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CORROSION BEHAVIOR OF LANDING GEAR STEELS

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The SCC rate is less and the threshold stress intensity for stress corrosion (K_{ISCC}) is greater in the AerMet 100 steel (33 ksi*in^1/2) than in the 300M steel (19 ksi*in^1/2), indicating better SCC resistance of the AerMet 100 steel. In the AerMet 100 steel, the stress corrosion crack grows along an intergranular and transgranular path in the direction of forging deformation. The immersion corrosion and salt spray corrosion rates of the AerMet 100 steel is 33 – 40% and 13 – 20% of those for the 300M steel, respectively. Evidence of humidity corrosion is not detectable in the AerMet 100 steel within the employed test period 1[illegible]0 days, whereas it is substantial (2.0413 mpy or 0.0447 mdd) in the 300M steel.

The overall results indicate that the AerMet 100 steel is superior to the 300M steel with respect to the corrosion resistance as well as the mechanical properties.

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AerMet 100 and 300M Steel, Stress Corrosion Cracking, SCC, Double Cantilever Beam, DCB

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CONTENTS

FIGURES

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INTRODUCTION

Carrier-based aircraft landing gear and other components demand corrosion resistant and tough materials in order to achieve higher performance and greater reliability at minimum life-cycle cost. Because of its high ultimate tensile strength, 300M steel was accepted as the standard material for landing gear. However, its corrosion resistance is poor and its fracture toughness is low. Consequently, it is highly susceptible to catastrophic failure by environment assisted cracking and fracture, and it is not suitable for advanced carrier-based aircraft landing gear.

Recently, Carpenter Technology Corp. developed AerMet 100, a nickel-cobalt alloy steel strengthened by carbon, chromium, and molybdenum. This steel has an outstanding combination of high fracture toughness, K_{IC}, exceeding 110 ksi*in^1/2, and high tensile strength, 280 - 300 ksi. Since its mechanical properties surpass those of the 300M steel, it has a great potential for application to aircraft landing gear and other fracture critical components. A typical example is its selection as the material for F/A-18E/F aircraft landing gear. However, its corrosion behavior was not fully understood. This study was initiated to characterize the corrosion behavior. The characterization efforts included clarification of stress corrosion cracking, immersion corrosion, salt spray corrosion, and humidity corrosion of AerMet 100 steel. For comparison, an identical study was concurrently performed for 300M steel.

EXPERIMENTAL PROCEDURE

1. Materials and Specimen

One of the two specimen materials, an AerMet 100 steel forging, was supplied by Carpenter Technology Corp. in the form of a 4.25 in. dia. round bar. Its chemical composition is given in Table 1.

Table 1. Chemical Composition of AerMet 100 Steel Bar (wt %)

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Co	Al	Ti	Fe
.230	.03	.03	.003	.0009	3.03	11.09	1.18	.01	13.44	.005	.009	Bal

This bar was cut into specimen blanks slightly larger than respective specimens. These blanks were subjected to the NAWCADWAR-modified heat treatment: 1625°F solution treatment for 1 hour, oil quenching, refrigeration in liquid nitrogen for 1 hour, and 900°F aging for 5 hours. The resultant plane strain fracture toughness, K_{IC}, was measured to be 115 ksi*in^1/2 in the C-R orientation and 127 ksi*in^1/2 in the L-R orientation, respectively. The microstructure is shown in Fig. 1(a).

The other specimen material, 300M steel, had a form of 1 in. x 1 in. rod and its nominal chemical composition is as follows.

Table 2. Chemical Composition of 300M Steel Rod (wt %)

C	Mn	Ni	Si	Cr	Mo	V	Fe
.43	.75	1.80	1.60	.83	.40	.08	Bal

The rod was austenitized at 1600°F, oil-quenched, and double-tempered at 575°F. The microstructure is shown in Fig. 1(b).

The blanks of both steels were machined into respective specimens by the method of elctro discharge machining. The double cantilever beam (DCB) specimen for the stress corrosion cracking test and the square sheet specimen for the immersion, salt spray, and humidity corrosion tests are shown in Fig. 2. The square sheet specimen had two small notches at a corner, where a nylon line was fastened. The nylon line was used to suspend the specimen in the respective test environments. All specimen surfaces were polished with abrasive papers, subjected to ultrasonic cleaning in acetone, and dried. The specimen corner with notches and a nylon line was covered with red micromask to prevent localized corrosion of the area.

2. Test Environments

For the stress corrosion cracking and immersion corrosion tests, an aqueous 3.5% NaCl solution of pH 7.3 was employed at room temperature. For the humidity corrosion test, an atmosphere of 100% relative humidity and 120°F was maintained with vapor from distilled water in a humidity chamber. For the salt spray test, an aqueous 5% NaCl solution of pH 5.5 was atomized by compressed air of 12 psi in a fog chamber. The fog chamber was maintained to hold its temperature at 95°F, its relative humidity at 95 - 98%, and its salt solution collection rate at 1.2 mL/hour.

3. Testing

a. Precracking and Loading of DCB Specimen

The SCC test with a DCB specimen is a constant crack opening displacement test with stress intensity decreasing for increasing crack length. The K_{ISCC} is defined as the stress intensity at crack arrest.

