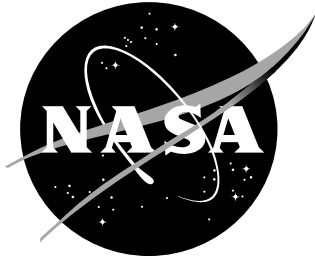


NASA/TM-2003-212443  
ARL-TR-3021



# Near-Threshold Fatigue Crack Growth Behavior of Fine-Grain Nickel-Based Alloys

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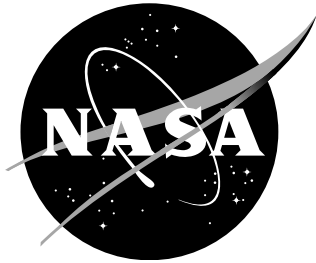
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August 2003

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## Abstract

Constant- $K_{max}$  fatigue crack growth tests were performed on two fine-grain nickel-base alloys – Inconel 718 (DA) and René 95 – to determine if these alloys exhibit near-threshold time-dependent crack growth behavior observed for fine-grain aluminum alloys in room-temperature laboratory air. Test results showed that increases in  $K_{max}$  values resulted in increased crack growth rates, but no evidence of time-dependent crack growth was observed for either nickel-base alloy at room temperature.

## Introduction

In cases where fatigue lives primarily depend on the early stages of crack growth, it is critical to understand the fatigue crack growth (FCG) characteristics in the near-threshold regime, defined schematically in Figure 1. Considerable research has shown that an increase in FCG rates ( $da/dN$ ) occurs with increasing stress ratio ( $R = K_{min}/K_{max}$ ) due to a reduction in crack closure effects (ref. 1). This R effect, schematically shown in Figure 1, is especially pronounced near the crack growth threshold. However, research has suggested that crack closure does not account for all stress ratio effects when R ranges from 0.5 to 0.95, and for  $K_{max}$  greater than  $0.4 K_{IC}$  (refs. 2 and 3). This work suggests that near threshold FCG can be influenced by other crack-tip damage mechanisms ( $K_{max}$  effects) that are not related to crack closure. For ingot metallurgy aluminum and titanium alloys, relatively small near threshold  $K_{max}$  effects have been observed during closure free FCG (ref. 3). Others have concluded that highly accelerated near threshold FCG rates during constant- $K_{max}$  testing of low toughness titanium and nickel-based alloys are due to hydrogen assisted cracking (refs. 4-6).

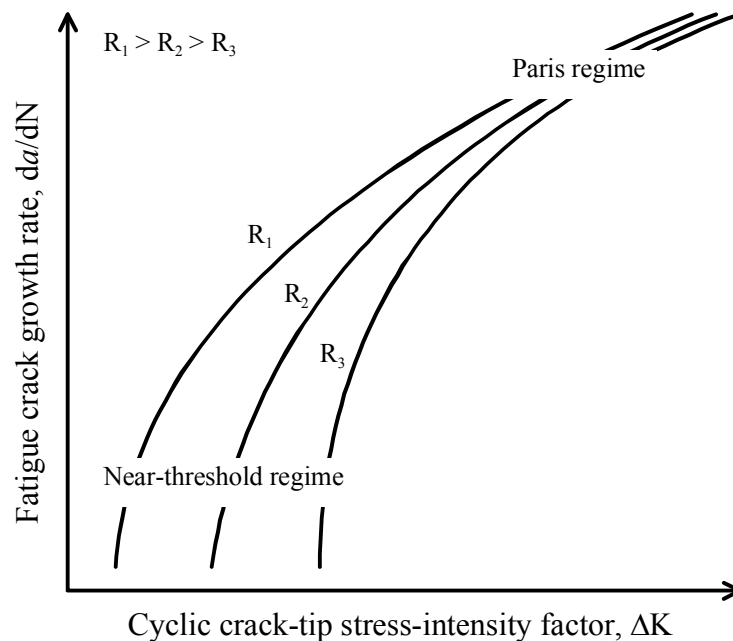


Figure 1. A schematic of the fatigue crack growth rate behavior in the near-threshold and Paris regimes.

