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FINAL REPORT - DEVELOPMENT AND TESTING OF AIR-MELTED NICKEL-MOLYBDENUM ALLOYS WITH MINOR ALLOYING ADDITIONS

O. Preston
C. F. Floe
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OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
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U.S. ATOMIC ENERGY COMMISSION

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INTRODUCTION

Results of creep-rupture testing in the range of 1350° to 1650°F, of room-temperature tensile testing and of 1500°F embrittlement exposure tensile tests on a series of five vacuum-melted nickel-molybdenum alloys, containing 17 to 36% Mo, were reported in "Final Report on Development and Testing of Nickel-Molybdenum Alloys" by Monkman, Grant, and Floe issued as ORNL-1990, Metallurgy and Ceramics, on November 10, 1955.

Severe embrittlement of the simple binary nickel-molybdenum alloys was observed in room-temperature tensile tests after exposure for 100 hr at 1500°F without stress. The effects of additions of chromium, iron, vanadium, and columbium in decreasing this embrittlement in two of these alloys of intermediate molybdenum content were reported in "Final Report on Development and Testing of Vacuum Melted Nickel-Molybdenum Alloys with Minor Alloying Additions" by Preston, Grant, and Floe, ORNL-2181, Metallurgy and Ceramics, October 18, 1956.

The present report covers stress-rupture, tensile and embrittlement testing of six 4800-lb air-melted experimental heats of nickel-molybdenum alloys containing 13 to 20% Mo with additions of Mn, Fe, Si, Cr, Al, Ti, W, Cb, and C. Results for commercial Hastelloy B are included for purposes of comparison.

PROCEDURE AND RESULTS

On the basis of the previous studies, a base composition was chosen containing 16% Mo with small amounts of Mn, Fe, and Si to which was added 5% Cr (alloy INOR-2), 1% Al + 1.5% Ti (alloy INOR-3), 2% Al + 1.5% Ti (alloy INOR-4), and 5% Cr + 1% Al + 1.5% Ti (alloy INOR-6). An alloy was included containing 20% Mo without Cr, Al, or Ti additions (alloy INOR-1). The remaining alloy (INOR-5) contained 0.1% C, 2.5% W, 2% Cb, and 13% Mo. Compositions of these alloys are given in Table I.

Bar stock from these experimental heats were received from International Nickel Company, Inc. in the form of 1/2-in. hot-rolled rounds.

Solution treatment in each case was for one hour at 2000°F (to avoid grain growth) and air-cooled in the form of 2.5-in. lengths of the 1/2-in. bar stock. Two pieces of each alloy were then aged for 100 hr at 1300°F along with two pieces of each of the five alloys covered in the previous work (ORNL-2181, Metallurgy and Ceramics, October 18, 1956). Test bars were machined from these samples and stress-rupture tested, together with specimens of commercial Hastelloy B, at 1300 and 1500°F at the stress for 100-hr rupture life for Hastelloy B as determined from the published data. Results of these tests are shown in Table II.

Stress-rupture tests were conducted at 1350, 1500, and 1650°F for each of the six alloys in two conditions of heat treatment with stresses chosen to give values of rupture life in the range of 1 to 500 hr. Alloys INOR-1 and INOR-2 were tested in the solution-treated condition and after aging for 16 hr at 1500°F. Alloys INOR-3, -4, -5, and -6 were tested in the 2000°F, 1-hr, solution-treated condition followed by aging for 16 hr either at 1300°F or at 1500°F. Test bars were machined after heat treatment in each case, with gauge dimensions of 0.225-in. dia by 1 in. long.

Results of stress-rupture testing of the six alloys are presented in Tables III through VIII. Plots of log-stress vs log-rupture life are shown in Figs. 1 through 6. A summary of stress-rupture values for each of the test temperatures is shown in Figs. 7, 8, and 9 together with the values obtained for Hastelloy B in the previous investigation.