DCB specimens were precracked by fatigue cycling to initiate a crack 0.068 in. beyond the chevron notch and then bolt loaded. The load was provided by two opposing bolts inserted across the notch with a steel ball between the bolts to give uniform loading. The following equation was used to determine the stress intensity values as a function of crack length a.

$$K_I = (ED\sqrt{3})/\left[4\sqrt{H}\left\{(a/H) + 0.673\right\}^2\right]$$

where

E : modulus of elasticity
H : half-width of the specimen
D : deflection of specimen arms at the load line
a : crack length, defined as the distance from the center of the loading bolts to the crack tip

With this equation, the starting stress intensity was determined to be 49 ksi*in^1/2.

b. Environmental Exposure

(i) Stress Corrosion Cracking Test

DCB specimens were continuously immersed in an aqueous 3.5% NaCl solution at room temperature. They were removed from solution at periodic intervals, and crack lengths were measured visually on each surface with a traveling optical microscope. The crack length versus time data were used to determine crack growth rate, da/dt. A stress intensity value was calculated for each measured crack length, and da/dt vs. stress intensity was plotted.

(ii) Immersion, Humidity, and Salt Spray Corrosion Tests

Prior to environmental exposure, each square specimen was weighed and its dimension was measured to permit accurate calculation of the exposure area. Subsequently, specimens were suspended in an aqueous 3.5% NaCl solution at room temperature for the immersion corrosion test, in a humidity chamber of 100% relative humidity and $120^{o}F$ for the humidity corrosion test, and in a fog chamber of atomized aqueous 5% NaCl solution and $95^{o}F$ for the salt spray corrosion test, respectively. Specimens were removed from the corrosive environments after each of the preset exposure periods. The exposure periods were 10 - 101 days for the immersion corrosion test, 110 days for the humidity corrosion test, and 17 - 208.5 hours for the salt spray corrosion test. Specimens were cleaned in a solution of 1000 ml hydrochloric acid, 20 g antimony trioxide, and 50 g stannous chloride to remove corrosion products, dried, and weighed. From the weight loss and the exposure period, the corrosion rate was determined.

c. Metallography

After stress corrosion cracking test, the cracked portion of the DCB specimen was cut, mounted, mechanically polished, etched in Picral, and examined under an optical microscope.

RESULTS AND DISCUSSION

1. Stress Corrosion Cracking

The variation of crack length with time of exposure to an aqueous 3.5% NaCl solution is shown for the AerMet 100 steel specimens of L-R and C-L orientations and a 300M steel specimen of T-L orientation in Fig. 3. The initial crack growth and the final crack length are much greater in the 300M steel than in the AerMet 100 steel. In the AerMet 100 steel, the crack plane orientation, L-R or C-L, results in little difference in the crack growth behavior, except an incubation period prior to the initial crack growth in the C-L orientation.

The plots of crack growth rate, da/dt, vs. stress intensity, K_I, are presented for the aforementioned specimens in Fig. 4. The K_{ISCC} values are determined to be 33 and 19 ksi*in^1/2 for the AerMet 100 and 300M steels, respectively. Furthermore, the crack growth rate is much greater for a given stress intensity in the 300M steel than in the AerMet 100 steel. A comparison in terms of K_{ISCC} values and SCC growth rates clearly shows that the SCC resistance of the AerMet 100 steel is superior to that of the 300M steel in an aqueous 3.5% NaCl solution. Previously, a lower K_{ISCC} value, 21 ksi*in^1/2, was reported by Atrens (1) for an AerMet 100 steel tested in a 3.5% NaCl solution. Prior to the Atrens' SCC test, the steel had been solution treated at 1625°F, air cooled, refrigerated at -108°F, aged at 900°F, and air cooled.

During the fatigue precracking in air, the crack grew straight from the notch tip in the longitudinal direction of the DCB specimens of both AerMet 100 and 300M steels. However, in the AerMet 100 steel, as soon as the SCC growth started in an aqueous 3.5% NaCl solution, the crack deviated and grew in the transverse direction of the specimen, Fig. 5. The crack deviation occurred in both smooth-faced and side-grooved specimens. The side groove had a depth of 10% of the specimen thickness and could not stop the crack deviation. Crack deviation was also observable during the later stage of the SCC growth in the 300M steel. Optical microscopy examination of the crack at an overetched specimen surface showed that the crack deviated and grew primarily along one of the parallel ghost lines, Fig. 6. The ghost lines (2, 3) indicate the principal direction of deformation during the prior forging. Lighter etching of the specimen revealed a microstructure and a crack path, which is intergranular and transgranular with respect to the prior austenite grains, Fig 7. From this observation, it is evident that in the AerMet 100 steel the SCC growth takes place along an intergranular and transgranular path in the direction of forging deformation.

2. Immersion and Humidity Corrosion

The immersion corrosion rates in an aqueous 3.5% NaCl solution, expressed by the reduction rates of specimen size and weight, and their variation with exposure time are shown for the AerMet 100 and 300M steels in Fig. 8. The immersion corrosion rate of the AerMet 100 steel is 33 - 40% of that for the 300M steel. This indicates that the AerMet 100 steel has better resistance to immersion corrosion than the 300M steel. The immersion corrosion rate is greatest at the initial stage of corrosion and it decreases with exposure time for both steels.

In a humidity chamber of 100% relative humidity and 120°F, the AerMet 100 steel specimens did not show any detectable corrosion in 110 days. On the other hand, the 300M steel specimens showed noticeable corrosion with size reduction rate of 2.0413 mils per year (mpy) and weight reduction rate of 0.0447 milligrams per square decimetre per day (mdd).

3. Salt Spray Corrosion

The corrosion rates in a salt spray chamber of atomized aqueous 5% NaCl solution, expressed by the reduction rates of specimen size and weight, and their variation with exposure time are shown for the AerMet 100 and 300M steels in Fig. 9. The salt spray corrosion rate of the AerMet 100 steel is 13 - 20% of the rate for the 300M steel. As for the immersion corrosion, the salt spray corrosion rate is greatest at the beginning of the exposure and it decreases with time.