The unusual room temperature near-threshold FCG behavior observed during constant- $K_{\max}$  testing (5.5 and 11.0  $\text{MPa}\sqrt{\text{m}}$ ) of aluminum alloy 8009 (a powder metallurgy alloy) is plotted in Figure 2a (ref. 7). Transitions to accelerated FCG rates – here seen as dramatic slope changes in the  $da/dN$  versus  $\Delta K$  data identified with arrows – were correlated with changes in crack surface morphology. The crack surfaces produced immediately after and before the  $K_{\max} = 11.0 \text{ MPa}\sqrt{\text{m}}$  transition at  $\Delta K = 1.3 \text{ MPa}\sqrt{\text{m}}$  are shown in Figures 2b and 2c, respectively. The crack surfaces produced immediately after and before the  $K_{\max} = 5.5 \text{ MPa}\sqrt{\text{m}}$  transition at  $\Delta K = 0.8 \text{ MPa}\sqrt{\text{m}}$  are shown in Figures 2d and 2e, respectively. For both levels of  $K_{\max}$ , a flat fatigue crack surface morphology (micrographs shown in Figures 2c and 2e) was observed at higher levels of  $\Delta K$ . As  $\Delta K$  was reduced and accelerated  $da/dN$  behavior was observed, the fatigue crack surface abruptly changed to a micro-void morphology (shown in Figures 2b and 2d) similar to that observed during elevated temperature creep crack growth (refs. 8 and 9). Additional testing showed that the unusual near-threshold behavior of alloy 8009 was the result of a transition to a room-temperature creep mechanism, and that another powder metallurgy aluminum alloy (IN-905x1) exhibits similar behavior (ref. 10). It is not known if this near-threshold creep mechanism is limited to fine-grain aluminum alloys, or is typical of fine-grain alloys in general. Two fine-grain nickel-base alloys, Inconel 718 (DA) and René 95, were identified as potential candidates to exhibit near-threshold creep. A series of constant- $K_{\max}$  fatigue crack growth tests were performed on these alloys to determine if these fine-grain nickel-base alloys are susceptible to a near-threshold creep mechanism.

