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VACUUM INVESTMENT CAST PH13-8Mo CORROSION RESISTANT STEEL

FOREWORD

This report represents the combined effort of the membership of The Aerospace Metals Engineering Committee of the Aerospace Materials Division of SAE. Specifically, the contributions of the following are acknowledged:

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1. SCOPE:

An industry-wide interest has arisen with regards to the properties and capabilities of investment cast PH 13-8Mo corrosion resistant steel. Specifically of interest are the structural applications in the aerospace industry for this product heat treated to the H1000 condition.

The objective of this AMEC cooperative test program was to generate and compile useful data for aerospace structural evaluation of investment cast PH 13-8Mo heat treated to H1000. The focus of the test program was the determination of overall mechanical properties, fatigue, fracture toughness, and crack growth data along with basic microstructural evaluation of the investment cast material.

Additional objectives included the evaluation of mechanical property variations between cast and machined tensile specimens and evaluation of microstructural constituents. All testing was performed to determine the suitability of PH 13-8Mo, H1000 investment castings for use in the aerospace industry.

2. REFERENCES:

AMS 5629 Bars, Forgings, Rings, and Extrusions, 13Cr-8.0Ni-2.2Mo-1.1Al, Vacuum Induction Plus Vacuum Consumable Electrode Melted, Solution Heat Treated, Precipitation Hardenable

3. PROCEDURE:

3.1 Materials and Processing:

The material tested was vacuum induction melted in two heats, having the following compositions conforming to AMS 5629 (see Table 1):

TABLE 1

Heat	C	Mn	Si	P	S	Cr	Ni	Mo	Al
1	0.018	0.0065	0.0052	0.0017	0.0016	12.70	7.97	2.11	1.11
2	0.024	0.0060	0.0063	0.0016	0.0016	12.59	7.98	2.13	1.15

The material was investment cast with a selective insulated wrap, poured under vacuum. Mold temperature was 2150°F ± 50 and metal temperature was 2725°F ± 50. Air cooling followed vacuum casting.

3.1 (Continued):

Thermal treatment processing of the material consisted of the following:

a. Homogenize at 2100°F ± 25 for 90 min in vacuum with argon gas fan cool to room temperature.

b. Solution treat at 1700°F ± 15 for 60 min in vacuum with argon gas fan cool followed by a water cool to below 60°F.

c. Age at 1000°F for 4 h in air with rapid air cool.

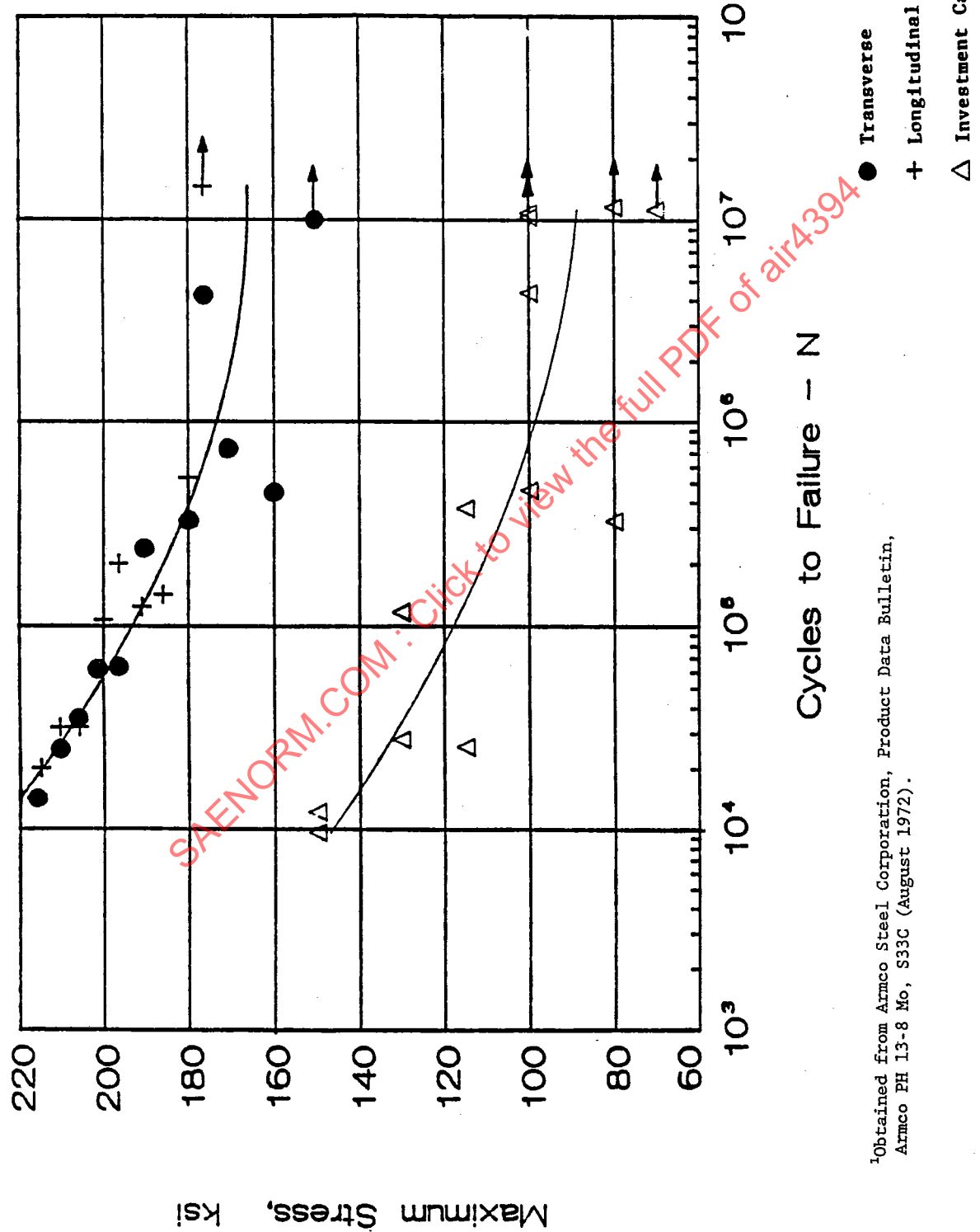
3.2 Testing:

Room temperature mechanical property tests were conducted on machined specimens and specimens which were cast to size for the purpose of establishing strength guidelines and for making a comparison between the two conditions. The results are presented in Table 2. The ultimate and yield strength properties of the cast-to-size and machined-to-size specimens were not statistically equivalent by a T-test comparison. However, since the values are slightly lower in both cases for the cast-to-size specimens, combining the data seems reasonable. The ductility of the two specimen types were statistically equivalent using an identical statistical analysis. However, due to the rather large standard deviations, the statistical minimums are very low. All statistical analyses of the mechanical property data are presented in Appendix A.

Plane strain fracture toughness was evaluated on five specimens primarily for information purposes. The results presented in Table 3 were relatively consistent for each test group.

A series of axial load fatigue tests were conducted. Stresses were selected so that cycles to failure ranged between 10^3 and 10^7. A single test using as-cast specimens from heat 2 at constant stress-ratio, R=+0.1, was conducted on 22 specimens to develop a satisfactory S/N curve. A comparison was made with an S/N curve derived from 14 machined-to-size specimens. The constant stress-ratio results are presented in Tables 3 and 4 and plots of the data are combined in Figure 2. The fatigue curve developed from tests of machined-to-size specimens is also shown in Figure 1, for comparison with fatigue data on rolled bar as reported by ARMCO.

The final results presented are comprised of data from a series of compact tension tests performed on specimens machined from plate stock to develop representative crack growth data for PH 13-8Mo, H1000. Five individual tests were conducted. Results are presented in Tables 5 through 9 with their respective plots in Figures 3 through 7.



[1]Obtained from Armco Steel Corporation, Product Data Bulletin, Armco PH 13-8 Mo, S33C (August 1972).

FIGURE 1 - S/N Curve for Unnotched Fatigue Behavior of PH 13-8 Mo (H1000) (Data includes longitudinal and transverse results for rolled bar[1] and for specimens machined from an investment casting.)