SUMMARY

1. The corrosion behavior of an AerMet 100 steel and a 300M steel was characterized. The characterization effort included clarification of stress corrosion cracking, immersion corrosion, salt spray corrosion, and humidity corrosion.

2. The AerMet 100 steel has superior corrosion resistance, compared to a 300M steel.

3. With DCB specimens in an aqueous 3.5% NaCl solution, the K_{ISCC} values of the AerMet 100 and 300M steels are determined to be 33 and 19 ksi*in^i/2, respectively. Under the employed SCC condition, the crack in the AerMet 100 steel grows along an intergranular and transgranular path in the direction of forging deformation.

4. The immersion corrosion and salt spray corrosion rates of the AerMet 100 steel are 33 - 40% and 13 - 20% of those for the 300M steel, respectively.

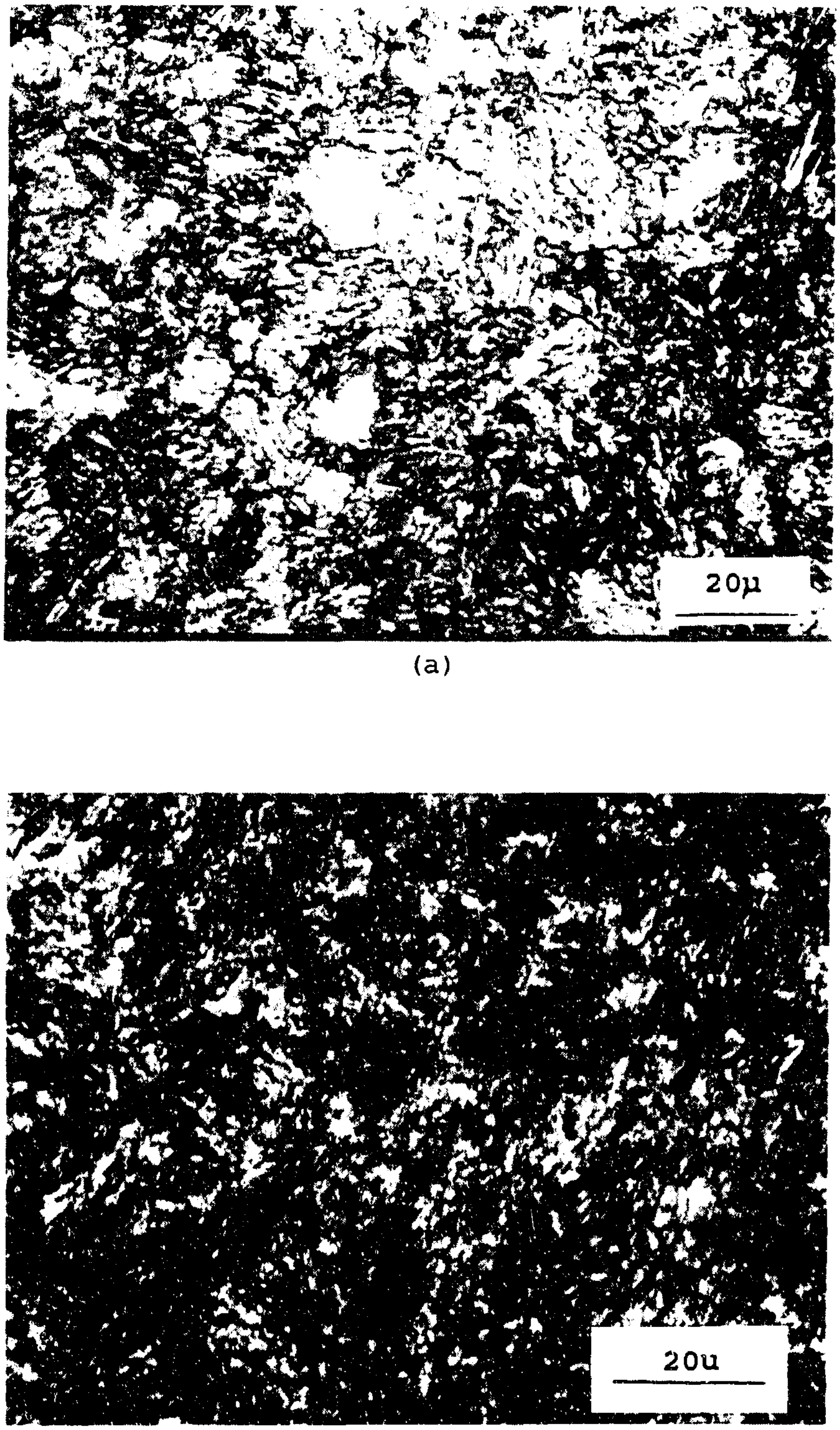
6. In a humidity chamber, the AerMet 100 steel is not corrodible within the employed test period of 110 days. But the 300M steel is susceptible to humidity corrosion, and its rate is 2.0413 mpy or 0.0447 mdd.

