side 1</u>

<u>a</u>	<u>N</u>
0.11410 0.09976	7310 7250
0.09030	7190
0.07480	7070
0.05946	6890
0.05269	6770 6710
0.04573	6650 6590
0.04089 0.03850	6530 6470
0.03739 0.03482	64 10 6350
0.03241 0.03070	8290 8230
0.02787	6170 6110
0.02560	5990 5930
0.02369 0.02279	5870 5810
0.02134 0.02069	5890 5630
0.01895	5570 5450
0.01647	5150 5020
0.01467	4490

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<u>Side 1</u>

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a	<u>N</u>	<u>a</u>	<u>N</u>
0. 10403	26460.	0 03070	10700
0.10167	26380.	0.03079	19760.
0.09848	26260.	0.02975	19000.
0.09709	26160.	0.02887	19300.
0.09569	26060.	0.02837	19080
0.09150	25960.	0.02780	18780
0.08871	25860.	0.02724	18660
0.08718	25780.	0.02638	18360
0.08588	25660.	0.02594	18260.
0.08304	25560.	0.02527	18180.
0.08184	25460.	0.02484	18080.
0.08007	25360.	0.02411	17760.
0.07905	25200.	0.02344	17330.
0.07345	25060	0.02274	16910.
0.07146	24960	0.02233	16730.
0.07016	24860.	0.02166	16490.
0.06842	24760.	0.02123	15430.
0.06795	24660.	0.02080	16070.
0.06614	24560.	0.01984	10010.
0.05489	24460	0.01939	18710.
0.06403	24360.	0.01867	14930
0.06253	24260.	0.01818	14870
0.06182	24160.	0.01746	14330
0.06011	23960.	0.01701	14270.
0.05737	23860.	0.01659	13850.
0.05802	23780.	0.01507	12780.
0.05581	23560.	0.01454	11880.
0.03366	23460.	0.01399	11220.
0.05265	23360.	0.01348	10680.
0.05123	23000.	0 01234	10380.
0.04888	22560	0.01183	10040.
0.04586	22380	0.01072	9160.
0.04365	22280	0:010/2	<b>\$080</b> .
0.04323	22160.		
0.04240	22060		
0.04199	21960.		
0.04091	21760.		
0.04045	21660.		
0.03940	21460.		
0.03731	21260.		
0.03677	21060.		
0.03622	20960.		
0.03548	20860.		
0.03443	20460.		
0.03309	20360.		
0.03265	20180.		
0.03171	19960.		•
#### <u>CC14</u> (Concluded)

<u>Side 2</u>

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<u>a</u>	<u>N</u>
0.11675	27560.
0.10929	27380.
0.10310	27160.
0.09212	26780
0.08709	26560.
0.08271	26360.
0.07914	26150.
0.07173	25760.
0.06859	25560.
0.06565	25360.
0.06407	25160.
0.05969	24780.
0.05659	24560.
0.05477	24360.
0.05217	24160.
0.05007	23960.
0.04597	23360.
0.04389	23160.
0.04162	22760.
0.03994	22560.
0.03753	2230U. 22160
0.03628	21960.
0.03516	21760.
0.03423	21560.
0.03293	21360.
0.03140	21160.
0.03088	20760
0 . 02969	20560.
0.02800	20160.
0.02/39	19860.
0.02596	19460
0.02545	19260.
0.02489	19160.
0.02449	18960.
0.02318	18360
0.02237	17960.
0.02193	17660.
0.02095	16840.
0.01579	14620.
0.01507	13840.
0.01464	13540.
0.01350	12700.
0.01260	12100.
0.01220	10900
0.01167	10180.