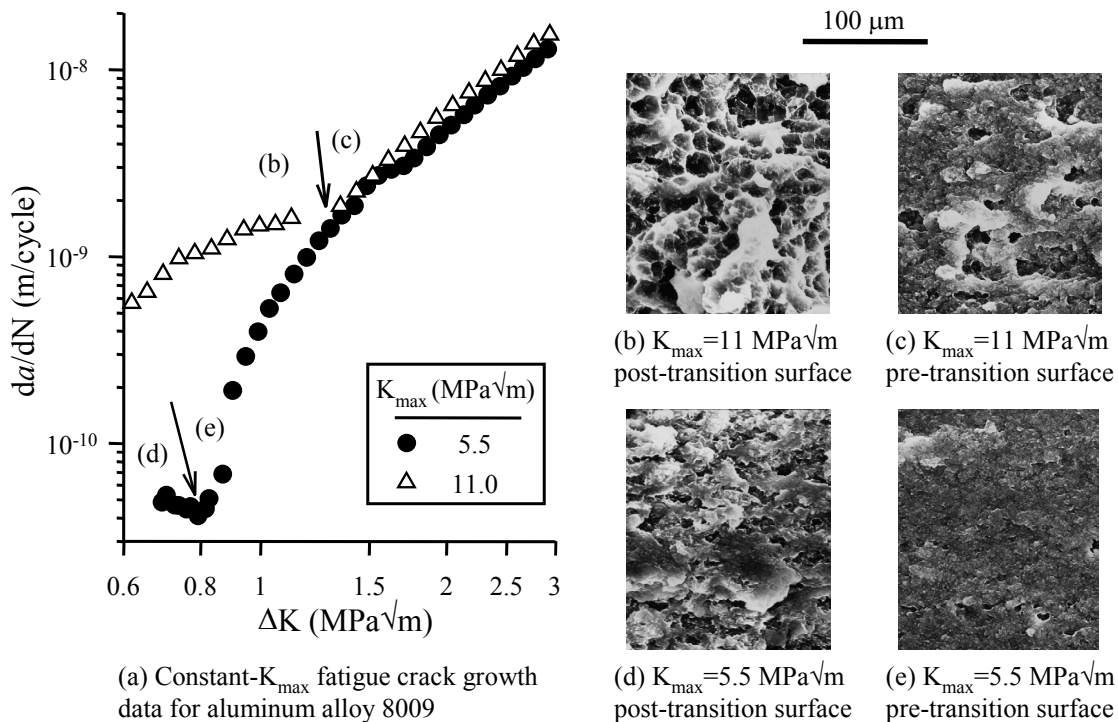


Figure 2. Experimental evidence of a near-threshold transition in the FCG behavior of aluminum alloy 8009.

## Materials

Both of the materials selected for study are nickel-base alloys that were developed for gas turbine applications. This class of alloys is termed “superalloys” due to their high strength, high stiffness, good corrosion resistance, and excellent properties at high temperatures including high creep resistance. The nominal chemical compositions of these alloys are listed in Table 1.

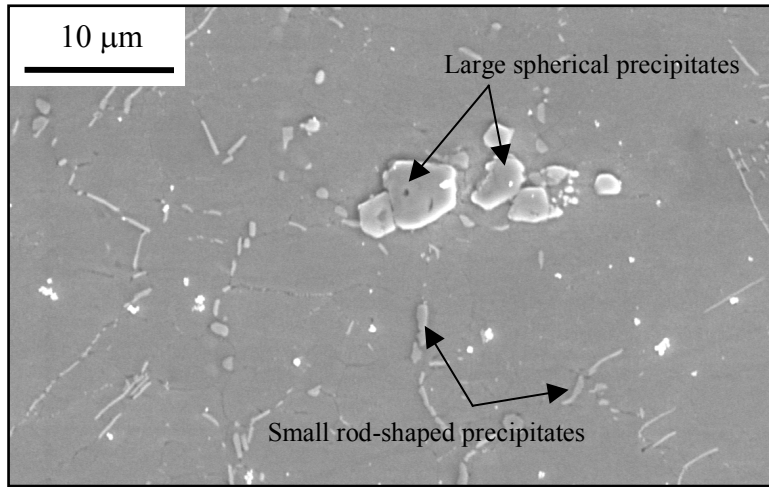
Table 1. Nominal chemical composition (by % wt.)

|                 | <b>Inconel 718</b> | <b>René 95</b> |
|-----------------|--------------------|----------------|
| Carbon (C)      | 0.04               | 0.15           |
| Manganese (Mn)  | 0.2                | -              |
| Silicon (Si)    | 0.2                | -              |
| Chromium (Cr)   | 18.5               | 14             |
| Cobalt (Co)     | -                  | 8              |
| Molybdenum (Mo) | 3                  | 3.5            |
| Tungsten (W)    | -                  | 3.5            |
| Niobium (Nb)    | 5.1                | 3.5            |
| Titanium (Ti)   | 0.9                | 2.5            |
| Aluminum (Al)   | 0.5                | 3.5            |
| Boron (B)       | -                  | 0.01           |
| Zirconium (Zr)  | -                  | 0.05           |
| Iron (Fe)       | 18.5               | -              |
| Copper (Cu)     | 0.2                | -              |
| Nickel (Ni)     | balance            | balance        |