REFERENCE

1. Andej Atrens: Private Communication.

2. W. Rostoker and J. R. Dvorak: "Interpretation of Metallographic Structures", Academic Press, New York, 1965, p. 17.

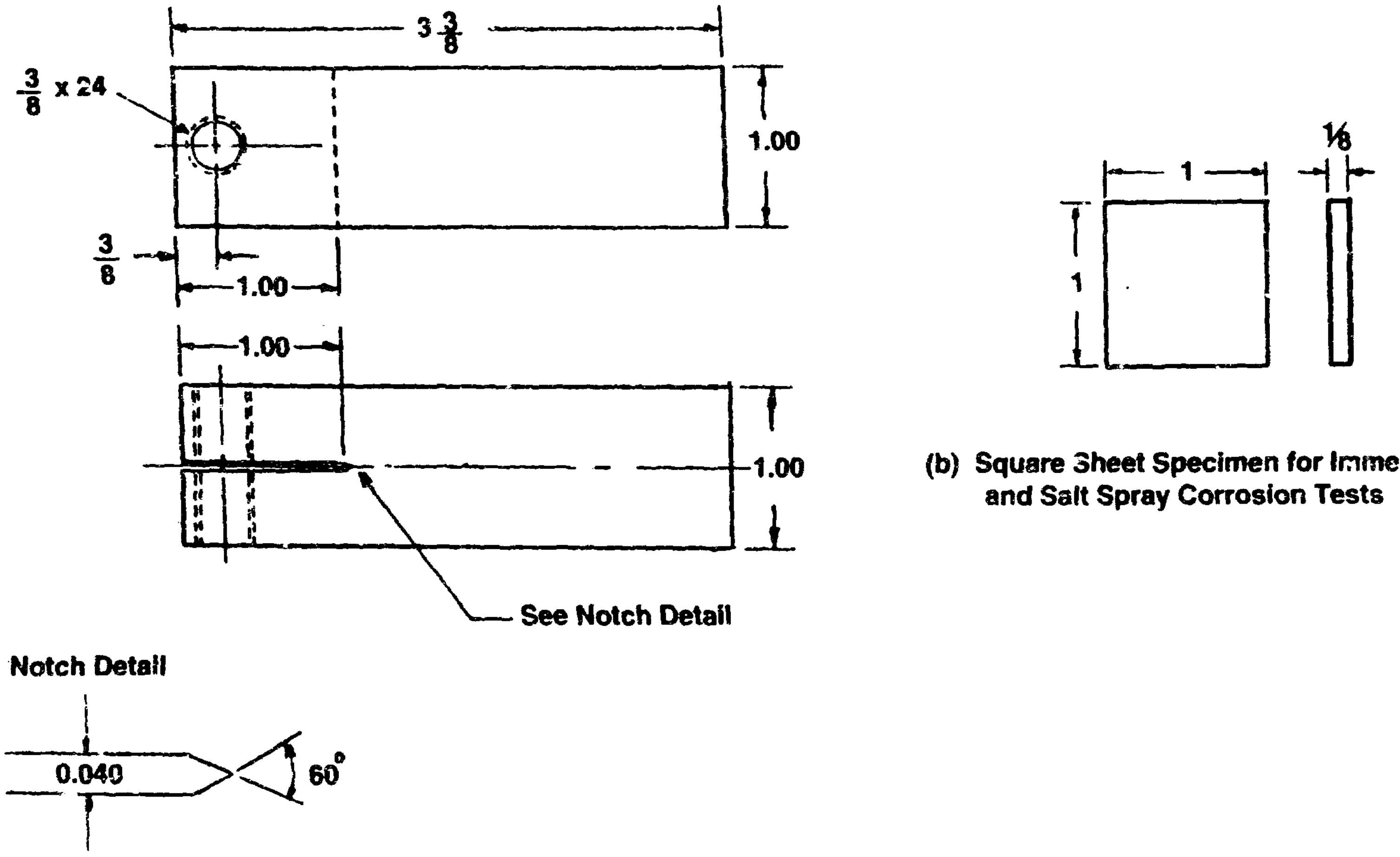
3. Annick and Jean Pokorny: Solidification and Deformation of Steels, in "Metallographic Atlas of Iron, Steels and Cast Irons", vol. III, W. B. Saunders Co., Philadelphia, 1967, pp. 50-55.



(a)

(b)

Figure 1. Microstructures of AerMet 100 and 300M Steels
(a) AerMet 100 Steel
(b) 300M Steel



