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FATIGUE CRACK GROWTH IN AerMet 100 STEEL

Eun U. Lee
Air Vehicle and Crew Systems Technology Department (Code 6063)
NAVAL AIR DEVELOPMENT CENTER
Warminster, PA 18974-5000

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Within the employed range of stress ratios, the greater the stress ratio, the smaller is the threshold stress intensity range for fatigue crack growth ΔK_{th} and the greater is the fatigue crack growth rate da/dN for lower ΔK. For higher ΔK, however, the da/dN values of different stress ratios are similar in both environments.

The ΔK_{th} is greater and da/dN is smaller for lower ΔK in a 3.5% NaCl solution than in dry nitrogen gas, whereas the da/dN values are quite close for higher ΔK in both

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ACKNOWLEDGEMENTS

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The author is grateful to Carpenter Technology Corp. for providing and heat-treating the specimen material, AerMet 100 steel, Mr. W. F. Warden for the fatigue testing, Mr. W. Weist for the SEM work, and Mr. E. Deesing for the microstructural examination.

INTRODUCTION

Carrier-based aircraft landing gears demand tough, corrosion resistant materials in order to achieve higher performance and greater reliability at minimum life-cycle cost. The performance and reliability can be determined from the fatigue behavior under testing conditions that simulate those encountered in actual service. Therefore, the fatigue behavior of potential materials for landing gears should be thoroughly investigated prior to their actual use.

For the past 20 years, 300M steel was accepted as the standard material for landing gears because of its high ultimate tensile strength. Recently, a newly developed landing gear steel, AerMet 100, has been found to be potentially better than 300M steel due to its greater fracture toughness and better resistance to stress corrosion cracking and hydrogen embrittlement. However, its fatigue behavior has not yet been fully characterized.

In this study, the fatigue behavior of AerMet 100 steel is investigated under constant amplitude loading in inert and corrosive environments. The fatigue behavior under spectrum loading will be studied in the near future.

EXPERIMENTAL PROCEDURE

MATERIAL AND SPECIMEN PREPARATION

The AerMet 100 steel used in this study was received from Carpenter Technology Corp. in the form of a 1 1/4 x 3 3/8 x 12 in. slab, which was initially forged at 1850°F and annealed at 1250°F for 16 hours. Its nominal chemical composition in weight percent is shown below.

C - - - 0.23	Ni - - - 11.1	Cr - - - 3.1
Co - - - 13.4	Mo - - - 1.2	Fe - - - Balance

The specimen material was subjected to the following heat-treatment.

1. solution treatment at 1625°F for 1 hour and air cooling
2. deep freezing at -100°F for 1 hour and air warming
3. aging at 900°F for 5 hours and air cooling

Its mechanical properties in the longitudinal orientation are:

Yield Strength (ksi)	250
Tensile Strength (ksi)	285
Elongation (%)	14
Reduction of Area (%)	65
K_{IC} (ksi $\sqrt{in}$)	115

After the heat-treatment, compact-type (CT) specimens of width W = 1.0 in., thickness B = 0.25 in., and notch-tip length a_n = 0.20 in. were prepared in the L-T orientation by the process of Electro Discharge Machining.

FATIGUE TEST

The fatigue tests were conducted using CT specimens on a 100,000 lb closed-loop servo-hydraulic Materials Testing System (MTS) machine, operating under constant amplitude loading at a cyclic frequency of 10 Hz (sine wave). Stress ratios (R = minimum stress/maximum stress) of 0.1, 0.5, and 0.8 were employed in controlled ambient temperature environments of dry nitrogen gas and a 3.5% NaCl solution in distilled water. Testing in dry nitrogen gas was carried out in a Plexiglas environmental chamber, which totally enclosed the specimen. Oil free nitrogen gas was dried to 5% relative humidity by passing through Drierite ($CaSO_4$) prior to entering the environmental chamber. A 3.5% NaCl solution environment was made by capillary-wetting of a wick. Its one end filled up the notch-tip of a CT specimen and the other end was in a bottle of a 3.5% NaCl solution in distilled water.

Crack length was continuously monitored employing the DC electrical potential drop method and it was also checked visually. Near-threshold crack growth rates were obtained under decreasing ΔK (load shedding) condition with K-gradient C = 3.5 in^{-1}.

MICROSTRUCTURAL AND FRACTOGRAPHIC EXAMINATION

The microstructure of the specimen material was examined with an optical microscope after etching in a solution of 10 gm of sodium meta-bisulfite in 100 ml of [illegible] water.

The fracture surface morphologies of the specimen [illegible]d with an AMR 100 scanning electron microscope operated at an accelerated voltage of [illegible]

RESULTS

FATIGUE CRACK GROWTH

The results of this study indicate that the fatigue behavior of AerMet 100 steel is predominantly affected by stress ratio and environment.

1. Effect of Stress Ratio

The variation of fatigue crack growth rate da/dN with stress ratio R for dry nitrogen gas and a 3.5% NaCl solution environment is shown in Figs. 1 and 2. For the fatigue tests in both environments, the fatigue crack growth rates above 10^{-6} in/cy[illegible]le are largely unaffected by stress ratio. On the other hand, at near-threshold levels, increasing stress ratio reduces the threshold stress intensity range for fatigue crack growth ΔK_{th} and increases the fatigue crack growth rate da/dN. The variation of ΔK_{th} with R is shown in Fig. 3.

2. Effect of Environment

The fatigue crack growth behavior in dry nitrogen gas and a 3.5% NaCl solution is compared for stress ratios R = 0.1, 0.5, and 0.8 in Figs. 4 - 6, respectively. At low da/dN below 10^{-6} in/cycle or near-threshold levels, da/dN is greater and ΔK_{th} is smaller in dry nitrogen gas than in a 3.5% NaCl solution for all stress ratios employed. However, at high da/dN levels above 10^{-6} in/cycle, the da/dN values for a given ΔK are quite close in both of the environments, indicating little effect of environment on da/dN.

MICROSTRUCTURE

The microstructure consists mostly of fine tempered martensite plates, Fig. 7.

FRACTOGRAPHY

The fractographs of the specimen, fatigue-tested in dry nitrogen gas, show patches of striations with some secondary cracks in the fatigue crack growth zone and dimples in the overload fracture zone, Fig. 8. There is no detectable indication of corrosion deposit in any part of the fracture surface.

After fatigue-testing in a 3.5% NaCl solution, except for the final fatigue crack growth zone of high da/dN and the adjacent zone of overload fracture, the fracture surface is covered by corrosion products with mud-cracks, Fig. 9. Patches of striations with secondary cracks are observable in the final fatigue crack growth zone and dimples in the overload fracture zone.