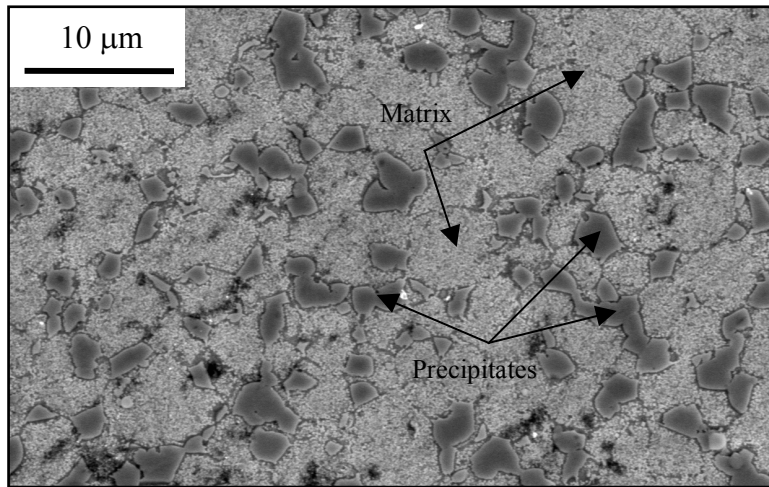
Inconel 718 was developed in the 1950s for gas turbine applications and is one of the most versatile and widely used superalloys. This alloy is heat treated to obtain the desired properties, based primarily on the precipitation of gamma-prime ( $\gamma'$ ) and gamma-double-prime ( $\gamma''$ ) phases for strengthening, and a delta ( $\delta$ ) phase for grain size control (ref. 11). The standard processing for Inconel 718 involves forging, annealing, and aging. Typically material is forged at 1950-2000°F with some finish forging at 1900-1950°F. Then the material is annealed at 1775°F for two hours followed by a water quench. The standard treatment calls for the material to be aged at 1325°F for 8 hours, furnace cooled to 1150°F, and held at this temperature for an additional 8 hours. However, the Inconel 718 used in this study was an ingot metallurgy alloy that was forged and processed according to a direct age (DA) schedule that results in smaller and more uniform grain sizes. The DA process calls for forging to occur at slightly lower temperatures (1900-1950°F, with finish forging at 1850-1900°F), which is immediately followed by the standard aging process (no annealing). A micrograph of the resulting microstructure of the Inconel 718 (DA) is shown in Figure 3a. The matrix consists of grains between 2  $\mu\text{m}$  and 5  $\mu\text{m}$  in diameter as reported by the manufacturer. Rod shaped precipitates, typically 0.5  $\mu\text{m}$  in diameter and 2-5  $\mu\text{m}$  long, primarily exist along grain boundaries. Larger particles are also seen that appear nearly spherical and typically 2-5  $\mu\text{m}$  in diameter. EDX (energy-dispersive X-ray) analysis indicates that the large spherical particles are rich in aluminum and titanium, and are therefore likely precipitates of the  $\gamma'$  phase ( $\text{Ni}_3(\text{Al}, \text{Ti})$ ). The absence of significant aluminum and titanium in the smaller rod-shaped particles suggests that these particles are either precipitates of the  $\gamma''$  or  $\delta$  phases (both  $\text{Ni}_3\text{Cb}$ ).

René 95 is a powder metallurgy alloy that was forged, heat treated, and aged. Powder René 95 was hot compacted and extruded at a subsolvus temperature. Isothermal forging and solution heat treating at a subsolvus temperature provided the uniform fine grain microstructure. Following the solution heat treat cycle, this material was given a single aging treatment. A micrograph of the resulting microstructure of the René 95 is shown in Figure 3b. The matrix is seen in the figure as light-colored regions and consists

of grains that are approximately 2-5  $\mu\text{m}$  in diameter as reported by the manufacturer. EDX analysis indicates that the dark colored regions are relatively rich in both aluminum and titanium and are presumably  $\gamma'$  precipitates.



(a) Inconel 718 (DA)



(b) René 95

Figure 3. Micrographs of fine-grain nickel-base alloys.

## Experimental Procedure

Fatigue crack growth tests were performed using compact tension specimens, shown schematically in Figure 4. The nominal thickness of Inconel 718 and René 95 specimens was 2.54 mm and 1.52 mm (0.100" and 0.060"), respectively. Constant- $K_{\text{max}}$  tests were performed on both alloys using computer-controlled servo-hydraulic test machines. Testing was performed in room-temperature laboratory air (18-24°C, relative humidity between 30% and 70%), at a cyclic loading rate of 10 Hz, and in accordance with ASTM standard E647 (ref. 13). Crack length was monitored during tests using specimen back-face compliance data, and loads were continuously adjusted by the computer-controlled system to achieve programmed stress intensity factors (ref. 14). Compliance-based crack length determinations were verified with visual measurements and the FCG test data was adjusted according to standard procedures



for the small differences ( $< 1\%$ ) between compliance-based and visual crack length measurements. During constant- $K_{\max}$  tests  $\Delta K$  was reduced (by increasing  $K_{\min}$ ) as defined by the K-gradient,  $C = -787 \text{ m}^{-1}$  ( $-20 \text{ inch}^{-1}$ ) (ref. 15).