(a) Double Cantilever Beam Specimen for SCC Test

(b) Square Sheet Specimen for Immersion, Humidity and Salt Spray Corrosion Tests

Figure 2. Spcimens

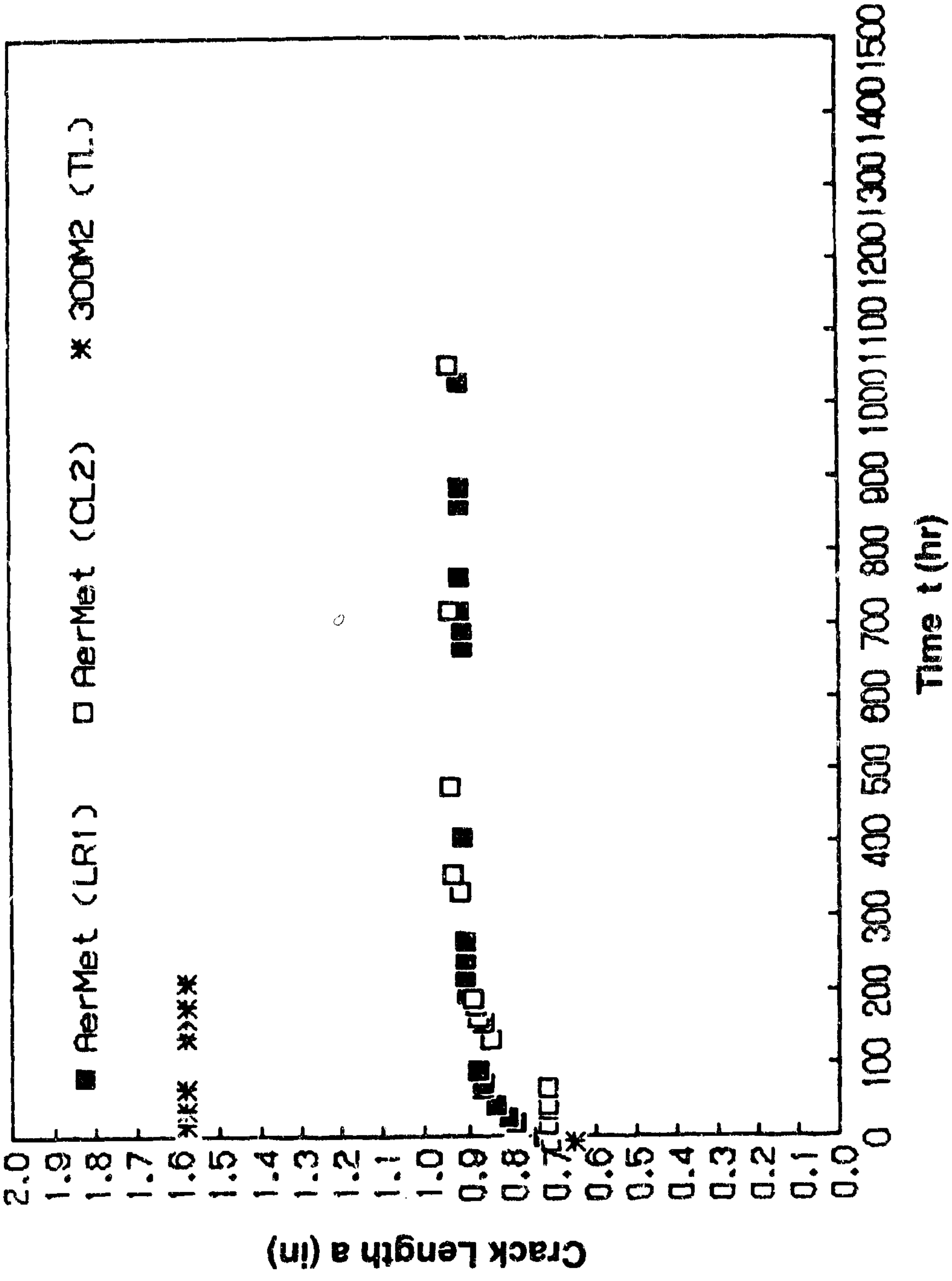


Figure 3. Stress Corrosion Crack Growth with Time