TABLE 2 - Tensile Test Results

Form	Heat	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (Percent)	Reduction of Area (Percent)
S	2	192.5	202.6	8.2	37.9
S	2	189.1	198.3	10.8	42.0
S	2	191.4	199.9	8.8	38.1
S	2	198.6	206.8	13.7	24.8
S	2	197.6	209.7	11.2	30.8
S	2	191.2	205.6	10.4	18.2
S	2	196.8	201.7	7.1	35.5
S	2	196.0	200.2	5.0	29.2
S	2	198.0	203.2	7.2	35.2
S	2	200.0	204.4	9.0	31.5
S	2	196.0	202.3	8.9	35.2
S	2	197.5	203.0	8.8	36.2
S	2	188.2	203.9	9.3	26.0
S	2	189.3	202.2	12.2	40.9
S	2	188.7	202.0	9.2	36.0
S	2	187.6	206.1	6.9	27.3
M	1	195.8	207.4	11.8	24.6
M	1	197.2	204.5	15.0	58.5
M	1	194.9	202.9	12.7	46.6
M	2	196.8	205.7	12.0	52.3
M	2	197.0	204.9	8.0	33.1
M	2	196.3	204.9	8.0	33.7
M	2	197.0	205.5	5.0	17.2
M	2	195.4	203.8	4.0	17.9
M	2	196.2	205.1	5.0	19.6
M	2	194.3	204.3	6.0	22.6
M	2	195.4	205.1	10.0	48.7
M	2	196.0	204.2	12.0	56.9
M	2	202.8	205.0	11.0	43.6
M	2	199.0	201.6	9.5	37.5

S - Specimens cast to size.

M - Specimens machined from any area of casting[1].

[1]Note - Machined to size specimens from heat 1 were cut from 1 in x 2.5 in x 5.5 in cast plate while those from heat 2 were cut from 0.325 in x 6 in x 6 in plate.

TABLE 3 - Room Temperature Fracture Toughness[1]

Test Facility	Fracture Toughness ksi-in^2
1	K_{IC} 80.8[2]
1	K_{IC} 84.7[3]
2	K_{IC} 79.8
2	K_Q 79.1[4]
2	K_{IC} 80.9

[1]All specimens machined from 1 x 2.5 x 5.5 in cast plate.
[2]Hardness checked at 45.4 HRC .
[3]Hardness checked at 46.0 HRC.
[4]P_{max}/P_o did not meet ASTM E 399 criteria of 1.10.

TABLE 4 - Axial Load Fatigue Data Summary
Constant Stress Ratio R=+0.1
Cast to Size Specimens
Heat #2

Test	Minimum Stress (ksi)	Maximum Stress (ksi)	Cycles N	Result @ N
A8	8	80	164 010	Failure
B8	8	80	132 330	Failure
B3	8	80	233 970	Failure
A1	6	60	10 262 800	No Failure
B4	10	100	67 900	Failure
B14	7	70	775 000	Failure
A1 (Retest)	10	100	96 000	Failure
A3	7	70	279 000	Failure
B1	7	70	250 000	Failure
B11	13	130	45 000	Failure
B10	13	130	56 000	Failure
7	18	180	5 440	Failure
5	13	130	28 450	Failure
3	10	100	81 660	Failure
4	8	80	142 380	Failure
6	7	70	620 890	Failure
8	6.5	65	313 500	Failure
14	18	180	25 000	Failure
13	8	80	133 000	Failure
12	7	70	1 344 690	Failure
10	6	60	644 620	Failure
11	6	60	10 149 830	No Failure

TABLE 5 - Axial Load Fatigue Data Summary
Constant Stress Ratio R=+0.1
Machined to Size Specimens

Test	Minimum Stress (ksi)	Maximum Stress (ksi)	Cycles N	Result @ N
2-2	8	80	325 500	Failure
2-3	10	100	10 366 220	No Failure
2-1	10	100	464 050	Failure
3-2	15	150	12 160	Failure
3-3	11.5	115	376 360	Failure
5-1	13	130	117 260	Failure
5-2	11.5	115	25 840	Failure
5-3	10	100	10 869 760	No Failure
6-1	7	70	11 278 000	No Failure
6-2	15	150	9 618	Failure
6-3	10	100	4 393 500	Failure
7-1	8	80	11 655 000	No Failure
7-2	13	130	28 020	Failure
7-3	13	130	116 585	Failure