DISCUSSION

It is interesting to compare the fatigue crack growth behavior of AerMet 100 and 300M steels, the latter of which has been widely used for aircraft landing gears. The respective plots of da/dN vs. ΔK for both steels in inert and corrosive environments are shown in Figs. 10 and 11. The testing conditions for the 300M steel (1) are not exactly identical to those in the current study on AerMet 100 steel. The inert environment is low-humidity-air for the 300M steel, and dry nitrogen gas for the AerMet 100 steel. The corrosive environment is simulated-sea-water for the 300M Steel, and a 3.5% NaCl solution for the AerMet 100 steel. The value of ΔK_{th} can not be found for the 300M steel from either of the figures. In the range of intermediate da/dN, there is little difference in fatigue crack growth rate for either environment. However, in the range of higher da/dN, the da/dN is drastically larger for the 300M steel than for the AerMet 100 steel, resulting in an earlier catastrophic fracture of the 300M steel under a given fatigue condition. This inferior fatigue crack growth resistance of the 300M steel is attributed to its inferior fracture toughness (K_{IC} = 55 ksi $\sqrt{in}$) and its much smaller critical crack size, compared to those for the AerMet 100 steel (K_{IC} = 115 ksi $\sqrt{in}$).

The present results show that environment and stress ratio can greatly influence the fatigue crack growth rates and ΔK_{th} at near-threshold stress intensities. The dry nitrogen gas environment accelerates near-threshold crack growth rates and reduces ΔK_{th} values relative to a 3.5% NaCl solution in distilled water. Furthermore, ΔK_{th} decreases more markedly with increasing stress ratio in a 3.5% NaCl solution than in dry nitrogen gas, as shown in Fig. 3. In each environment, there is an approximately linear relationship between the values of ΔK_{th} and R, in agreement with Stewart's observation (2). However, the effects are considerably reduced at higher stress intensities (ΔK greater than 10 ksi $\sqrt{in}$).

Similar features of environmental and stress ratio effects have also been reported by other workers, confirming the present results. Testing ASTM A533 B-1 steel, Paris et al (3) observed that the near-threshold fatigue crack growth rates and the ΔK_{th} values are greater and lower, respectively, in a distilled water environment than in air at room temperature. They also reported that for crack growth rates above 5×10^{-6} in/cycle, the distilled water environment cracking rate begins to exceed that in the air for an equivalent ΔK. In the test of 3NiCrMoV steel, Stewart (2) demonstrated that in dry gaseous environments of hydrogen, air, and argon and at low stress ratio, ΔK_{th} values are much lower than in moist laboratory air. On the other hand, at high stress ratio (R = 0.88 - 0.92), ΔK_{th} values were found to be generally insensitive to environment. Ritchie et al (4) studied the near-threshold fatigue crack growth in a 2.25Cr - 1Mo pressure vessel steel in moist air, dry hydrogen gas, and dry argon gas, and reported the following. Near-threshold crack growth rates, in addition to showing a marked sensitivity to stress ratio, are significantly enhanced in the dry gaseous environments compared to moist air.

A rationale for the effect of environment and stress ratio on fatigue crack growth rate and ΔK_{th} value can be found in terms of a crack closure concept (5). Elber (5) originally suggested that crack closure may occur at positive loads in a tension-tension fatigue cycle as a result of plastic deformation produced

in the wake of a fatigue crack. This is known as plasticity-induced crack closure. This reduces the applied stress intensity range to a lower effective value, ΔK_{eff}, actually experienced at the crack tip. Crack closure has also been known to be induced by corrosion products formed within growing cracks. This is known as corrosion-product-induced or oxide-induced crack closure. A number of previous investigators, notably Paris et al (3), Tu and Seth (6), Skelton and Haigh (7), Stewart (2), and Suresh and Ritchie (4,8), have suggested the possibility of crack closure due to corrosion products influencing near-threshold crack growth rates and ΔK_{th} values. In a corrosive environment, corrosion products are formed within the fatigue crack, thickened at low stress ratios, and continuously broken and reformed behind the crack tip due to repeated contact between the crack surfaces. The presence of such corrosion products in the crack will increase the load in the fatigue cycle at which crack closure occurs. Therefore, the effective stress intensity range ΔK_{eff} will be lower than that applied, leading to lower crack growth rates and higher apparent ΔK_{th} values. However, as stress ratio is increased, less crack closure occurs thereby increasing crack growth rates and lowering ΔK_{th} values (9).

Considering the crack growth characteristics and formation of corrosion product on the crack surface during fatigue loading in a 3.5% NaCl solution, observed in this study, the near-threshold fatigue crack growth behavior in the corrosive environment is attributed to a mechanism involving corrosion-product-induced crack closure.

CONCLUSION

Based on a study of fatigue crack growth in AerMet 100 steel, tested in dry nitrogen gas and a 3.5% NaCl solution, the following conclusions can be drawn:

1. The fatigue crack growth resistance of the AerMet 100 steel is superior to that of the 300M steel in inert and corrosive environments.

2. The significant features of fatigue crack growth in the AerMet 100 steel are:

a. Near-threshold fatigue crack growth rates, below 10^{-6} in/cycle, are faster in dry nitrogen gas than in a 3.5% NaCl solution.

b. For each of the employed stress ratios, R = 0.1, 0.5, and 0.8, the ΔK_{th} value is less in dry nitrogen gas than in a 3.5% NaCl solution.

c. The larger the stress ratio, the greater is the near-threshold fatigue crack growth rate and the smaller is the ΔK_{th} value in both environments.

d. At high fatigue crack growth rates, above 10^{-6} in/cycle, the effects of environment and stress ratio are substantially reduced.

e. The near-threshold fatigue crack growth behavior in a 3.5% NaCl solution is attributed to a mechanism involving corrosion-product-induced crack closure.