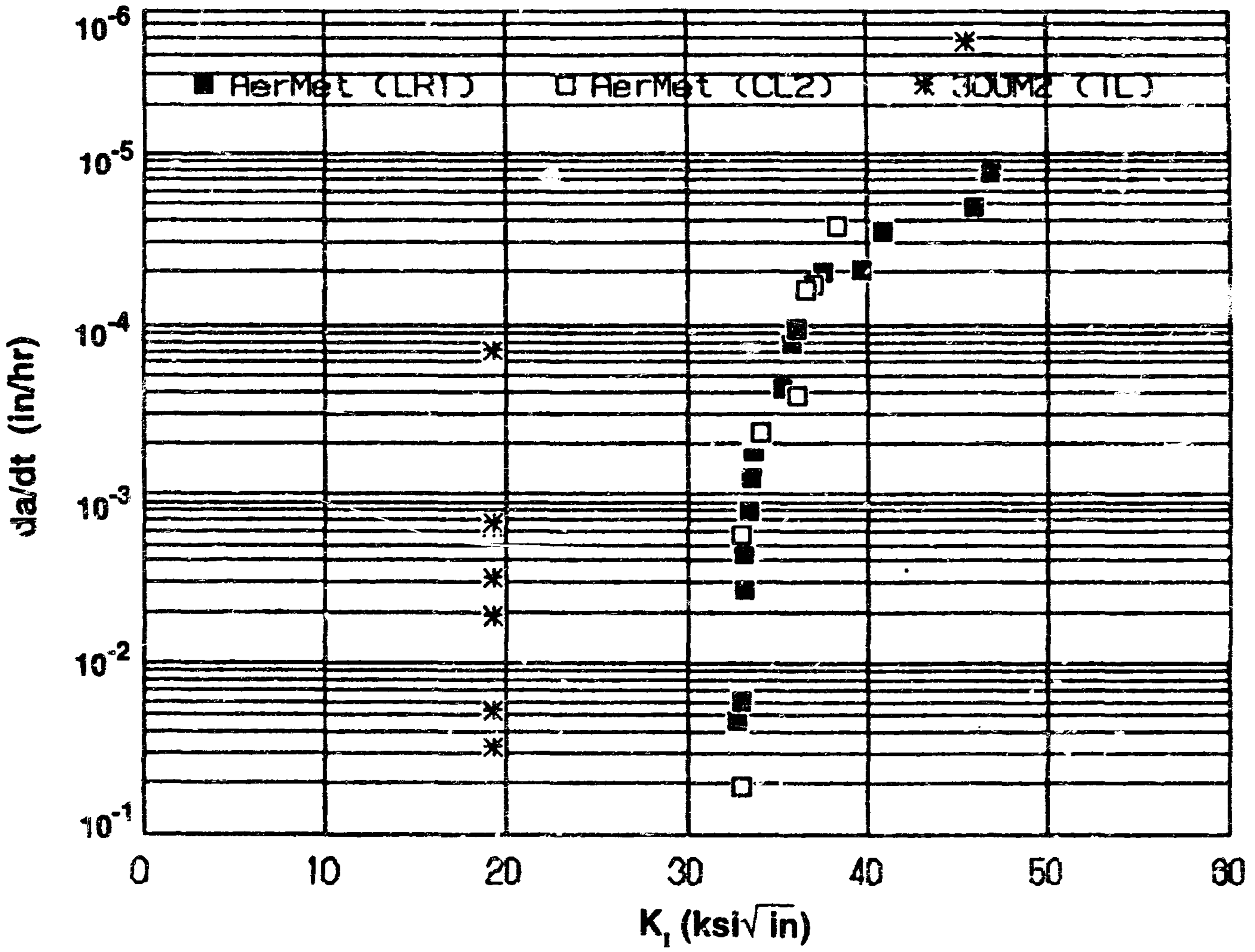


Figure 4. Variation of Stress Corrosion Crack Growth Rate da/dt with Stress Intensity K_I

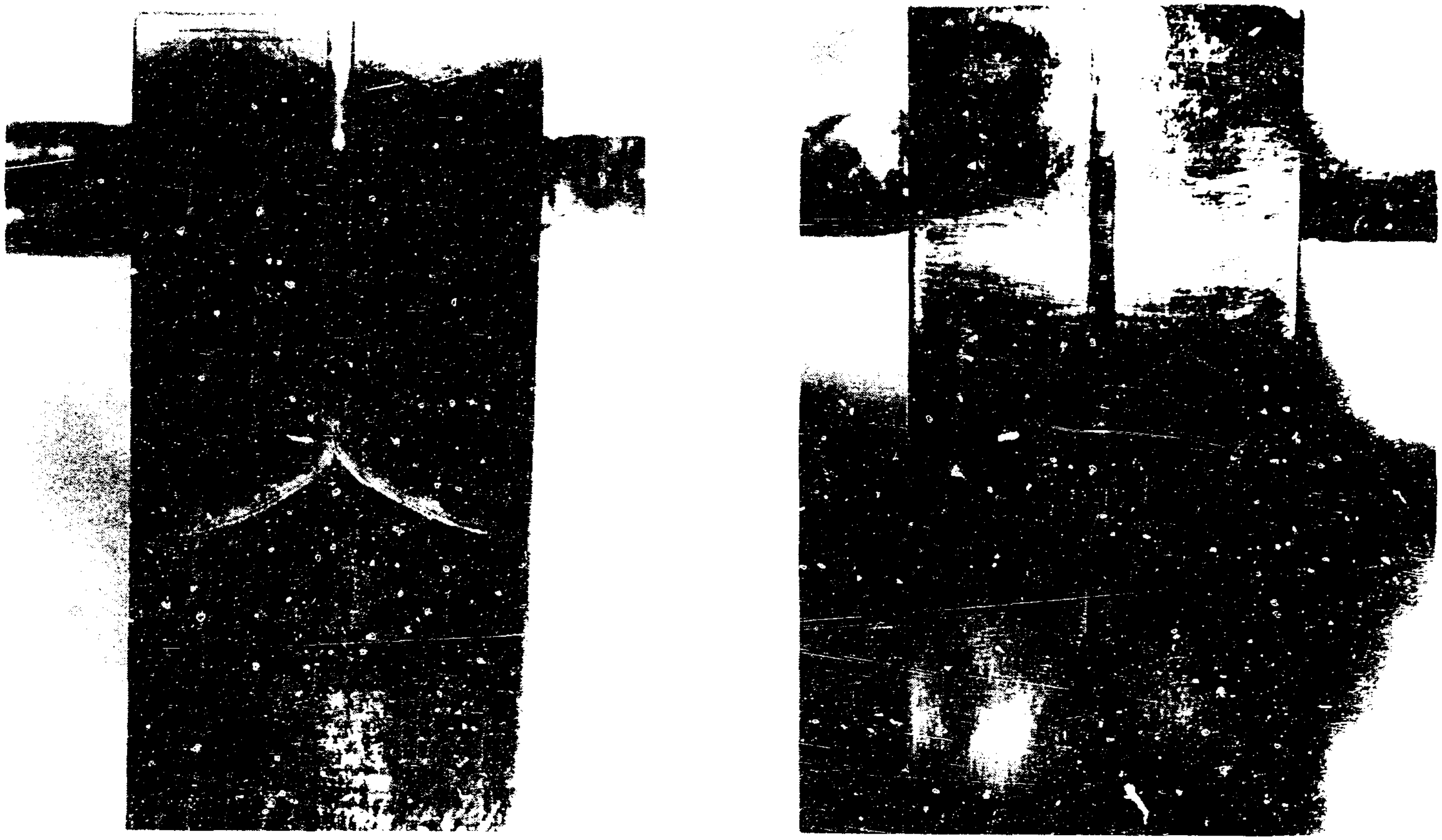


Figure 5. (a) Crack at Surface of Fatigue Precracked and SCC Tested Specimen (AerMet 100 Steel)