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<u>Side 1</u>

<u>Side 2</u>

<u>a</u>	<u>N</u>		<u>a</u>	<u>N</u>
0.10326	13720.		0.11178	13920.
0.09851	13620.		0.10735	13820.
0.09390	13520.		0.10236	13720.
0.08751	13320.		0.09387	13520.
0.08293	13220.		0.09128	13420.
0.08129	13120.		0.08722	13320.
0.07557	12920.		0.08099	13120.
0.07234	12820.		0.07812	13020.
0.07149	12720.		0.07517	12920.
0.06685	12520.		0.07023	12720.
0.06431	12420.		0.06705	12620.
0.06223	12320.		0.06508	12520.
0.05843	12120.		0.06082	12320.
0.05753	12020.		0.05911	12220.
0.05562	11920.		0.05799	12120.
0.05219	11620.		0.05432	11920.
0.05100	11520.		0.05299	11820.
0.04906	11420.		0.05244	11720.
0.04664	11220.		0.04912	11520.
0.04577	11120.		0.04877	11420.
0.04460	11020.		0.04776	11320.
0.04270	10720.		0.04338	10920.
0.04177	10620.		0.04248	10820.
0.04051	10520.		0.04166	10720.
0.03813	10120.		0.03965	10620.
0.03764	9720.		0.03898	10420.
0.03438	<b>962</b> 0.		0.03804	10320.
0.03360	9520.		0.03581	10220.
0.03250	8920.		0.03536	9920.
0.03147	8720.		0.03465	9720.
0.02894	8420.		0.03297	9520.
0.02836	8000.		0.03268	9420.
0.02688	7900.		0.03238	9320.
0.02543	7700.		0.03122	9120.
0.02432	7600.		0.03082	9020.
0.02284	7200.		0.02989	882O.
0.02228	6900. 6800		0.02811	8520.
0.02124	6400.		0.02753	8420.
0 01940	8300		0.02592	8100.
0 01879	5800.		0.02456	7800.
0.01836	5400.		0.02414	7700.
0.01686	5000.		0.02353	7600.
0.01637	4800.		0.02057	6700.
0.01470	4200.		0.01997	6400.
0.01365	3300.		0.01947	6300. EE00
0.01311	3100.		0.01772	5400.
0.01204	2900.		0.01663	4700.
0.01112	4000.		0.01531	4400.
			0.01391	3700.
			0.01331	3100.
			0.01251	2500.
			0.01139	2000.
			0.01063	1600.
		135	0.01008	1200.

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<u>Side 2</u>

	<u>Side 1</u>
<u>a</u>	<u>N</u>
0.10252 0.09348 0.08758 0.08528 0.07883 0.07330 0.06823 0.06548 0.05091 0.05732 0.05369 0.05732 0.05369 0.04782 0.02875 0.02875 0.02957 0.02989 0.02875 0.02297 0.02495 0.02297 0.02495 0.02287 0.02297 0.02495 0.02287 0.02297 0.02495 0.02297 0.02495 0.02283 0.02284 0.02297 0.02485 0.02287 0.02288 0.02287 0.02287 0.02287 0.02289 0.02287 0.02287 0.02287 0.02287 0.02287 0.02287 0.02287 0.02287 0.02287 0.02287 0.02287 0.02597 0.02495 0.02184 0.02080 0.01834 0.01634 0.01557 0.01383 0.01317 0.01383	4450. 4390. 4330. 4270. 4090. 4030. 3970. 3970. 3850. 3730. 3670. 3550. 3430. 3550. 3430. 3550. 3430. 3550. 2520. 2550. 2580. 2520. 2580. 2520. 2460. 2460. 2400. 2340. 2280. 2280. 2280. 2280. 2340. 2340. 2020. 1960. 1960. 1840. 1780. 180. 1300.
0.01217 0.01173 0.00962	820. 760. 700.

a	N
0.02784	2580
0.02571	2400
0.02450	2340
0.02384	2280
0.02239	2180
0.02217	1920
0.01816	1200
0.01757	1890
0.01874	1000.
0.01557	1440.
0.01402	1320.
0.01702	1200.
0.01387	1140.
0.01187	840.
0.01127	660.
<b>0.00970</b>	800

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0.01480

0.01441

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0.01186

0.01146

0.01131

0.01110 0.01090

<u>Side 2</u>

5600.

5500.

3700.

3600.

3400.

3300.

3000.

2800. 2600.

a	N	<u>a</u>	<u>N</u>
0.03892	11700.	0.03460	11700.
0.03648	11400.	0.03273	11600.
0.03328	11200.	0.03145	11500.
0.03188	10800.	0.03107	11400.
0.03094	10800.	0.03026	11300.
0.03012	10400.	0.02944	11200.
0.02852	10000.	0.02894	11100.
0.02742	<b>960</b> 0.	0.02860	11000.
0. <b>026</b> 50	9300.	0.02817	10900.
0.01803	6800.	0.02771	10800.
0.01714	6400.	0.02737	10700.
0.01679	6300.	0.02704	10500.
0.01640	6000.	0.02655	10500.
0.01593	5900.	0.02599	10200.
0.01563	5400.	0.02559	10100.
0.01508	5100.	0.02465	10000.
0.01413	4800.	0.02422	9900.
0.01333	4700.	0.02330	9700.
0.01298	4800.	0.02275	9500.
0.01262	4300.	0.02238	9400.
0.01237	4100.	0.02016	<b>9300</b> .
0.01173	3600.	0.02176	9100.
0.01129	3100.	0.02120	9000.
0.01087	<b>290</b> 0.	0.02054	8800.
0.01056	2700.	0.02004	8800.
0.01017	2200.	0.01947	8500.
0.00975	1900.	0.01924	8400.
0.00948	1200.	0.01900	8300.
0.00912	900.	0.01859	8200.
0.00851	800.	0.01834	7500.
		0.01816	7400.
		0.01787	7200.
		0.01762	7100.
		0.01735	7000.
		0.01569	6100.
		0.01531	6000.
		0.01505	5800.