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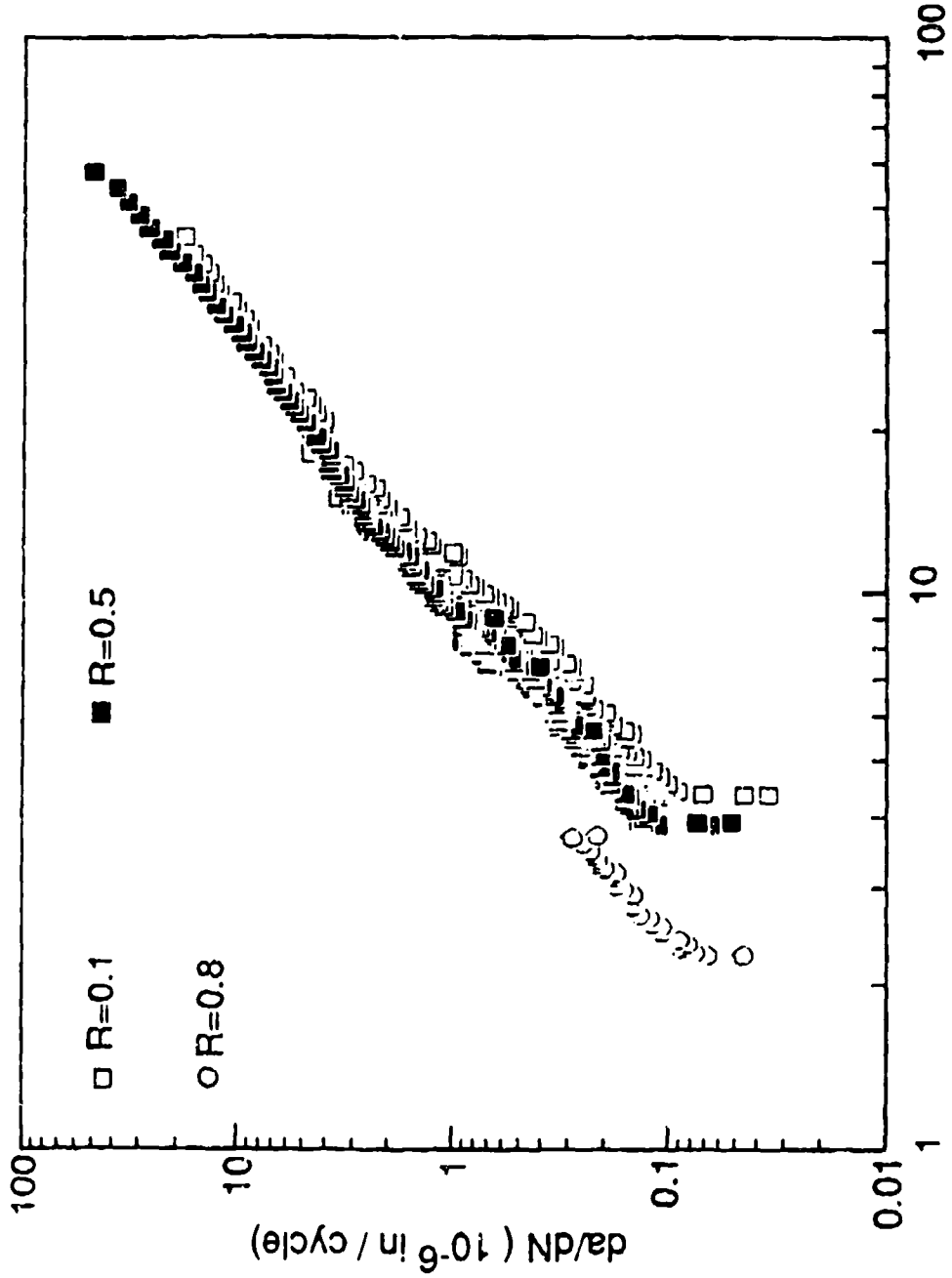


Figure 1. Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for Stress Ratio R = 0.1, 0.5, and 0.8 in Dry Nitrogen Gas.

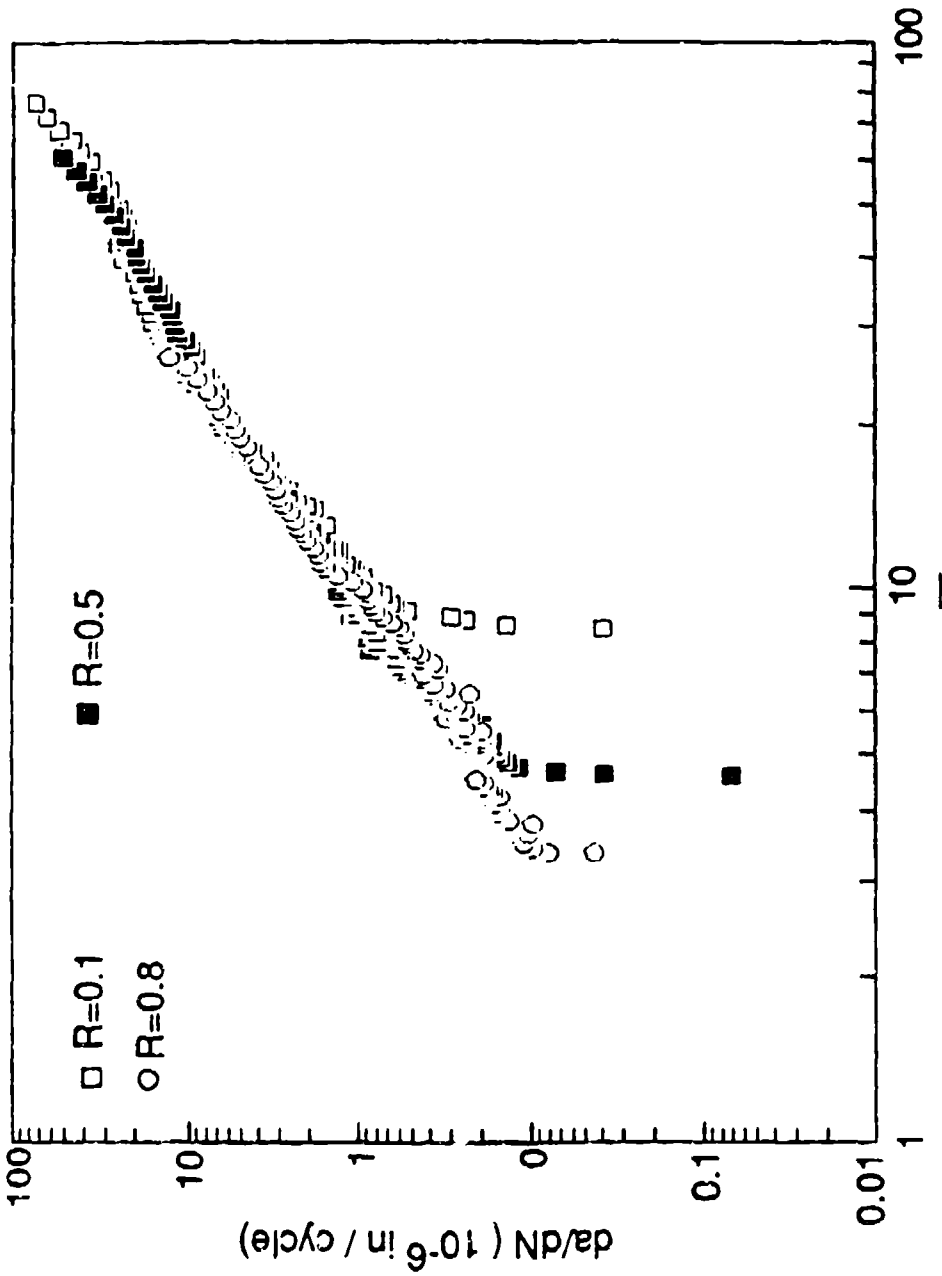


Figure 2. Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for Stress Ratio R = 0.1, 0.5, and 0.8 in a 3.5% NaCl Solution.