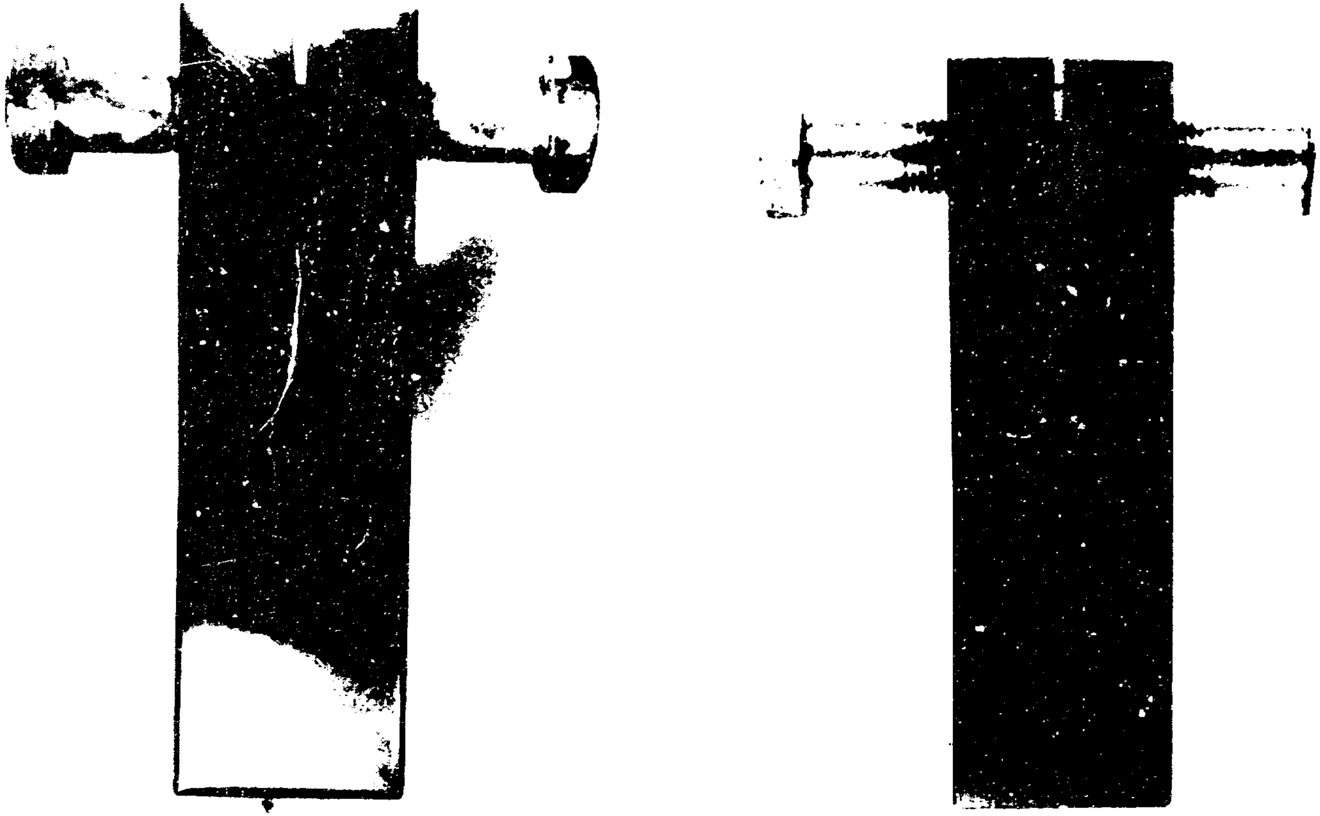


Figure 5. (b) Crack at Surface of Fatigue Precracked and SCC Tested Specimen (300M Steel)

Figure 6. Crack in Fatigue Precracked, SCC Tested, and Overetched AerMet 100 Steel Specimen

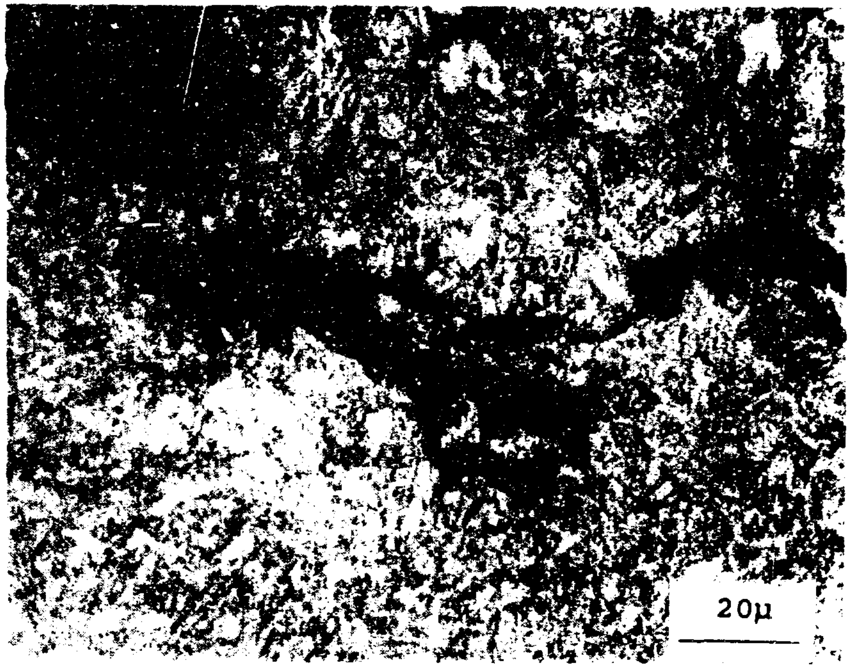
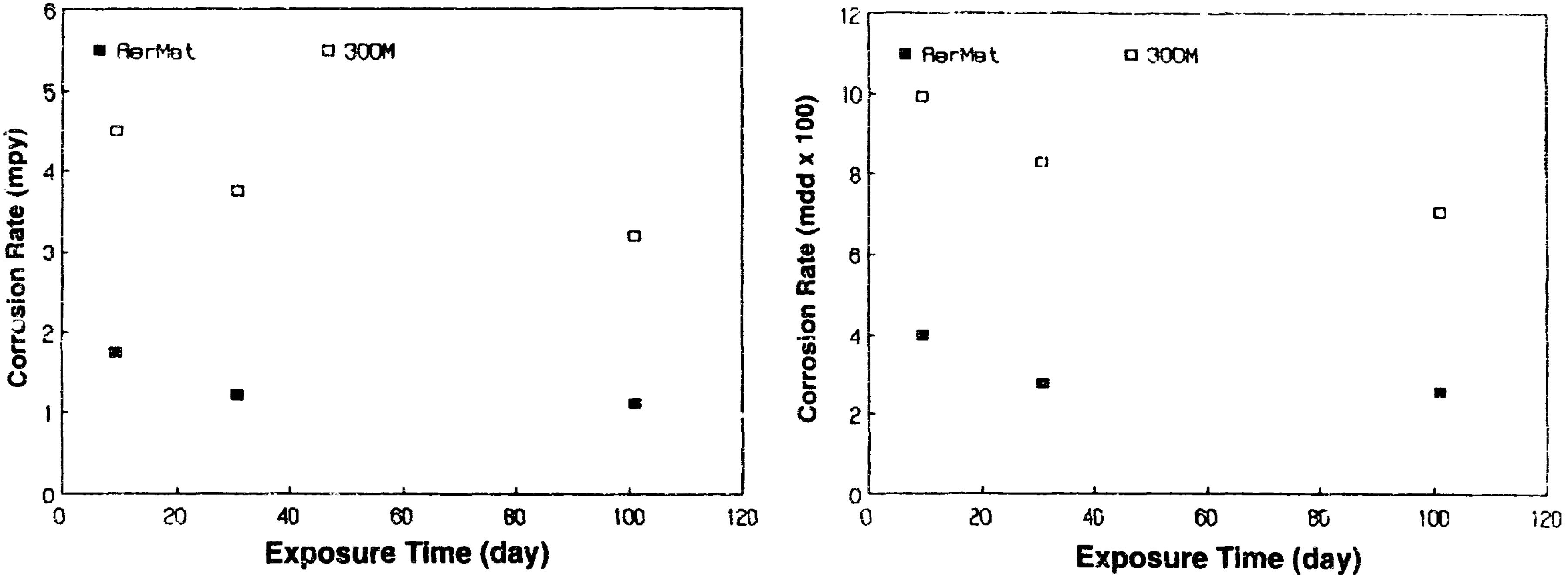