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# <u>Side 1</u>

## <u>Side 2</u>

<u>a</u>	<u>N</u>
0.10051	2700.
0.07392	2040.
0.06489	2520
0.06116	2460.
0.05797	2400.
0.05224	2340.
0.04719	2280.
0.04390	2220.
0.03939	2100.
0.03735	2040
0.03574	1980.
0.03439	1920.
0.03238	1860.
0.03122	1800.
0.03033	1740.
0.0233/	1680.
0.02645	1520.
0.02514	1500.
0.02441	1440.
0.02374	1380.
0.02209	1320.
0.02121	1260.
0.02051	1200.
0.01982	1140.
0.01840	1080.
0.01764	960
0.01682	900.
0.01643	840.
0.01596	780.
0.01516	720.
0.01493	660.
0.01406	600
0.01289	540
0.01261	420
0.01177	360
0.01148	300.

<u>a</u>	N
0.09595	2700
0.07719	2640
0.06437	2580
0.05596	2520
0.05182	2460
0.04762	2400
0.04214	2340
0.03605	2280
0.03242	2220
0.02961	2160
0.02602	2100
0.02387	2040
0.02303	1920
0.02100	1000
0.01839	1920
0.01805	1800
0.01714	1740
0.01622	1740
0.01405	1080
0.01400	1620
0.01402	1560
0.01288	1500

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Crack 1/Side 1

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Crack 1/Side 2

<u>c</u>	<u>N</u>
0.01537	29120.
0.01701	29130.
0.02029	29140.
0.02254	20150.
0.02357	29180.
0.025 0.02582 0.02684 0.02787 0.02910 0.02910 0.02971	29190. 29220. 29230. 29300. 29310. 29330.
0.03094 0.03238 0.0332 0.03381 0.03463 0.03545	29340. 29350. 29490. 29520. 29580.
0.03568	29670.
0.03791	29690.
0.03955	31620.
0.04201	31640.
0.04303	31860.
0.04406	31750.
0.04467	31830.
0.04831	32080.
0.04754	32220.
0.04816	32230.
0.05	32630.
0.05594	32840.
0.06025	33140.
0.08557	33180.
0.07541	33280.
0.08074	33310.
0.08566	33390.
0.09221	33410.
0.09713	33450.
0.10041	33480.
0.10553	33510.
0.11004	33540.
0.11516	33580.
0 . 12090	33610.
0 . 12602	33650.
0 . 13033	33680.
0 . 13586	33720.
0 . 15061	33820.
0 . 15615	33860.

<u>c</u>	<u>N</u>
0.0	33180.
0.00102	33190.
0.00963	33200.
0.01926	33210.
0.02623	33220.
0.03135	33230.
0.03832	33240
0.03934	33250
0.04795	33280.
0.05	33290.
0.05594	33320
0.05639	33370
0.07172	33400
0.07623	33440
9.08258	33470
0.08627	33510
0.09037	33340
0.05528	33370
0.10200	22850
0.10333	33050
0.11837	33720
0.11557	33790
0.13135	33830
0.13525	33850
0.14119	33910
0.14508	33940
0.15143	33980
0.15594	34010
0.16107	34940
0.10557	34080
6.17131	34120
0.17480	34140

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		<u>CH1</u>		
1/Side 2	<u>Crack</u>		<u>1/Side 1</u>	Crack
<u>N</u>	<u>c</u>		N	<u>c</u>
3190 3185 3180 3175 3170 3185 3160 3155 3150 3155 3150 3155 3150 3155 3120 3074 3074 3074 2994 2974 2994 2974 2934 2934 2894 2894	0.21499 0.20957 0.20480 0.19712 0.19027 0.18704 0.18127 0.17800 0.17800 0.17008 0.15529 0.14757 0.14757 0.14757 0.14757 0.12769 0.07069 0.07069 0.07069 0.08258 0.05313 0.04929 0.04249 0.04249 0.04249 0.04249 0.04295 0.03270 0.03204 0.02955		3130. 3125. 3120. 3074. 3014. 2994. 2954. 2954. 2794. 2734. 2714. 2214. 2014. 1934.	0.13840 0.13033 0.12300 0.03022 0.01200 0.01223 0.01150 0.01109 0.01036 0.00924 0.00886 0.00924 0.00886 0.00927 0.00757 0.00711
2614 2774	0.02029 0.01967			

3190. 3185. 3180. 3175.