TABLE I

COMPOSITION OF ALLOYS IN THIS INVESTIGATION
Wt %

Alloy	Heat No.	C	Mn	Fe	S	Si	Cu	Ni	Cr	Al	Ti	W	Mo	Cb
INOR-1	Y-8195	0.01	0.47	0.28	0.002	0.47	0.02	78.44	-	-	-	-	20.29	-
INOR-2	Y-8197	0.04	0.54	0.69	0.002	0.52	0.02	76.72	5.28	-	-	-	16.17	-
INOR-3	Y-8196	0.01	0.53	0.18	0.001	0.57	0.02	79.86	-	1.08	1.62	-	16.11	-
INOR-4	Y-8198	0.01	0.49	0.49	0.001	0.53	0.02	77.83	-	1.96	1.68	-	16.97	-
INOR-5	Y-8200	0.10	0.94	1.66	0.002	0.68	0.02	78.59	-	-	-	2.69	13.15	2.15
INOR-6	Y-8199	0.02	0.57	0.59	0.003	0.62	0.02	74.01	5.30	1.15	1.69	-	16.01	-

TABLE II

STRESS-RUPTURE DATA FOR ELEVEN EXPERIMENTAL ALLOYS, SOLUTION-TREATED AND AGED 100 HR AT 1300°F, AND FOR COMMERCIAL HASTELLOY B

Alloy Number	Elongation, %	Reduction of Area, %	Rupture Life, Hr
(a) Tested at 1300°F and 37,000 psi			
1	12.8	13.7	50.8
3	14.5	11.5	66.6
4	1.0	1.0	160.0
5	16.0	31.7	88.1
6	1.8	2.7	203.5
INOR-1	19.0	11.1	63.8
INOR-2	8.4	8.4	23.0
INOR-3	6.4	7.7	146.6
INOR-4	2.7	4.5	127.9
INOR-5	15.2	22.8	94.4
INOR-6	10.1	4.5	318.4
Hastelloy B	5.7	6.2	86.1
(b) Tested at 1500°F and 16,500 psi			
1	13.2	7.0	12.9
3	11.7	16.2	34.9
4	14.9	24.8	126.0
5	-	41.7	102.5
6	3.7	2.5	143.3
INOR-1	29.8	23.1	20.1
INOR-2	13.3	8.7	7.4
INOR-3	18.7	20.3	30.9
INOR-4	3.5	5.6	60.9
INOR-5	24.8	26.6	16.9
INOR-6	10.0	7.7	160.6
Hastelloy B	17.7	24.8	168.4

TABLE III

STRESS-RUPTURE DATA FOR ALLOY INOR-1

Temp., °F	Stress, psi	Elongation, %	Reduction of Area, %	Rupture Life, Hr
(a) One hour at 200°F, air-cooled				
1350	40,000	13	15	6.6
	35,000	13	16	17.5
	25,000	22	21	85.2
	17,500	14	15	187.3
	12,500	Test discontinued at 622.1 hr		
1500	15,000	19	21	19.3
	10,000	16	15	51.2
	7,500	11	12	124.9
	5,500	12	14	360.5
1650	12,000	35	24	4.3
	10,000	27	25	7.6
	7,500	17	20	19.9
	5,000	17	19	57.1
	4,000	17	14	99.7
	2,000	Test discontinued at 682.7 hr		
(b) One hour at 2000°F, air-cooled; 16 hr at 1500°F, air-cooled				
1350	50,000	12	19	1.1
	50,000	12	14	0.9
	40,000	12	20	8.2
	25,000	15	20	55.2
	15,000	21	15	656.3
1500	30,000	13	23	1.4
	20,000	15	23	5.7
	10,000	20	14	76.6
	7,500	18	16	266.7
1650	12,000	30	17	2.1
	10,000	20	19	5.4
	7,500	19	21	19.6
	4,000	19	20	80.0
	2,500	22	16	606.7

TABLE IV

STRESS-RUPTURE DATA FOR ALLOY INOR-2

Temp., °F	Stress, psi	Elongation, %	Reduction of Area, %	Rupture Life, Hr
(a) One hour at 2000°F, air-cooled				
1350	40,000	11	11	2.3
	30,000	5	7	6.5
	15,000	6	6	112.7
	10,000	10	7	284.7
1500	30,000	21	11	0.5
	22,500	11	11	1.9
	16,500	6	12	8.3
	10,000	12	10	35.5
	6,000	17	19	158.9
1650	10,000	14	15	4.1
	7,500	11	14	8.4
	4,000	17	10	64.2
	3,000	23	11	183.7
	2,000	28	14	401.3
(b) One hour at 2000°F, air-cooled; 16 hr at 1500°F, air-cooled				
1350	40,000	11	11	2.1
	30,000	8	10	9.4
	20,000	11	10	29.0
	14,000	11	10	160.7
	12,000	-	10	264.6
1500	30,000	9	12	0.5
	20,000	8	11	2.1
	16,500	15	11	8.0
	10,000	9	11	35.9
	6,000	15	10	270.9
1650	10,000	19	14	4.8
	7,500	11	13	10.5
	4,000	18	12	64.7
	2,000	23	13	692.5