TABLE 6 - Crack Growth Data Summary
Test 1

Growth Rate [In/Cyc]	Delta K [KIP*IN^-1.5]	Growth Rate [In/Cyc]	Delta K [KIP*IN^-1.5]
2.23364E-06	17.1112	8.42996E-06	32.0349
1.03317E-04	17.3809	7.82717E-06	32.5821
1.15420E-06	17.6493	8.30710E-06	33.0543
2.45868E-06	17.8727	1.02092E-05	33.6007
2.80247E-06	18.0934	8.81727E-06	34.1994
2.80459E-06	18.374	9.56945E-06	34.7437
2.73573E-06	18.6067	9.18061E-06	35.4528
2.38590E-06	18.9126	1.05603E-05	35.9544
2.86370E-06	19.1573	1.00409E-05	36.6656
3.98950E-06	19.4392	1.17991E-05	37.3185
3.25248E-06	19.6887	1.22354E-05	37.9637
3.28552E-06	20.0058	1.28814E-05	38.6654
3.20697E-06	20.2367	1.31239E-05	39.3863
3.58418E-06	20.5312	1.47022E-05	40.1922
3.59754E-06	20.7728	1.55787E-05	40.9955
3.65848E-06	21.0759	1.58407E-05	41.8558
4.04528E-06	21.3804	1.34417E-05	42.661
3.96993E-06	21.6392	1.42263E-05	43.5319
4.27182E-06	21.987	1.57453E-05	44.4191
4.07788E-06	22.2675	1.58856E-05	45.2638
4.56150E-06	22.56	1.77359E-05	46.3037
4.74706E-06	22.8698	1.96749E-05	47.3073
4.79267E-06	23.2247	2.05173E-05	48.4836
4.63267E-06	23.4971	2.41439E-05	49.5353
5.04558E-06	23.8428	2.04221E-05	50.8627
4.68435E-06	24.1702	2.32340E-05	52.0693
5.35167E-06	24.4759	2.52015E-05	53.3819
5.16509E-06	24.8138	3.02906E-05	54.8665
5.42580E-06	25.2063	3.16486E-05	56.4773
5.18696E-06	25.5605	3.38242E-05	57.9237
5.66025E-06	25.9544	3.91055E-05	59.5952
5.31902E-06	26.317	4.33073E-05	61.3479
5.65409E-06	26.7337	4.11887E-05	63.1512
6.48519E-06	27,0648	5.12377E-05	65.1547
5.57188E-06	27.4523	5.60801E-05	67.1962
6.23259E-06	27.8912		
6.48329E-06	28.3254		
7.03149E-06	28.6884		
6.96957E-06	29.1571		
7.45210E-06	29.6016		
7.79220E-06	30.01		
7.10646E-06	30.493		
8.24097E-06	31.0297		
8.80168E-06	31.4917		

TABLE 7 - Crack Growth Data Summary
Test 2

Growth Rate [In/Cyc]	Delta K [KIP*IN^-1.5]	Growth Rate [In/Cyc]	Delta K [KIP*IN^-1.5]
4.22395E-06	20.1744	8.45749E-06	30.7388
4.58654E-06	20.4486	9.37152E-06	31.2383
4.17414E-06	20.7673	1.02060E-05	31.7387
4.98682E-06	21.061	9.24075E-06	32.2268
4.59386E-06	21.375	9.17738E-06	32.7534
4.77221E-06	21.6687	1.06055E-05	33.2276
4.87826E-06	22.0222	1.04530E-05	33.7687
5.21339E-06	22.3074	1.01866E-05	34.331
5.23071E-06	22.6747	1.16253E-05	34.872
5.21031E-06	22.9398	9.48818E-06	35.556
5.24467E-06	23.3222	1.19029E-05	36.1382
5.60012E-06	23.6253	1.08554E-05	36.7167
5.55532E-06	24.0639	1.29709E-05	37.3371
4.68401E-06	24.3844	1.29649E-05	37.8671
5.95472E-06	24.7546	1.41962E-05	38.5978
5.95212E-06	25.0568	1.29887E-05	39.2233
6.75525E-06	25.4375	1.40638E-05	40.0067
6.83478E-06	25.8287	1.53161E-05	40.6525
6.31470E-06	26.1653	1.54293E-05	41.4585
7.35617E-06	26.5496	1.52062E-05	42.1629
7.11484E-06	26.9464	1.63897E-05	42.9626
7.20395E-06	27.282	1.61252E-05	43.8699
7.82588E-06	27.6908	1.84416E-05	44.6379
7.89084E-06	28.1373	1.86957E-05	45.5437
6.98193E-06	28.5547	1.97896E-05	46.4792
8.82370E-06	28.9934	2.05734E-05	47.4436
8.29700E-06	29.358	2.01548E-05	48.357
8.52611E-06	29.8371	2.21113E-05	49.4269
8.50899E-06	30.2871	2.38674E-05	50.4631
		2.27191E-05	51.5834
		2.43854E-05	52.7488
		2.47842E-05	53.9445
		2.64847E-05	55.385
		2.84986E-05	56.7598
		3.30740E-05	58.1823