#### <u>CH1</u> (Concluded)

## Crack 2/Side 1

<u>c</u>	N
0. 16519	3331.
0.11435	3326.
0.09086	3321.
0.07385	3316.
0.08297	3311.
0.05607	3306.
0.05094	3301.
0.04485	3296.
0.04038	3291.
0.03670	3283.
0.03454	3278.
0.02496	3255.
0.02431	3250.
0.02318	3240.
0.02176	3235
0.02077	3230
0.01825	3195
0.01788	3185.
0.01635	3180
0.01533	3165
0.01343	3155
0.01317	3145.
0.01278	3140.
0.01156	3130.
0.01115	3125.
0.00969	3120.

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## Crack 1/Side 1

Crack 1/Side 2

<u>c</u>	<u>N</u>
0.14527	3341.
0.13890	3334.
0.13202	3327.
0.12170	3312
0.11270	3306
0.10605	3299
0.10103	3292.
0.09458	3285.
0.08972	3278.
0.08208	3271.
0.07892	3264.
0.07495	3257.
0.07075	3250.
0.06763	3243.
0.00021	3230.
0.05854	3222
0.05601	3215
0.05467	3208
0.05174	3201.
0.04906	3194.
0.04750	3180.
0.04488	3173.
0.04319	3166.
0.03317	3131.
0.03167	3111.
0.03019	3091.
0.02755	3051
0.02626	3031.
0.02458	3011.
0.02092	2991.
0.01959	2911.
0.01704	2891.
0.01650	2831.
0.01447	2811.
0.01363	2731.
0.01306	2711.
0.0121/	2091. 2811
0.00987	2011.
0.00887	2391
0.00837	2311.
0.00785	2171.
0.00738	3131.
0 . <b>006</b> 36	2111.

c	N
-	<u></u>
0.18353	3405
0.16466	3391
0.15830	3384
0.15158	3377
0.14330	3370
0.13633	3363
0.13049	3356
0.12161	3349
0.11584	3342
0.10844	3335
0.10267	3328
0.09671	3321
0.08843	3314
0.07942	3307
0.07132	3300
0.06298	3293
0.05327	3286
C. 04075	3279
0.02057	3272

#### <u>CH16</u> (Concluded)

## Crack 2/Side 1

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<u>c</u>	<u>N</u>
0.14603	3425.
0.12282	3418.
0.10635	3411.
0.09136	3404.
0.07986	3397.
0.07424	3390.
0.06318	3383.
0.03914	3376.
0.05466	3309.
0.05015	JJDZ. 2255
0.04585	3335.
0.04318	3341
0.04073	3334
0.03873	3327
0.03753	3320
0.03536	3313.
0.03341	3306.
0.03135	3292.
0.02950	3285.
0.02871	3278.
0.02360	3271.
0.02273	3243.
0.02304	3236.
0.01864	3215.
0.01809	3137.
0.015/0	3111.
0.01312	3091.
0.01343	3011
0.01060	2991
0.00943	2871
0.00887	2831
0.00803	2751.
0.00735	2631.
0.00580	2491.
0.00505	2431

Crack	1/Side 1	Crack 1	/Side 2	
<u>c</u>	<u>N</u>	<u>c</u>	<u>N</u>	
<u>c</u> 0.15881 0.14817 0.13093 0.11924 0.09699 0.07400 0.06518 0.05785 0.04537 0.03938 0.03304 0.02351 0.02072 0.01768 0.01359 0.0877	11   500.   495.   490.   485.   480.   475.   470.   465.   480.   455.   450.   455.   430.   445.   435.   430.   425.   420.   415.   400.   375.	0. 19253 0. 17490 0. 15791 0. 14380 0. 12909 0. 11773 0. 10548 0.09609 0. 08252 0. 07260 0. 06747 0. 05755 0. 04932 0. 04184 0. 03639 0. 03097 0. 02689 0. 02506 0. 01977	515. 510. 505. 500. 495. 490. 485. 480. 475. 470. 465. 480. 455. 450. 445. 440. 435. 430. 420.	
0.00689 0.00633 0.00578 0.00508 0.00457	357. 337. 332. 317. 312	0.01829 0.01632 0.00576 0.00144	415. 405. 362. 357.	