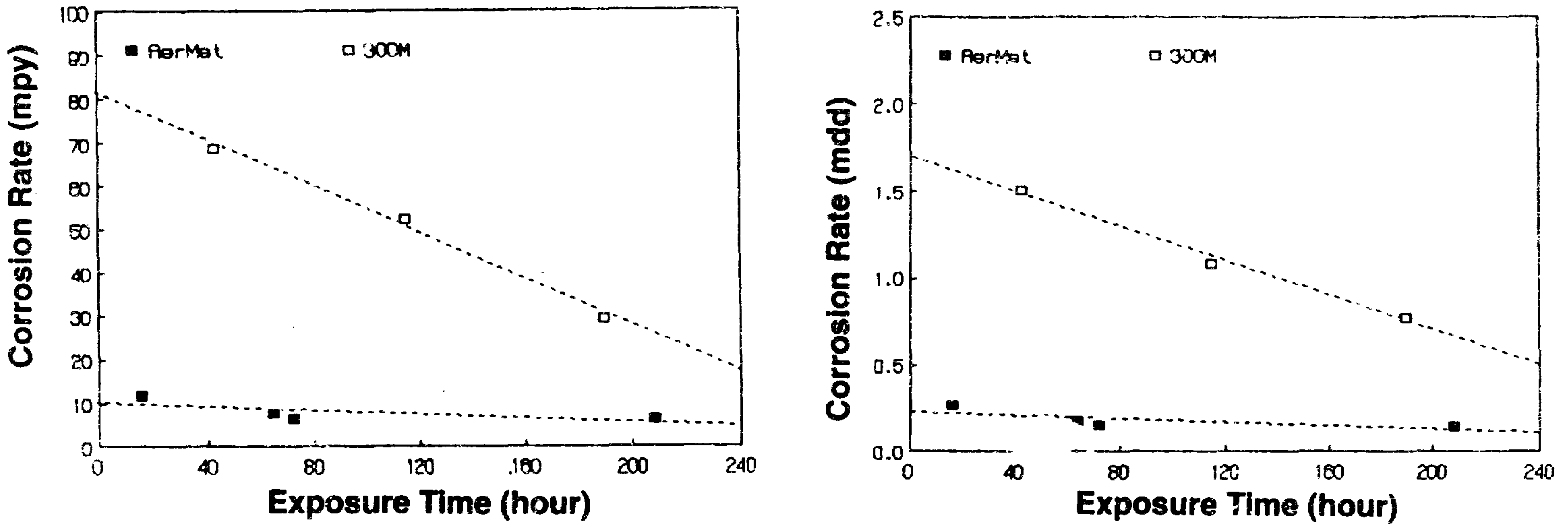
Figure 7. Micrograph showing Intergranular and Transgranular Stress Corrosion Cracking in AerMet 100 Steel Specimen



(a)

(b)

Figure 8. Immersion Corrosion Rates of AerMet 100 Steel and 300M Steels
(a) Size Reduction Rate
(b) Weight Reduction Rate
(mpy: mils per year, mdd: milligrams per square decimetre per day)



(a)

(b)

Figure 9. Salt Spray Corrosion Rates of AerMet 100 and 300M Steels
(a) Size Reduction Rate
(b) Weight Reduction Rate

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