TABLE V

STRESS-RUPTURE DATA FOR ALLOY INOR-3

Temp., °F	Stress, psi	Elongation, %	Reduction of Area, %	Rupture Life, Hr
(a) One hour at 2000°F, air-cooled; 16 hr at 1500°F, air-cooled				
1350	50,000	6	14	1.9
	40,000	3	7	12.8
	30,000	6	4	80.9
	22,500	4	5	177.2
	15,000	Test discontinued at 632.2 hr		
1500	30,000	16	19	1.4
	25,000	19	21	3.1
	16,500	25	24	21.7
	10,000	19	19	92.9
	7,500	13	17	294.7
1650	12,500	38	27	3.9
	10,000	32	23	10.0
	7,500	21	21	31.3
	5,000	9	17	97.1
	3,000	Test discontinued at 644.5 hr		
(b) One hour at 2000°F, air-cooled; 16 hr at 1300°F, air-cooled				
1350	50,000	5	5	2.5
	40,000	10	7	6.6
	30,000	6	5	69.1
	30,000	6	6	57.6
	22,500	5	5	153.5
	13,000	Test discontinued at 1001.7 hr		
1500	30,000	20	-	1.0
	22,500	18	24	3.7
	16,500	17	21	26.0
	10,000	14	17	172.8
	8,000	16	20	215.2
1650	10,000	31	25	7.6
	7,500	20	24	22.7
	5,000	22	16	116.6
	3,500	26	17	351.1

TABLE VI

STRESS-RUPTURE DATA FOR ALLOY INOR-4

Temp., °F	Stress, psi	Elongation, %	Reduction of Area, %	Rupture Life, Hr
(a) One hour at 2000°F, air-cooled; 16 hr at 1500°F, air-cooled				
1350	60,000	2	4	2.9
	50,000	2	4	7.5
	40,000	1	1	20.1
	30,000	1	2	50.6
	17,500	Test discontinued at 692.7 hr		
1500	30,000	9	3	2.6
	22,500	3	2	10.4
	16,500	3	2	32.2
	10,000	6	3	130.8
	7,500	7	5	594.5
1650	15,000	4	5	4.1
	12,500	5	2	13.0
	10,000	4	5	29.1
	7,500	11	8	60.2
	6,000	12	8	113.6
	6,000	13	9	147.7
	4,000	22	13	314.5
(b) One hour at 2000°F, air-cooled; 16 hr at 1300°F, air-cooled				
1350	60,000	3	7	0.4
	50,000	1	5	6.2
	40,000	1	3	30.9
	30,000	2	2	84.7
	20,000	3	1	344.5
1500	30,000	8	3	2.7
	22,500	2	2	7.5
	16,500	2	2	51.0
	10,000	8	4	142.0
	7,500	8	6	502.0
1650	21,500	5	5	1.1
	17,500	4	5	2.4
	15,000	7	4	5.5
	10,000	10	7	25.7
	6,000	6	9	127.6
	4,750	-	-	364.1

TABLE VII

STRESS-RUPTURE DATA FOR ALLOY INOR-5

Temp., °F	Stress, psi	Elongation, %	Reduction of Area, %	Rupture Life, Hr
(a) One hour at 2000°F, air-cooled; 16 hr at 1500°F, air-cooled				
1350	50,000	17	21	0.9
	37,500	16	24	5.5
	30,000	25	26	20.4
	20,000	20	26	183.0
	15,000	Test discontinued at 691.1 hr		
1500	30,000	33	26	1.0
	22,500	28	27	2.7
	16,500	18	5	13.4
	10,000	30	20	49.4
	6,000	23	20	399.2
1650	10,000	32	25	3.2
	9,000	34	25	5.5
	7,500	20	25	13.4
	4,000	32	23	86.1
	2,500	-	29	268.3
(b) One hour at 2000°F, air-cooled; 16 hr at 1300°F, air-cooled				
1350	50,000	20	20	1.2
	40,000	16	25	5.1
	25,000	13	24	44.3
	15,000	25	18	622.0
1500	30,000	23	28	0.9
	11,500	14*	22	20.6
	8,000	29	21	84.5
	7,000	28	20	157.4
1650	10,000	22	25	4.4
	6,500	35	25	13.4
	4,000	33	25	66.2
	3,000	-	23	216.2