TABLE 8 - Crack Growth Data Summary
Test 3

DA/DN (Inches/Cycle) (X 10E-07)	Delta K (ksi-IN^2)
5.17	11.02
7.51	11.90
10.39	12.76
15.38	13.98
26.78	14.75
28.84	15.43
42.63	16.07
51.50	16.84
55.89	17.61
74.80	18.42
113.82	19.39
97.48	20.44
118.15	21.38
155.32	22.47
136.67	23.44
101.36	24.17
149.92	27.22
145.71	28.51
178.03	29.94
188.50	31.49
234.45	32.89
316.84	34.51
393.57	38.98
280.24	40.66
480.08	42.75
665.92	45.00
748.73	47.08
1204.20	49.99
604.00	50.82
3244.90	59.78
1669.30	63.10
2436.70	66.49
2795.30	70.05
6197.70	75.05
22315.00	83.02

TABLE 9 - Crack Growth Data Summary
Test 4

DA/DN (Inches/Cycle) (X 10E-07)	Delta K (ksi-IN^2)
5.75	12.50
9.64	13.50
14.96	14.70
20.12	16.00
28.26	17.40
42.54	18.80
47.74	19.50
53.38	21.10
72.83	21.70
82.78	23.00
62.73	24.00
116.67	25.80
161.31	27.40
102.92	29.10
163.79	29.40
187.61	31.20
295.16	32.60
367.42	36.40
233.15	37.70
712.52	40.30
250.95	41.60
451.21	43.50
454.54	45.80
477.92	51.30
650.56	55.00
832.27	58.60
1035.90	62.40
1508.00	66.90
1824.30	71.30
1922.20	76.00
2998.70	83.20
7182.10	92.80
27135.00	116.70

TABLE 10 - Crack Growth Data Summary
Test 5

DA/DN (Inches/Cycle) (X 10E-07)	Delta K (ksi-IN^2)
4.35	11.64
7.16	12.88
11.90	13.88
13.25	14.38
22.16	15.37
18.82	15.93
29.27	16.94
30.22	17.57
29.55	18.95
37.45	20.00
43.80	21.87
52.10	23.14
61.41	24.38
64.92	25.49
76.08	27.82
81.99	29.59
114.15	31.89
121.34	33.93
137.50	35.65
135.97	37.76
70.64	38.95
174.71	41.70
359.25	44.25
886.88	47.56
3853.30	83.61