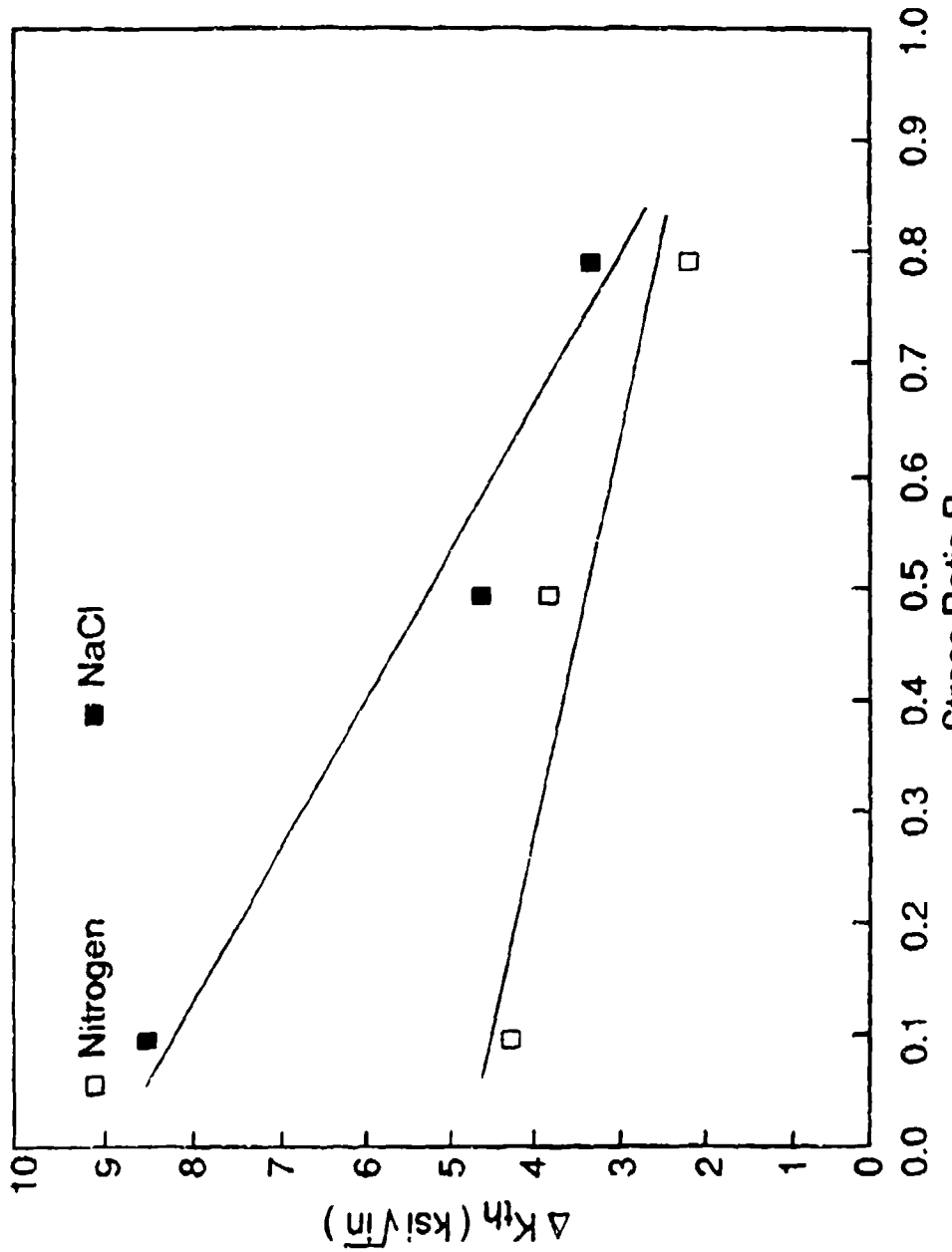


Figure 3. Variation of Threshold Stress Intensity Range for Fatigue Crack Growth, ΔK_{th} with Stress Ratio, R, in Dry Nitrogen Gas and a 3.5% NaCl Solution.