* Broke at radius

TABLE VIII

STRESS-RUPTURE DATA FOR ALLOY INOR-6

Temp., °F	Stress, psi	Elongation, %	Reduction of Area, %	Rupture Life, Hr
(a) One hour at 2000°F, air-cooled; 16 hr at 1500°F, air-cooled				
1350	75,000	4	8	3.8
	60,000	5	6	14.5
	55,000	5	7	26.5
	45,000	3	5	71.1
	35,000	7	7	166.5
	30,000	3	6	224.7
1500	40,000	5	10	3.0
	30,000	6	10	10.6
	16,500	9	10	171.6
	13,000	11	14	580.2
1650	15,000	17	27	5.5
	10,000	17	29	22.5
	6,500	-	24	72.1
	4,000	27	25	282.2
(b) One hour at 2000°F, air-cooled; 16 hr at 1300°F, air-cooled				
1350	75,000	5	9	0.9
	60,000	2	6	14.4
	55,000	4	6	21.0
	45,000	10	6	44.8
	35,000	3	4	173.6
	25,000	2	5	571.6
1500	40,000	6	7	2.5
	30,000	9	6	10.9
	16,500	11	6	88.8
	10,000	13	11	877.2
1650	15,000	12	32	2.9
	12,500	48	41	5.8
	10,000	16	31	13.7
	7,000	28	25	63.3
	5,000	21	24	196.0

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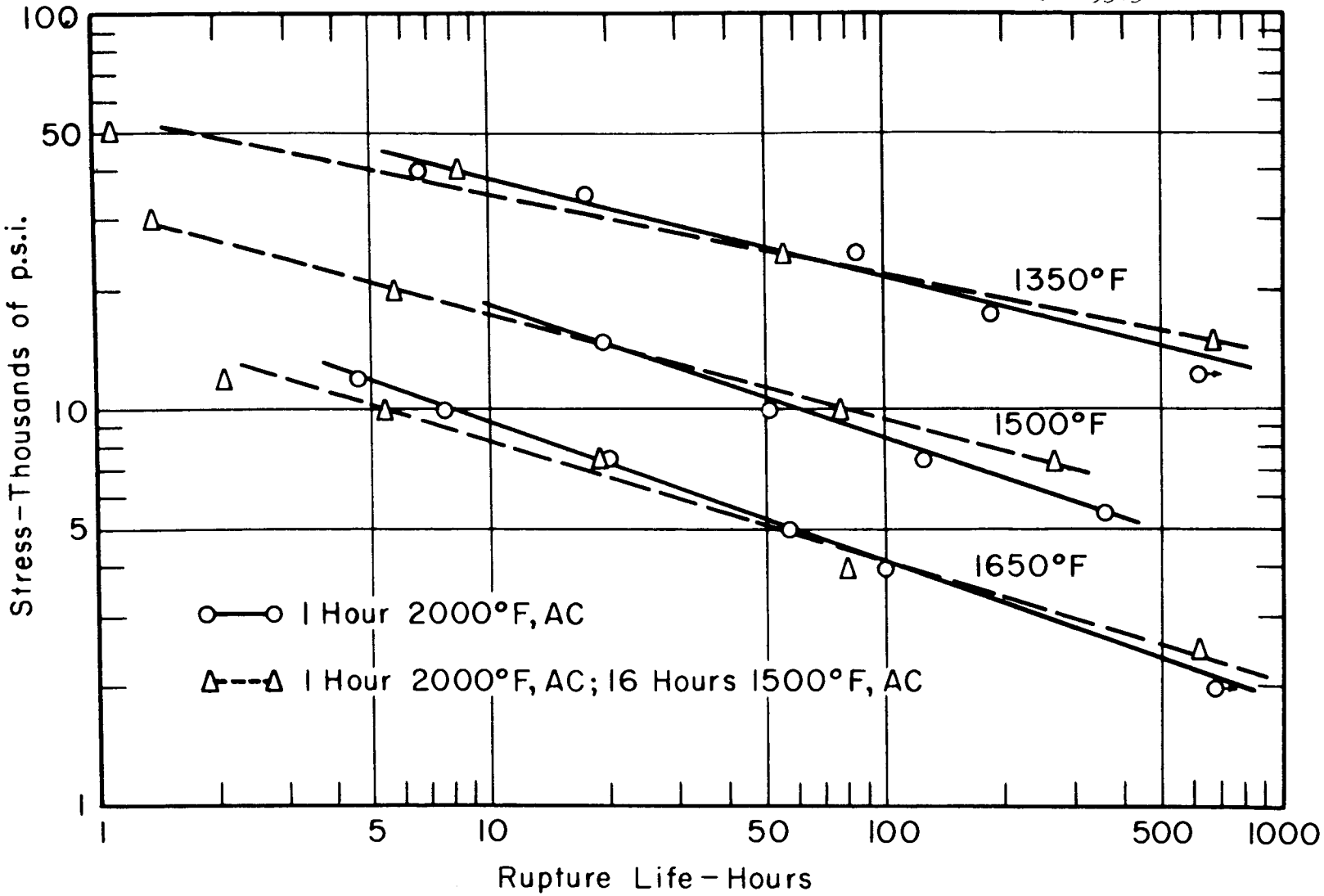