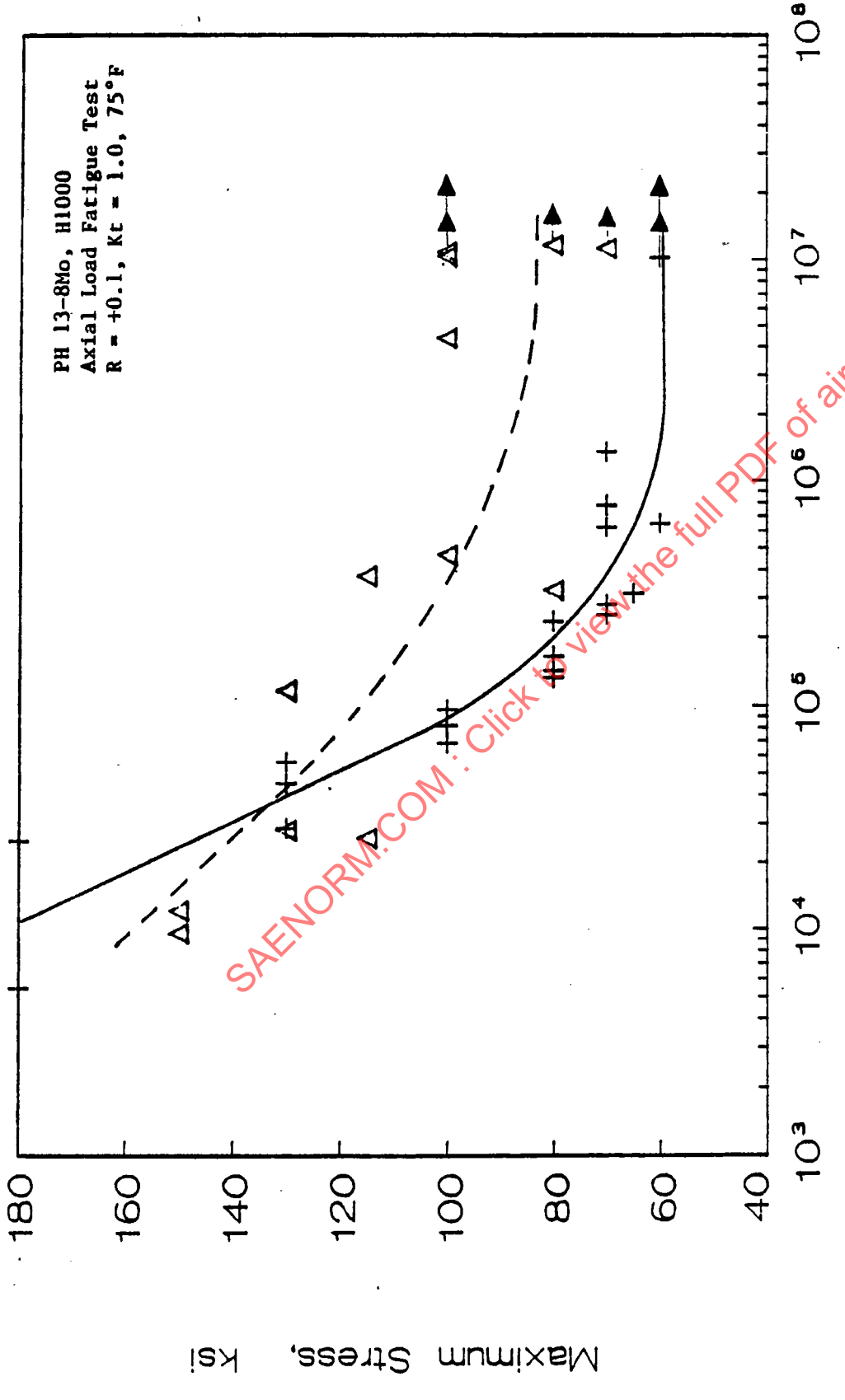


FIGURE 2 - Fatigue Test Results, Constant Stress Ratio, R=+0.1