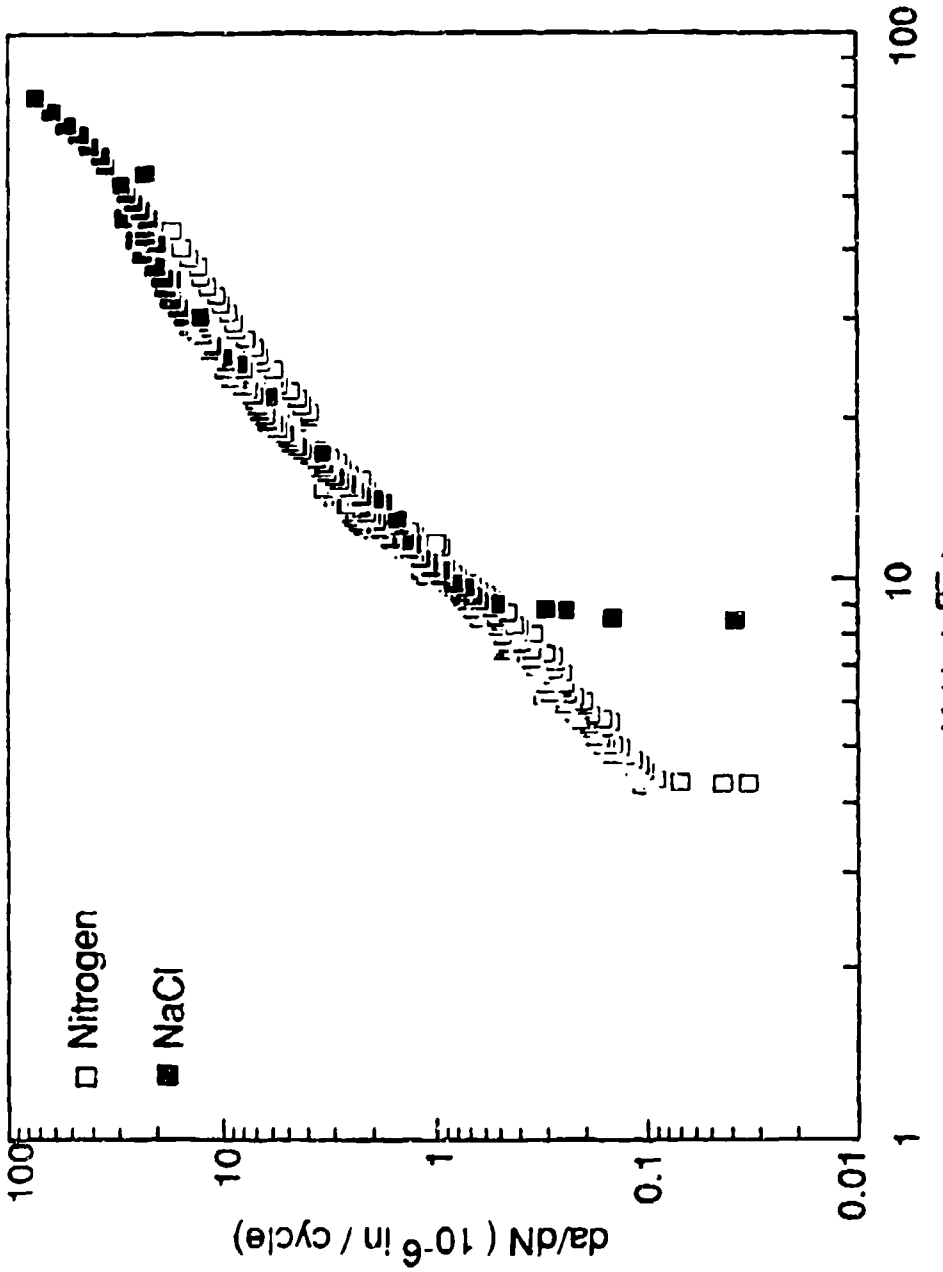


Figure 4. Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for Stress Ratio R = 0.1 in Dry Nitrogen Gas and a 3.5% NaCl Solution.

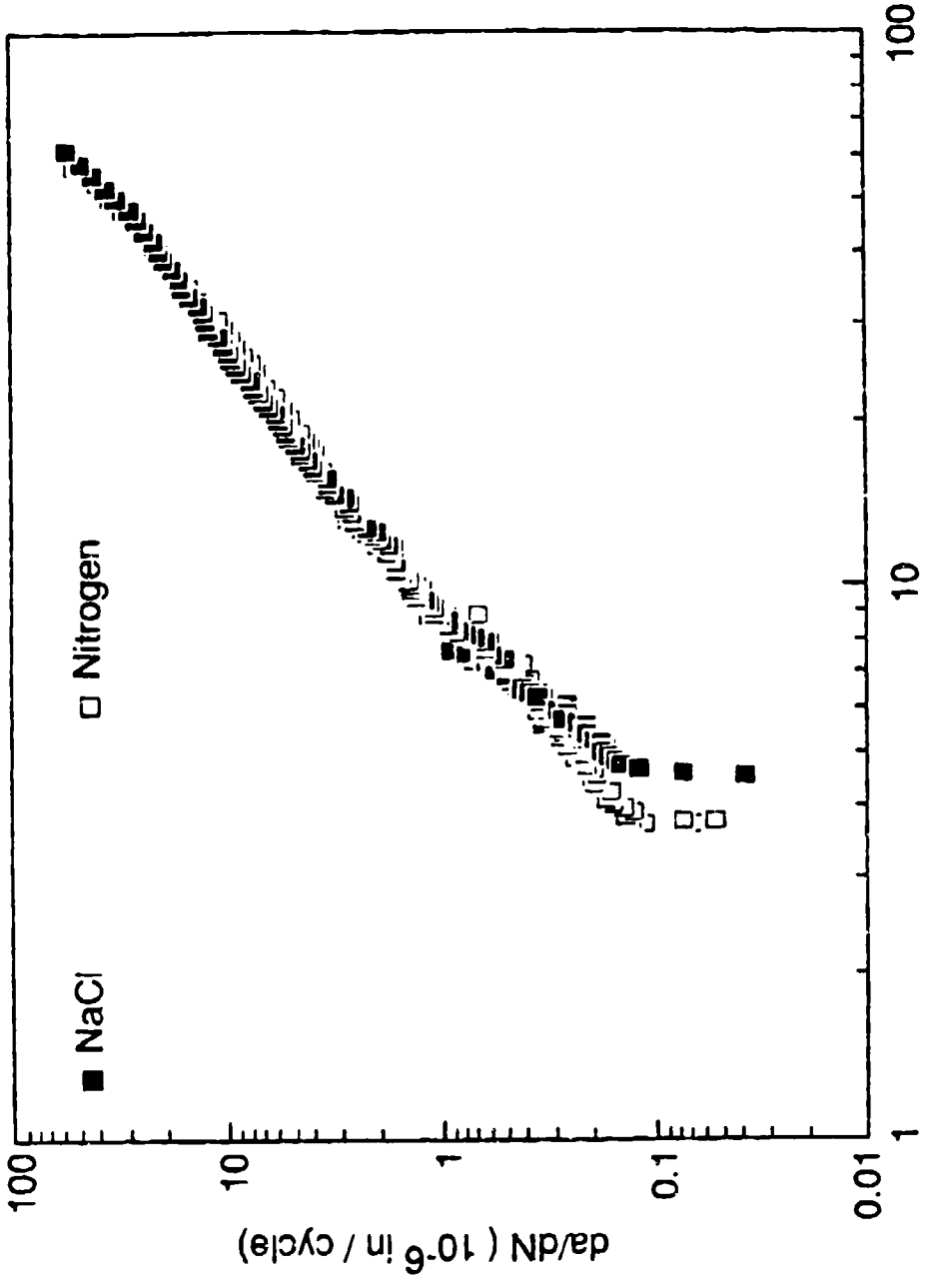


Figure 5. Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for Stress Ratio R = 0.5 in Dry Nitrogen Gas and a 3.5% NaCl Solution.