<u>CH4</u> (Concluded)

Crack	2/Side 1	
<u>c</u>	<u>N</u>	
0.1 <b>540</b> 3 0.1 <b>5226</b>	450. 445	
0.15033	435.	
0.14474	430.	
0.13695	425.	
0.12795	420.	
0.11707	415.	
0.11144	410.	
0.09503	400	
0.08418	395.	
0.07225	390.	
0.06242	385.	
0.05440	380.	
0.04075	375.	
0.02998	367.	
0.02468	367	
0.01632	352	
0.01558	347.	
0.01251	342.	
0.01166	337.	
0.00860	327.	
0.00640	287	
0.00507	277.	
0.00405	257.	

<u>c</u>	<u>N</u>
	N 470 485 480 455 450 445 440 435 430 425 430 425 430 425 430 395 390 385 385 385 387 362 357 362 327 322 317 322 297 297 297 297 297 297 297 2
0.00609 0.00561 0.00485 1.30419	245. 235. 215. 200 <i>PT</i>

Crack 2/Side 2

Crack 1/Side 1		Crack 1/	Side 2
<u>c</u>	<u>N</u>	<u>c</u>	N
0.14154	309.	0.19808	344.
0.13080	302.	0. <b>18669</b>	337.
0.12047	295.	0.17888	330.
0.10724	288.	0.15883	323.
0.09532	281.	0.14799	316.
0.08754	274	0.13426	309.
0 07394	267	0.12154	302.
0.06577	260	0.11064	295.
0.05392	253	0.10010	288.
0.04572	246	0.08816	281.
0.03593	239	0.07700	274.
0.03984	232	0.06557	267.
0.02304	225	0.05530	260.
0.02381	218	0.04741	253.
0.01457	215.	0.03792	246.
0.01995	203.	0.03088	239.
0.01335	190	0.02396	232.
0.01212	180.	0.02001	225.
0.01117	180.	0.01724	210.
0.00351	105.	0.01491	205.
0.00/5/	150.	0.01368	200.
0.00524	140.	0.01257	185.
0.00531	125.	0.01031	165.
0.00442	120.	0.00910	150.
0.00365	115.	0.00748	130.
		0.00636	110.

<u>CH3</u>

<u>CH3</u> (Concluded)

Crack 2/Side 1		<u>Crack 2/Side 2</u>	
<u>c</u>	N	<u>c</u>	<u>N</u>
0.15018 0.10881	365. 358.	0. 19828 0. 12050	372. 365.
0.08309 0.05407 0.03920	351. 344. 337.	0.08516 0.05925 0.03752	358. 351. 344.
0.02739 0.02344 0.01927	330. 323. 318	0.01993 0.01231	337. 330.
0.01618 0.01332	309. 302.	0.00774 0.00490	323. 316. 302.
0.01009 0.00891 0.00811	281. 274. 253.	0.00368 0.00252 0.00155	267. 253. 245.
0.00622	205.	2.00120	2