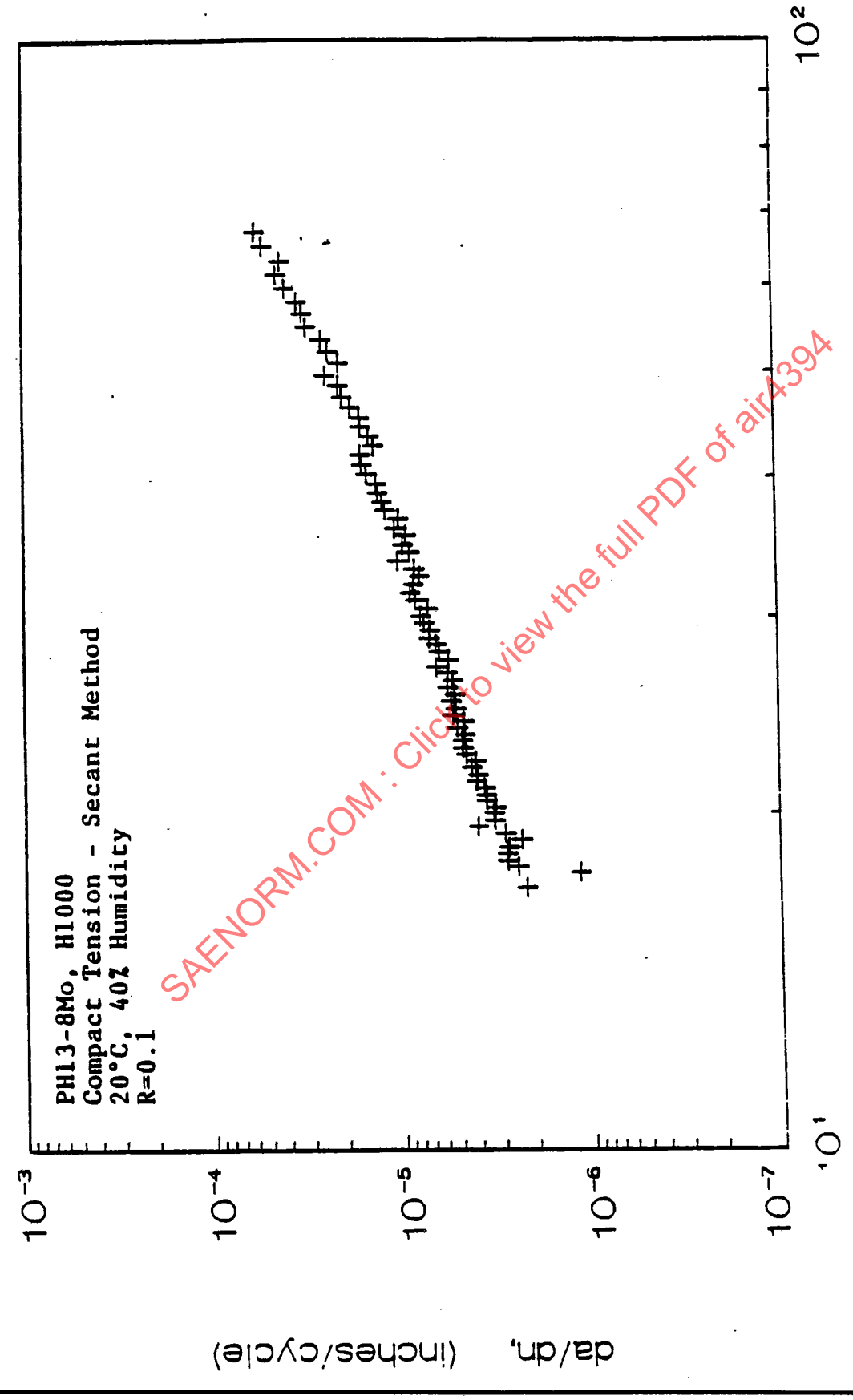


FIGURE 3 - Crack Growth Results, Test 1

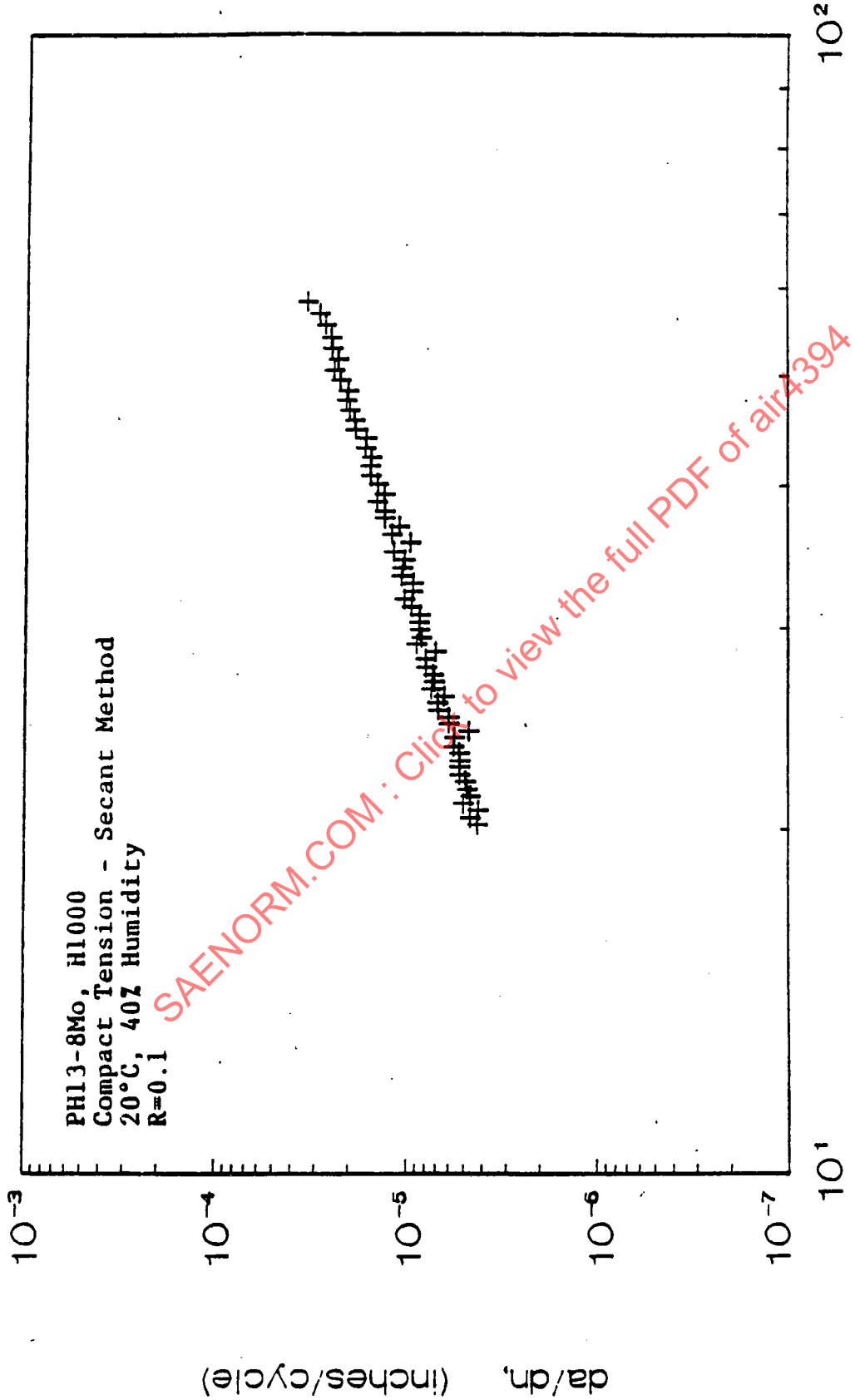