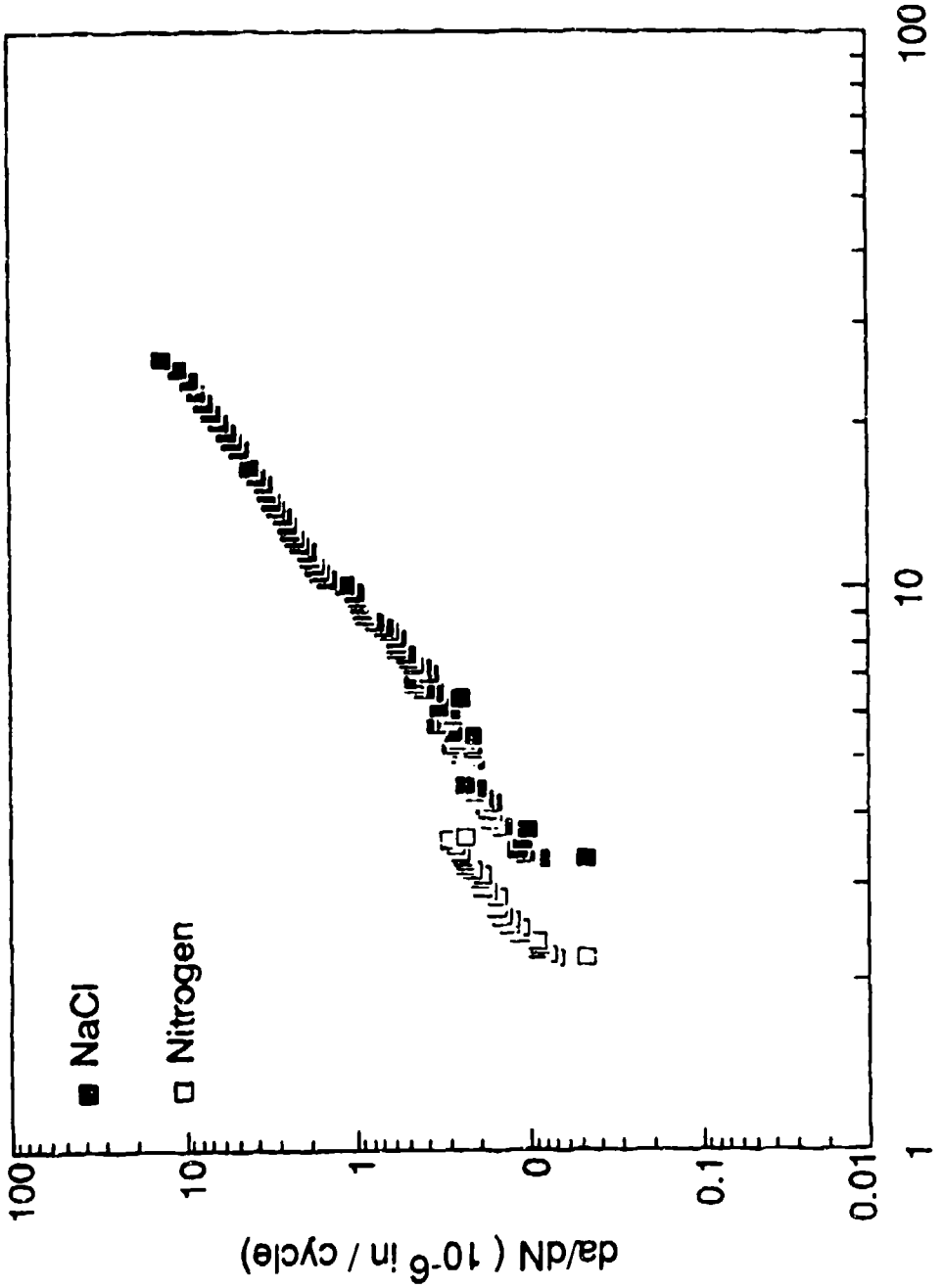


Figure 6. Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for Stress Ratio R = 0.8 in Dry Nitrogen Gas and a 3.5% NaCl Solution.

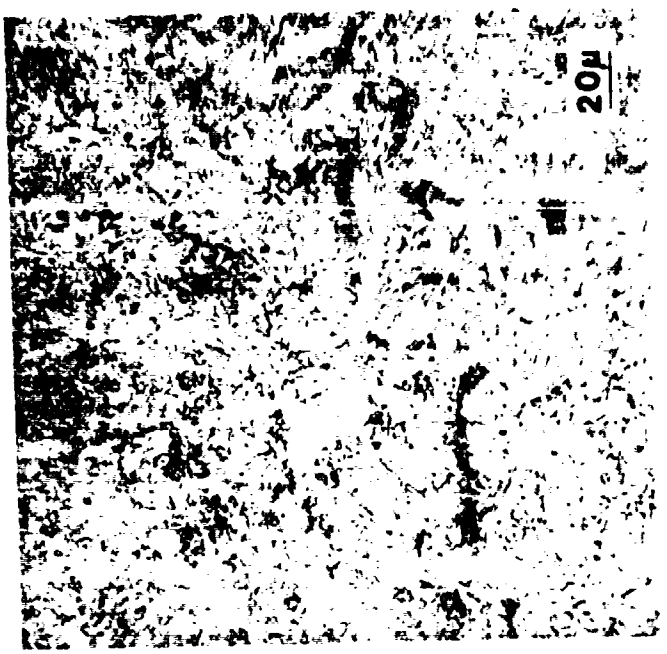
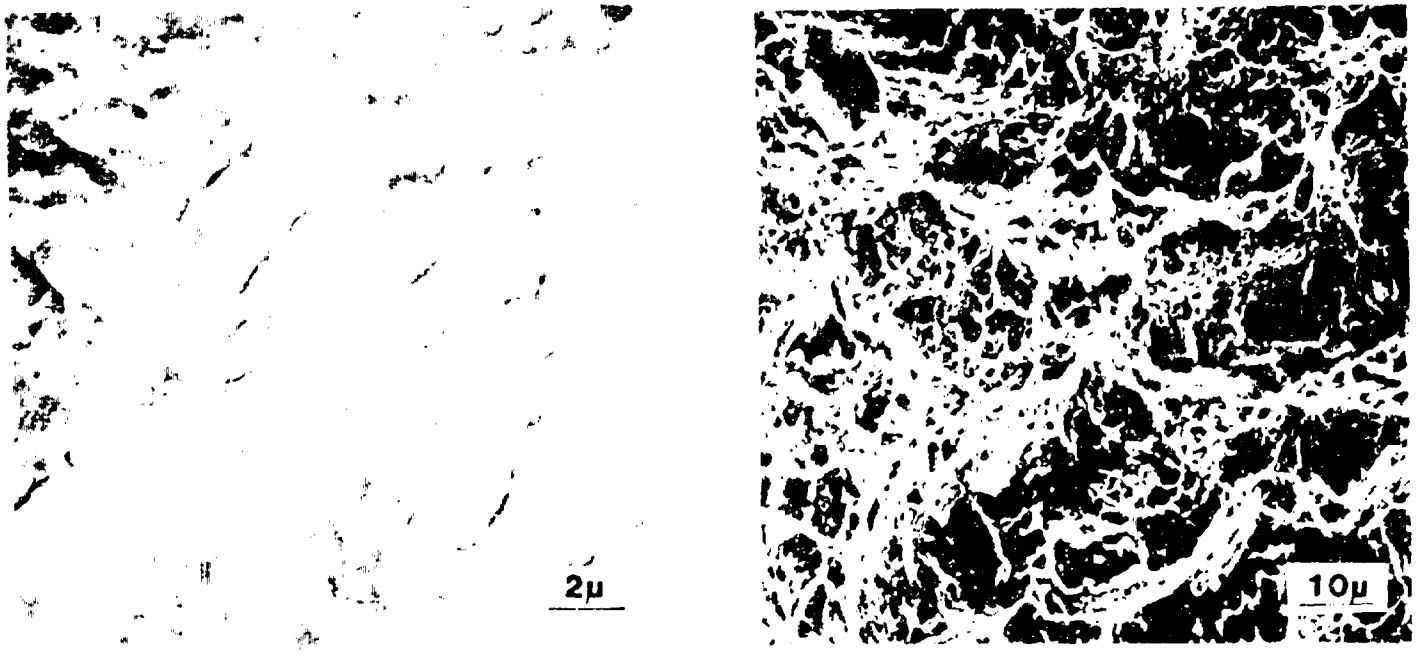