Crack 1/Side 1

## Crack 1/Side 2

<u>c</u>	N	<u>c</u>	N
0.15668	4030.	0.20237	4570
0.14962	3970.	0. 19586	4510
0.14721	3910.	0.19141	4450
0 13845	3050.	0.18459	4390.
0.13072	3730.	0.17977	4330
0.12740	3670.	0.17300	4210
0.12427	3610.	0, 16322	4150
0.11947	3550.	0.15784	4090
0.11651	3490.	0.15182	4030
0.11118	3430.	0.14775	3970.
0,10788	3370.	0.14354	3910.
0.10450	3250	0.13785	3850
0.09716	3190.	0.13281	3790.
0.09324	3130.	0.12800	3730.
0.08952	3070.	0.12080	3570.
0.08762	3010.	0.12133	3010.
0.08544	2929.	0.11320	3490
0.08026	2859.	0.10978	3430.
0.07752	2809.	0.10371	3370.
0.08995	2689.	0.10317	3310.
0.06825	2629.	0.09606	3250.
0.06556	2569.	0.09372	3190.
0.06177	2509.	0.09120	3130.
0.05998	2449.	0.08663	3070.
0.05633	2389.	0.08041	2950
0.05380	2329.	0.07552	2809.
0.04934	2280.	0.07255	2749.
0.04611	2205.	0.07012	2689.
0.04458	2165.	0.08533	2629.
0.04259	2125.	0.06488	2569.
0.04042	2085.	0.05141	2508.
0.03904	2045.	0.05801	2329
0.03731	2005.	0.05030	2285.
0.03515	1903.	0.04761	2245.
0.03207	1885	0.04571	2205.
0.03076	1845.	0.04493	2185.
0.02963	1805.	0.04237	2125.
0.02807	1725.	0.04071	2085.
0.02552	1645.	0.03690	2045.
0.02258	1600.	0.03436	1985.
0.02207	1580.	0.03317	1925.
0.02136	1500.	0.03109	1885.
0.01886	1480.	0.03052	1845.
0.01801	1440.	0.02929	1765.
0.01667	1400.	0.02654	1060. 1845
0.01820	1320.	0.02551	1605
0.01505	1300.	0.01321	1060.
0.01461	1280.	0.01232	660.
0.01416	1240.		
0.01321	1040.		
0.01136	880		
0.01014	860.		
0.00908	800.		
0.00637	580.		
0.00578	500.		
0.00531	420.		
0.00486	400.		

<u>CH20</u> (Concluded)

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Liack 2, Side 1		<u>Crack 2/Side 2</u>	
<u>c</u>	<u>N</u>	<u>c</u>	N
0.14836	4570.	0.14729	4570.
0.14080	4510.	0.14002	4510.
0.13100	4450.	0.13106	4450.
0.12551	4390.	U.12403	4390.
0 10876	4270	0.11858	4330.
0.10382	4210	0.10073	4270.
0.09690	4150	0.08723	4210.
0.08953	4090	0.09023	4190.
0.08530	4030	0.08623	4030
0.07911	3970.	0.07934	3970
0.07219	3910.	0.07323	3910.
0 . <b>066</b> 08	3850.	0.06597	3850.
0.05764	3790.	0.06256	3790.
0.05318	3730.	0.05449	3730.
0.04835	3670.	0.04967	3670.
0.04401	3610.	0.04840	3610.
0.04045	3550.	0.04146	3550.
0.03550	3490.	0.03763	3490.
0.03197	3430.	0.03428	3430.
0.02870	3370.	0.02981	3370.
0.0204/	3250.	0.02940	3310.
0.02100	3190.	0.02369	3250.
0.01833	3130.	0.02237	3190.
0.01830	3070.	0.02037	3130.
0.01593	3010. 2950	0.01910	3070.
0.01466	2020	0.01832	3010.
0.01418	2889	0.01691	2950.
0.01350	2809	0.01311	2809.
0.01199	2749.	0.01338	2089.
0.01058	2689.	0.01355	2509.
0.01005	2449.	0.01200	2320
0.00813	2245.	0.00958	2025
0.00784	2205.	0.00913	2005
D. <b>00713</b>	2165.	0.00769	1925
0.00495	1805.	0.00590	1605
0.00439	1540.	• • • • • • • •	
0.00333	1520.		
0.00304	1400.		
).00269	1120.		

Crack 1/Side 1

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C	N
0.14301	14840.
0.13917	14630. 14420.
0.12871 0.12350	14210. 14000.
0.11859 0.11390	13790. 13580
0.10899 0.10373	13370.
0.09858	12950.
0.08927	12530.
0.08058	12320. 12110.
0.07624	11900. 11690.
0:06894 0.06433	11480. 11270.
0.06119 0.05677	11080. 10850
0.05447 0.05166	10640.
0.04895	10220.
0.04146	9800.
0.03556	9380.
0.03000	\$170. 8960.
0.02423	8750. 8540.
0.02189	8330. 8120.
0.01901 0.01720	7910. 7700.
0.01553 0.01432	7490. 7280.
0.01376 0.01252	7070. 6860
0.01147 0.01061	6650. 6440
0.00981	6230. 6020
0.00825	5810. 58020
0.00699	5390.
0.00567	4970. 4780.
0.00499	4550. 4130.
0.00385	3920. 3360.
0.00301	3080. 3010.
0.00211	2940.