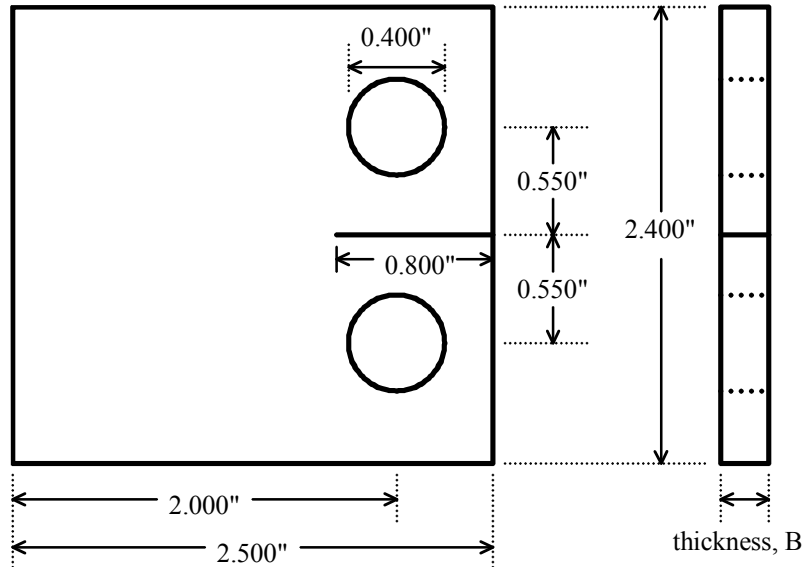


Figure 4. Compact tension (CT) specimen configuration.

## Experimental Results and Discussion

Fatigue crack growth data for Inconel 718 DA and René 95 are plotted in Figures 5 and 6, respectively. For each alloy constant- $K_{\max}$  tests were performed at  $K_{\max}$  values ranging from  $22 \text{ MPa}\sqrt{\text{m}}$  ( $20 \text{ ksi}\sqrt{\text{in}}$ ) to  $132 \text{ MPa}\sqrt{\text{m}}$  ( $120 \text{ ksi}\sqrt{\text{in}}$ ) in increments of  $22 \text{ MPa}\sqrt{\text{m}}$  – a total of 6 tests per alloy. Examination of Figure 5 reveals a slight  $K_{\max}$  effect for the Inconel 718 (DA) data. In other words, fatigue crack growth rates,  $da/dN$ , increase with increasing values of  $K_{\max}$ , and the data for higher  $K_{\max}$  values are shifted slightly to the left (lower  $\Delta K$ ) in Figure 5. This  $K_{\max}$  effect affects crack growth data similar to load ratio ( $R$ ) effects. However,  $R$  effects are generally associated with crack closure effects and  $K_{\max}$  effects occur at high values of  $R$  in the absence of crack closure. Using the ASTM working definition for determining the fatigue crack growth threshold values about  $10^{-10} \text{ m/cycle}$ , threshold values decrease from  $\Delta K_{\text{th}} = 2.8 \text{ MPa}\sqrt{\text{m}}$  at  $K_{\max} = 22 \text{ MPa}\sqrt{\text{m}}$  to  $\Delta K_{\text{th}} = 2.1 \text{ MPa}\sqrt{\text{m}}$  at  $K_{\max} = 88 \text{ MPa}\sqrt{\text{m}}$  (a 25% reduction in  $\Delta K_{\text{th}}$ ). Testing at higher  $K_{\max}$  values was terminated before achieving  $da/dN = 10^{-10} \text{ m/cycle}$  because the cyclic loads for these conditions was too small to ensure adequate load control. The  $K_{\max}$  effects observed for the Inconel 718 (DA) material is typical of many well-behaved materials and is not considered an indicator of time-dependent crack growth similar to that observed for alloy 8009. Based on the observations that no abrupt slope changes were noted in the crack growth data (Figure 5) or the crack surface morphology, Inconel 718 (DA) does not appear to exhibit a room-temperature creep crack growth mechanism similar to aluminum PM alloys (Figure 2).