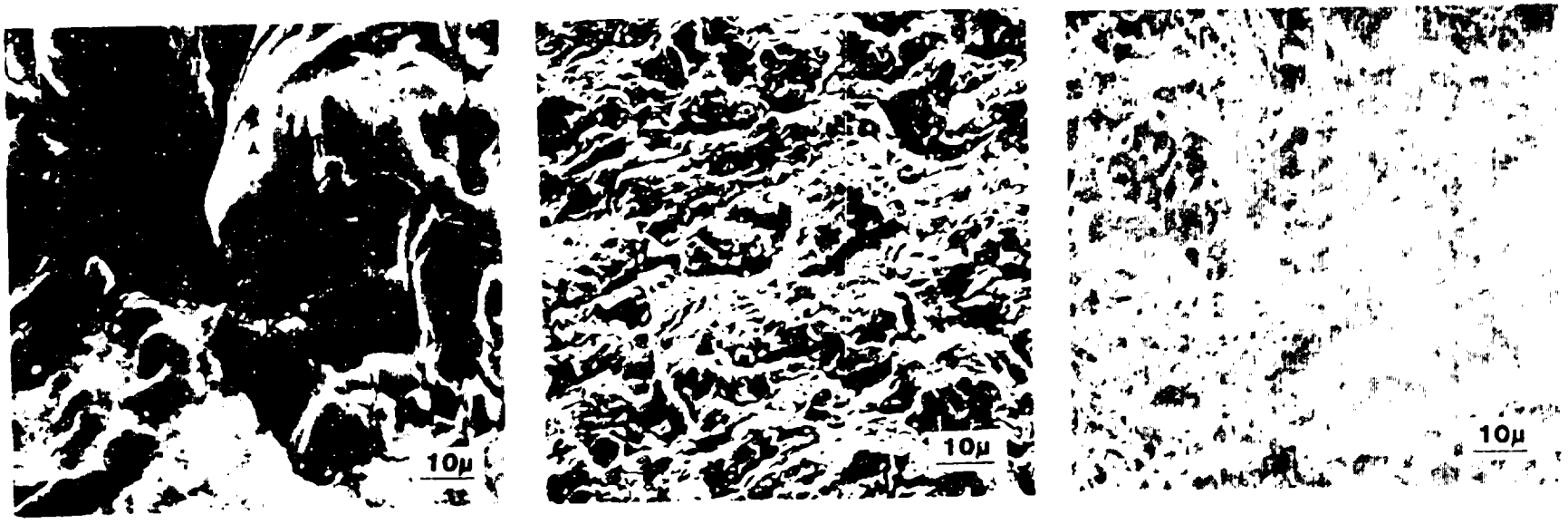
Figure 7. Micrograph of Specimen Material, AerMet 100 Steel.



(a) Fatigue Crack Growth Zone

(b) Overload Fracture Zone

Figure 8. Fractographs of Specimen Fatigue-Tested in Dry Nitrogen Gas.



(a) Fatigue Crack Growth Zone of Low and Intermediate da/dN

(b) Final Fatigue Crack Growth Zone of High da/dN

(c) Overload Fracture Zone

Figure 9. Fractographs of Specimen Fatigue-Tested in a 3.5% NaCl Solution.