FIG. 1-STRESS RUPTURE DATA FOR ALLOY INOR 1

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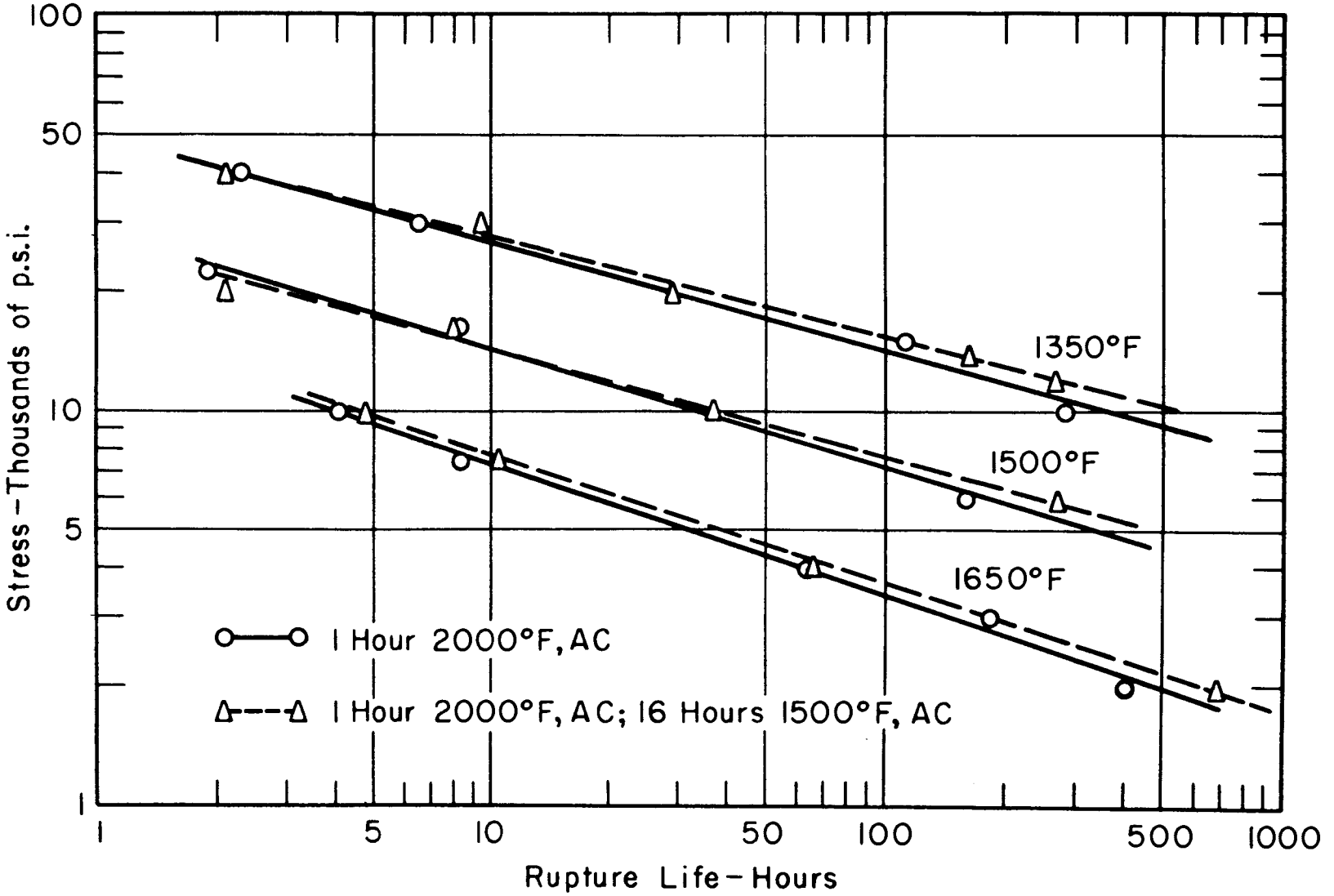