The fatigue crack growth data for René 95, shown in Figure 6, is similar to that of Inconel 718 (DA) in that no abrupt slope changes were observed in the fatigue crack growth data. Using the ASTM working definition for determining the fatigue crack growth threshold values about  $10^{-10} \text{ m/cycle}$ , threshold values decrease from  $\Delta K_{\text{th}} = 2.9 \text{ MPa}\sqrt{\text{m}}$  at  $K_{\max} = 22 \text{ MPa}\sqrt{\text{m}}$  to  $\Delta K_{\text{th}} = 2.3 \text{ MPa}\sqrt{\text{m}}$  at  $K_{\max} = 88 \text{ MPa}\sqrt{\text{m}}$  (a

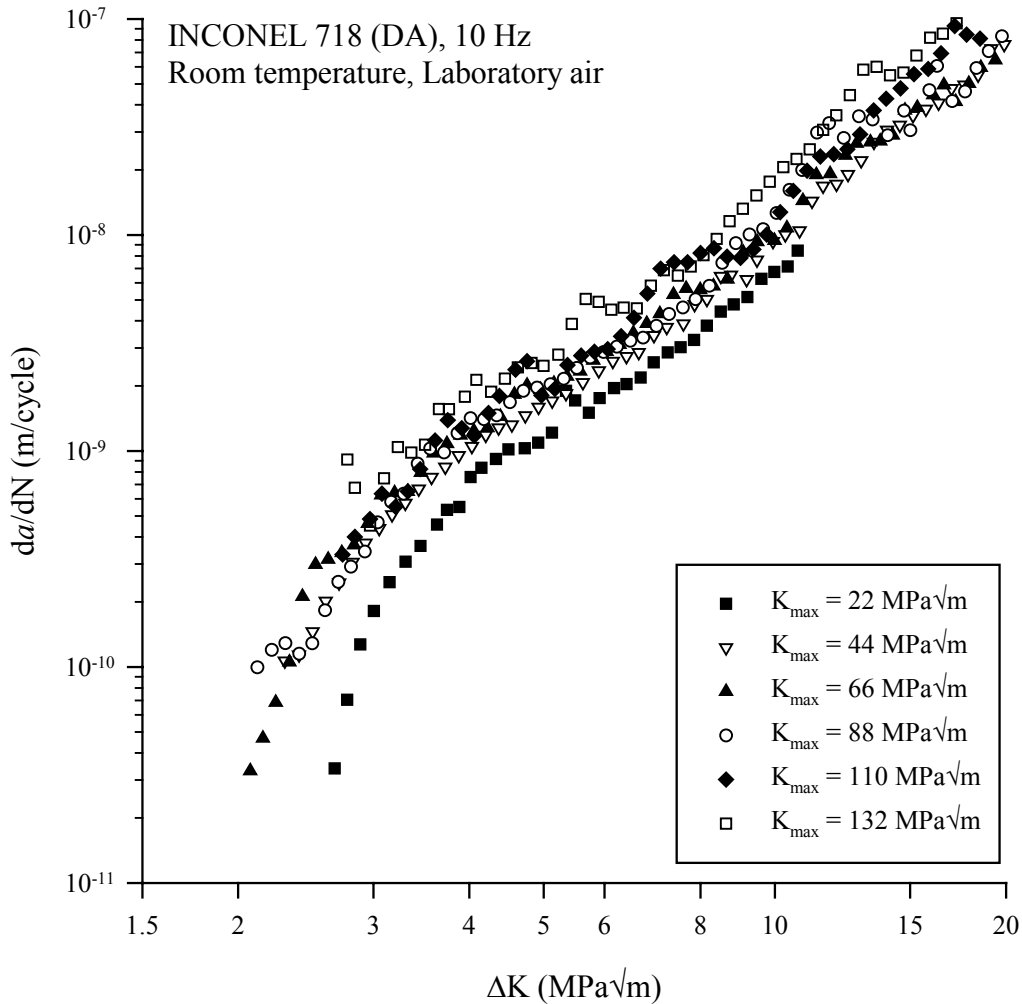


Figure 5. Constant- $K_{max}$  fatigue crack growth data for Inconel 718 (DA).