<u>c</u>	N
0.20234	17360.
0.20033	17220.
0.19876	17150.
0.19482	17080.
0.19387	18940.
0.19387 0.19053	16870. 16800
0.18927	16730.
0.18280	18520.
0.17194	16100.
0.16802	15890.
0.15601	15680. 15470
0.15031	15280.
0.14563	15050.
0.13631	14630.
0.12971	14420.
0.12087	14210. 14000.
0.11493	13790.
0.11037	13580.
0.10060	13160.
0.09734	12950.
0.08691	12530.
0.08430	12320.
0.07457	12110.
0.08934	11690.
0.05605	11060.
0.05488	10640.
0.05003	10430.
0.04444	10220.
0.04014	9800.
0.03623	9590. 9380
0.03009	9170.
0.02684	8960.
0.02219	8750. 8540
0.02056	8330.
0.01780	8120. 7910
0.01356	7490,
0.01219	7280.

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Crac	k 2/Side 1	Crack	<u> 2/Side 2</u>
<u>c</u>	<u>N</u>	<u>c</u>	N
<u>fir</u>	<u>st crack</u>	0 . 18378 0 . 15122	26720
0.02312 0.02206	<b>26020</b> . 25920.	0.12977 0.11149 0.08224	26520
0.02142	25820. 25720.	0.08443 0.07215	26320
0.01459 0.01290	25620. 25520. 25420	0.06082 0.05366	26020 25920
0.00910	25320. 25220.	0.04597 0.04067 0.03524	25820. 25720.
0.00583	25120. 25020.	0.03105 0.02611	25520. 25420.
0.00451 0.00397 0.00368	24920. 24620. 24420	0.02268 0.01962	25320. 25220.
0.00331 0.00284	24120. 24020.	0.01358 0.01037	25120. 25020. 24920.
0.00256 0.00224 0.00192	23520. 23220. 23120.	0.00924 0.00746 0.00692	24820. 24720. 24620.
crac	k causing	0.00639	24320.
f	ailure		
0.14711 0.12576 0.10653	26620. 26520. 26420		
0.09223 0.07591	26320. 28220.		
0.05901 0.02319 0.02226	26120. 26020. 25920		
0.02015	25820. 25720.		
0.01477 0.01244 0.01082	25620. 25520. 25420		
0.00908 0.00792	25320. 25220.		
0.00560 0.00425	25120. 24920.		

#### <u>Appendix F. Considerations in the Choice of K</u> <u>Solution for Finite Width CNP Specimens</u>

Because the focus of this study is on physically small cracks, it is important that the K solution used adequately characterize the crack driving force local to the notch root. This means that for finite width specimens, a finite width correction for the far boundary must be applied. But, more important for short cracks is the need to account for variations in the peak stress and the stress gradient as a function of width. To this end, this appendix considers the choice of the K solution such that the chosen solution matches the limit given by Equation 2a for small cracks. Specifically this appendix considers bounds on the validity of Equation 2a as a function of crack size so as not to erroneously bias the selection process. The bounds on crack length are chosen with respect to (1) the error in stress as a function of c introduced by setting stress equal to  $K_tS$  and (2) dominance of the crack's stress field and the notch stress field as a function of crack length.

The error made by fixing  $\sigma$ , the local stress in the material element at the crack tip, equal to  $K_tS$  can be estimated by comparison of  $K_tS$  with the value of  $K_tS$  reduced by the gradient. Backlund and Karlsson [30] discuss analysis convenient for this purpose, for small cracks. Their work notes that Equation 2a can be more accurately written as follows:

$$K/S = (1.22 K_t + (0.683 \partial \sigma_v / \partial x|_{x=r})c) \sqrt{\pi c};$$
 (F.1)

but, it should be emphasized that this form is also only valid for small cracks. In view of this result, Equation 2a can be used for crack lengths up to about 490  $\mu$ m within a +5% error. Such an error is considered acceptable in a practical context in that typically load is only controlled to within ±1%. Therefore, an upper bound to the validity of Equation 2a is tentatively taken as 490  $\mu$ m. In the limit, as c  $\rightarrow$  0, Equation 2a approaches the exact result so that the corresponding lower bound to the validity of Equation 2a is zero crack length.

Consider now control of the crack driving force in terms of the coupled effects of the crack stress field and the notch stress field. The

purpose here is to calculate the range of crack lengths controlled by these fields. Because differences in accounting for the notch stress field is the essential difference between the various K solutions for a CNP, the desire is to limit the comparison of Equation 2a and the various K solutions to the range of crack lengths where K is controlled by terms involving  $F(\mathfrak{k})$ . To simplify the analyses, an infinite plate solution with crack length expressed as a function of notch root radius is used as the basis for the study. Thereafter, the results are made specific to the present application by the introduction of the crack length and notch dimensions relevant to this study. In view of the above analysis the results are accurate in an absolute sense within +5%, for cracks less than 490 µm long.