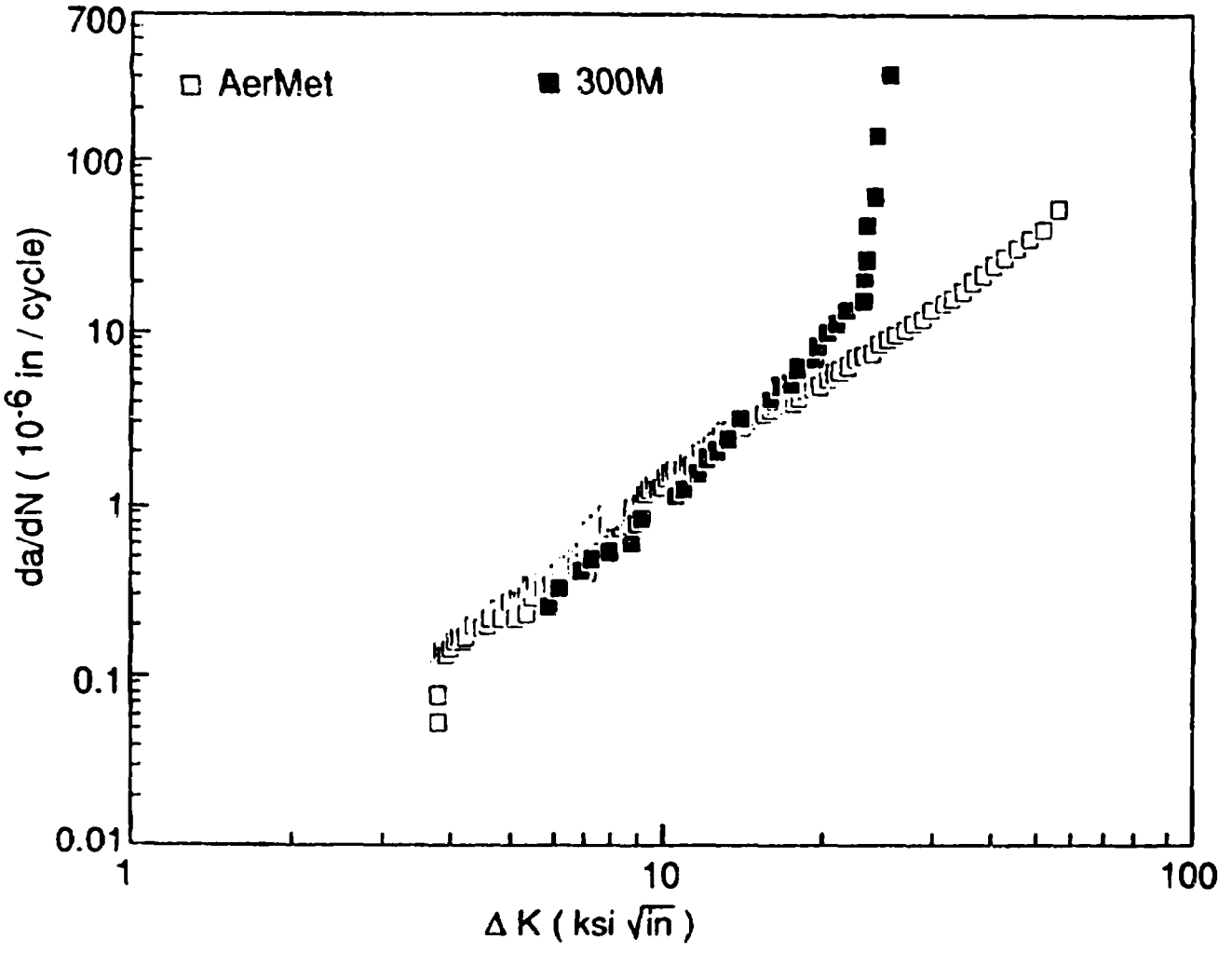


Figure 10. Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for AerMet 100 and 300M Steels in Inert Environments.

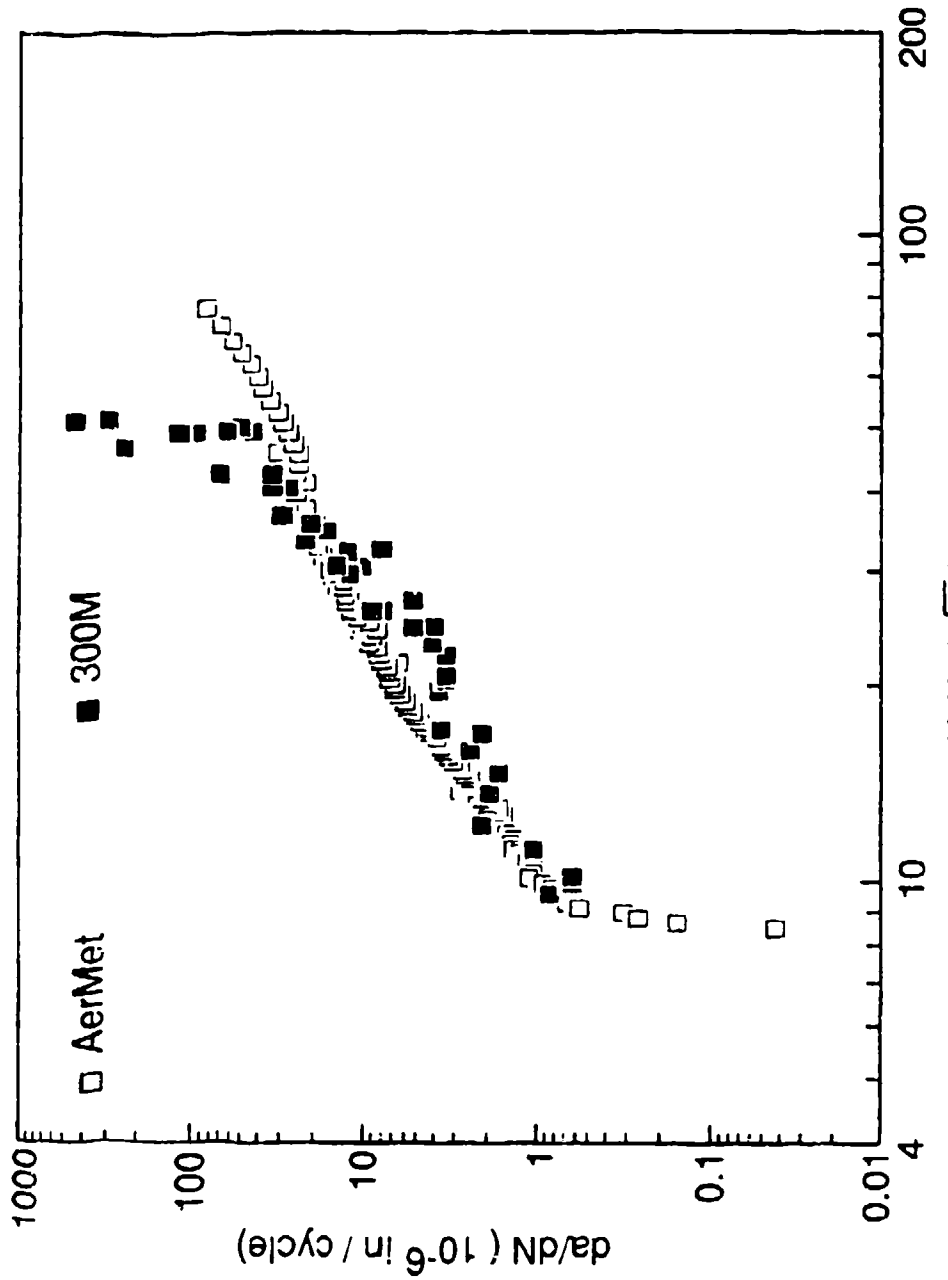


Figure 11. Variation of Fatigue Crack Growth Rate, da/dN, with Stress Intensity Range, ΔK, for AerMet 100 and 300M Steels in Corrosive Environments.

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