20% reduction in  $\Delta K_{th}$ ). Testing at higher  $K_{max}$  values was terminated before achieving  $da/dN = 10^{-10}$  m/cycle because the cyclic loads for these conditions was too small to ensure adequate load control. Further, no abrupt changes in crack surface morphology were seen. These observations suggest that René 95 also does not exhibit a time-dependent crack growth mechanism at room temperature similar to aluminum PM alloys (Figure 2).

Most of the crack growth tests were stopped at approximately  $da/dN = 3 \times 10^{-11}$  m/cycle, so it is possible that a time-dependent crack growth mechanism occurs in these alloys that is only activated at crack growth rates below  $10^{-11}$  m/cycle. Additionally, creep deformation rates tend to be strongly dependent on temperature. Typical creep deformation models relate the creep rate to the ratio of the test temperature and the melting temperature (ref. 16). Considering that these nickel-base alloys have a significantly higher melting temperature than aluminum alloys, creep mechanisms are less likely to be active for nickel-base alloys at room temperature.

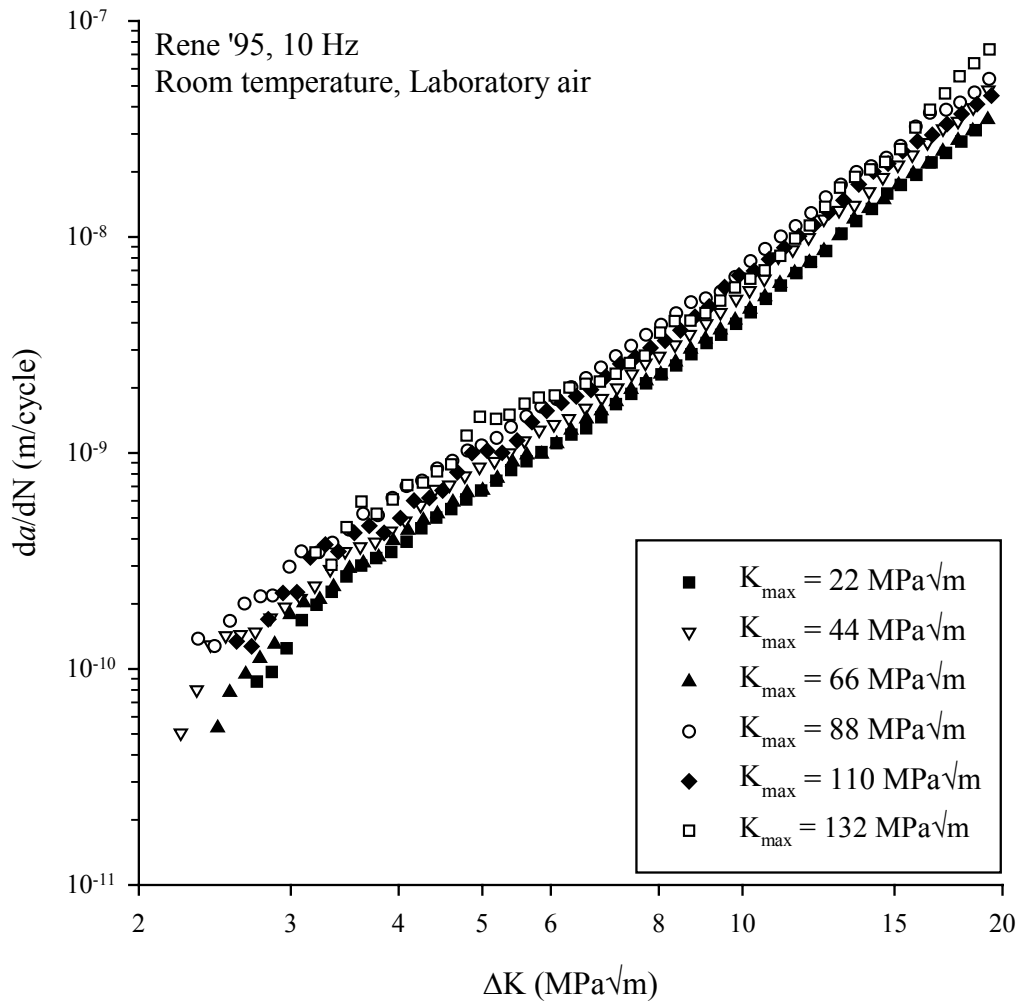


Figure 6. Constant- $K_{max}$  fatigue crack growth data for René 95.

## Conclusions

Constant- $K_{max}$  fatigue crack growth tests were performed on two fine-grained nickel-base alloys – Inconel 718 (DA) and René 95 – to determine if these alloys exhibited a room-temperature creep crack growth mechanism similar to that observed in fine-grained aluminum alloys. Increasing crack growth rates and decreasing values of fatigue crack growth threshold were observed as  $K_{max}$  increased. However, this behavior is typical of well-behaved alloys and is not considered an indication that these alloys are susceptible to a time-dependent crack growth mechanism at room temperature.

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| 1. AGENCY USE ONLY (Leave blank)   |  | 2. REPORT DATE<br>August 2003                           | 3. REPORT TYPE AND DATES COVERED<br>Technical Memorandum                             |  |