FIGURE 4 - Crack Growth Results, Test 2

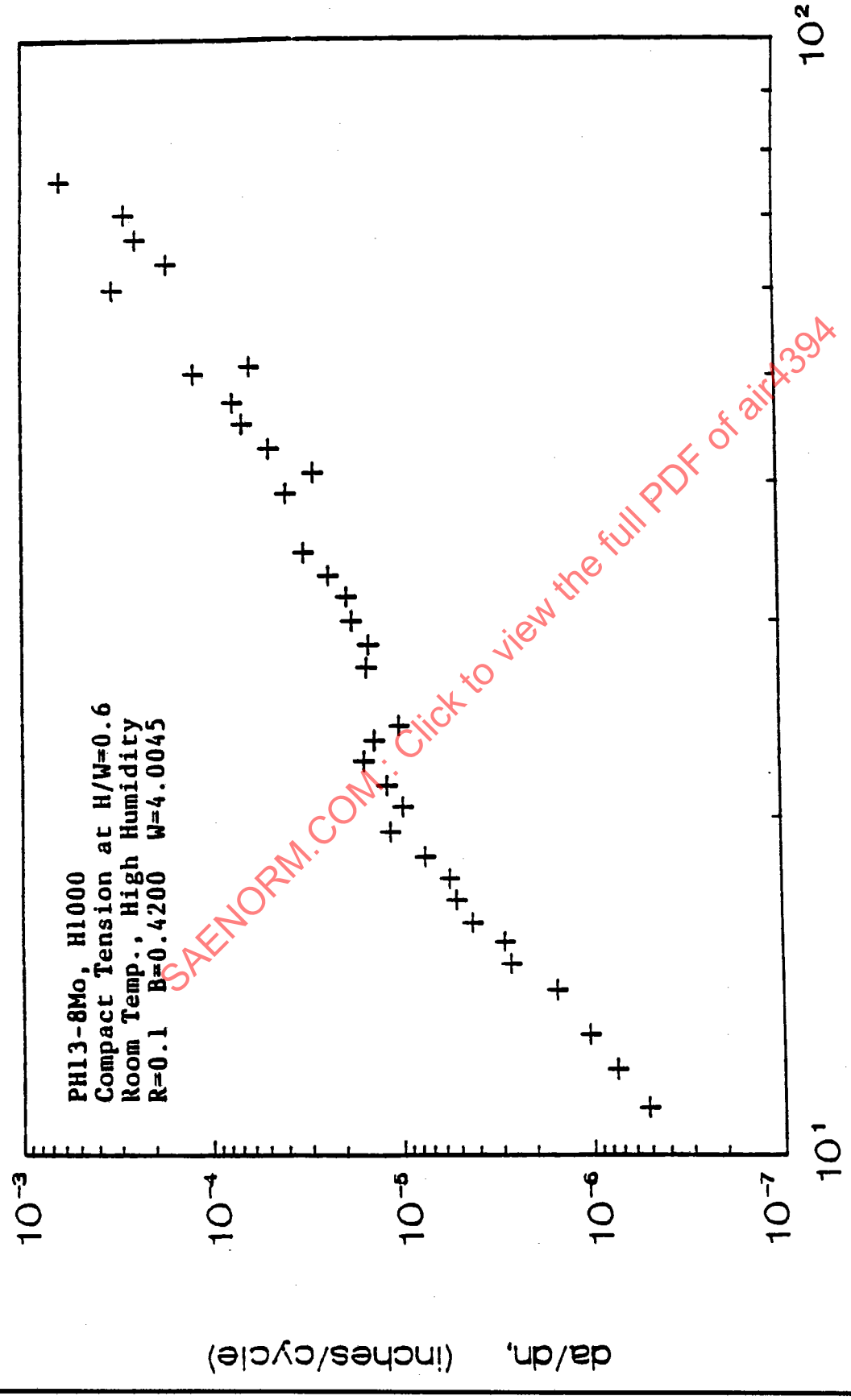


FIGURE 5 - Crack Growth Results, Test 3