The results of Newman as expressed by Tada [25] for the situation considered indicate K has the form

$$\frac{K}{S} = F(\ell) \sqrt{\pi c}$$
 (F.2)

where l = c/(r+c), and r = the radius of the hole. Dominance of the stress field of the crack, embedded in terms involving  $\sqrt{\pi c}$ , and that of the notch, embedded in terms involving F(l), can be established by examining the rate of change in K/S as a function of c. To this end:

$$\frac{d}{dc}(K/S) = \frac{\pi}{2} (\pi c)^{-\frac{1}{2}} F(l) + (\pi c)^{\frac{1}{2}} \frac{d}{dc} F(l)$$
(F.3)

Since  $\ell = c/(r+c)$ , then

$$\frac{\mathrm{d}}{\mathrm{d}c}^{(F(\ell))} = \frac{\mathrm{d}}{\mathrm{d}\ell} F(\ell) \cdot \frac{\mathrm{d}\ell}{\mathrm{d}c}$$
$$= \frac{\mathrm{d}}{\mathrm{d}\ell} F(\ell) \left(\frac{1}{\mathrm{r+c}} - \frac{\mathrm{c}}{(\mathrm{r+c})^2}\right)$$

Here  $F'(\ell)$  is the slope of the function  $F(\ell)$  (denoted F(c/W) in regard to Equation 2) for the function catalogued by Tada et al [25].

Thus for the CNP of interest:

$$\frac{d}{dc}(K/S) = -(\pi c)^{\frac{1}{2}} F(\ell) + (\pi c)^{\frac{1}{2}} F'(\ell) \left(\frac{1}{0.25+c}\right) - \frac{c}{(0.25+c)^2}$$

c → 0:	→ C <sup>3</sup>	finite
c = .001"	: (1.57)(17.84)(3.36)	(0.056)(6.5)(3.96)
c = .01":	(1.57)(5.64)(3.1)	(0.18)(6.27)(3.69)
c = .1":	(1.57)(1.78)(1.8)	(0.56)(2.5)(1.93)
c = 1":	(1.57)(0.56)(1.12)	(1.77)(0.06)(0.14)

As noted earlier, for  $c > 490 \mu m$ , discrepancies in Equation 2a between  $K_{+}S$  and the actual stress for that crack length are considered to be excessive. Another upper bound follows from Equation A6.2 which shows that at about 800  $\mu$ m the  $\sqrt{\pi c}$  term in Equation 2 begins to dominate K/S, whereas for smaller cracks the notch field  $F(\ell)$  dominates. Obviously the smaller of these two upper limits controls, so that 490 µm is adopted as the upper bound on the validity of Equation 2a. As is evident from the behavior of d(K/S)/dc there is also a lower bound in c below which crack growth driving force is also controlled by the  $\sqrt{\pi c}$  term. The above table shows the influence of the  $\sqrt{\pi c}$ related terms in Equation 22 will be balanced by those related to F(L) for  $c \ge -G.002"$  (50 µm) and  $c \le -0.1"$  (25 mm). Since the upper bound here exceeds that noted above, the previously stated upper bound of 490 µm is retained. It will be used in conjunction with a lower bound on the validity of Equation 2a which, based on the tabulated results, should be less than the initial balance point between the  $\sqrt{\pi c}$  term and those related to F(2). Since this initial balance occurs at about 0.002 inch or 50  $\mu$ m, a lower bound for present purposes is a crack size less than 0.002 inch. For the present, a length of 0.001 inch or 25  $\mu$ m is arbitrarily selected. This avoids transients associated with small cracks related to the unbounded tendency of d(K/S)/dc as  $c \rightarrow 0.$ 

Note that calculated values of d(K/S)/dc for various K solutions are significantly different for short cracks. However, once the crack is about

3.5 mm long the values of d(K/S)/dc are comparable. Note too that as  $c \neq 0$ , d(K/S)/dc approaches infinity. That is, the crack driving force for small cracks at notches is changing very rapidly. It is doubtful that a "steady state" growth process can develop under such conditions in real materials. But it is also clear that as  $c \neq 0$  continuum mechanics becomes inappropriate for applications to real materials. In view of the above analysis, it is asserted that K does not adequately characterize the driving force for growth for values of c less than 25  $\mu$ m. The use of K already has been so restricted in this study by the lower bound associated with the free surface effect.