| 4. TITLE AND SUBTITLE<br>Near-Threshold Fatigue Crack Growth Behavior of Fine-Grain Nickel-Based Alloys  |  |   | 5. FUNDING NUMBERS<br>23-762-30-71   |  |
| 6. AUTHOR(S)<br>John A. Newman and Robert S. Piascik   |  |   |  |  |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>NASA Langley Research Center<br>Hampton, VA 23681-2199   |  |   | 8. PERFORMING ORGANIZATION REPORT NUMBER<br>L-18314                                  |  |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>National Aeronautics and Space Administration<br>Washington, DC 20546-0001<br>and<br>U.S. Army Research Laboratory<br>Adelphi, MD 20783-1145  |  |   | 10. SPONSORING/MONITORING AGENCY REPORT NUMBER<br>NASA/TM-2003-212443<br>ARL-TR-3021 |  |
| 11. SUPPLEMENTARY NOTES  |  |   |  |  |
| 12a. DISTRIBUTION/AVAILABILITY STATEMENT<br>Unclassified-Unlimited<br>Subject Category 26                      Distribution: Standard<br>Availability: NASA CASI (301) 621-0390  |  |   | 12b. DISTRIBUTION CODE   |  |
| 13. ABSTRACT (Maximum 200 words)<br>Constant-Kmax fatigue crack growth tests were performed on two fine-grain nickel-base alloys – Inconel 718 (DA) and René 95 – to determine if these alloys exhibit near-threshold time-dependent crack growth behavior observed for fine-grain aluminum alloys in room-temperature laboratory air. Test results showed that increases in Kmax values resulted in increased crack growth rates, but no evidence of time-dependent crack growth was observed for either nickel-base alloy at room temperature.   |  |   |  |  |
| 14. SUBJECT TERMS<br>Nickel-base alloys, fine-grain alloys, fatigue crack growth threshold,<br>Rene 95, Inconel DA 718, microstructure   |  |   | 15. NUMBER OF PAGES<br>13  |  |
|  |  |   | 16. PRICE CODE   |  |
| 17. SECURITY CLASSIFICATION OF REPORT<br>Unclassified  | 18. SECURITY CLASSIFICATION OF THIS PAGE<br>Unclassified | 19. SECURITY CLASSIFICATION OF ABSTRACT<br>Unclassified | 20. LIMITATION OF ABSTRACT<br>UL   |  |