FIG. 2 - STRESS RUPTURE DATA FOR ALLOY INOR 2

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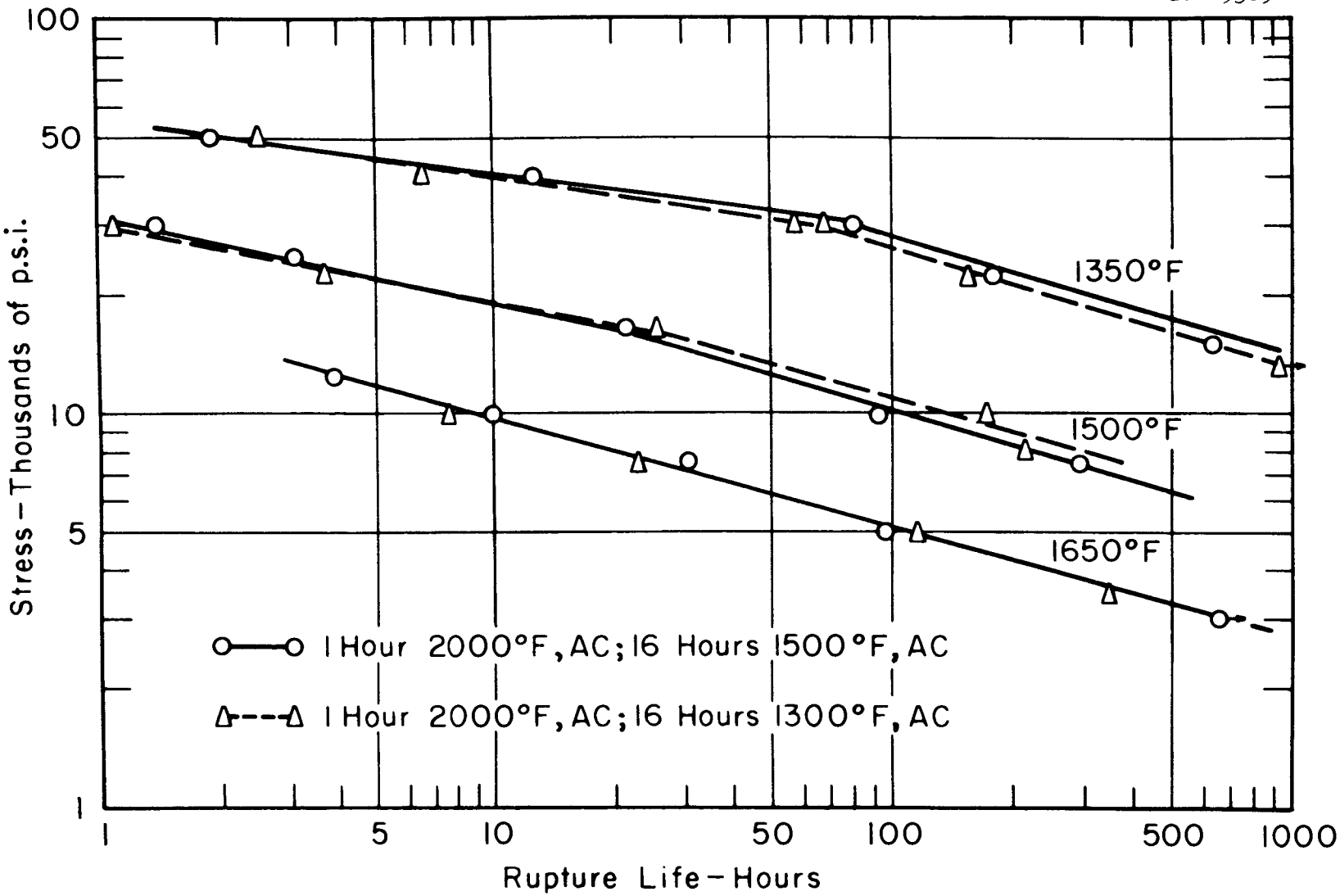

FIG. 3 – STRESS RUPTURE DATA FOR ALLOY INOR 3

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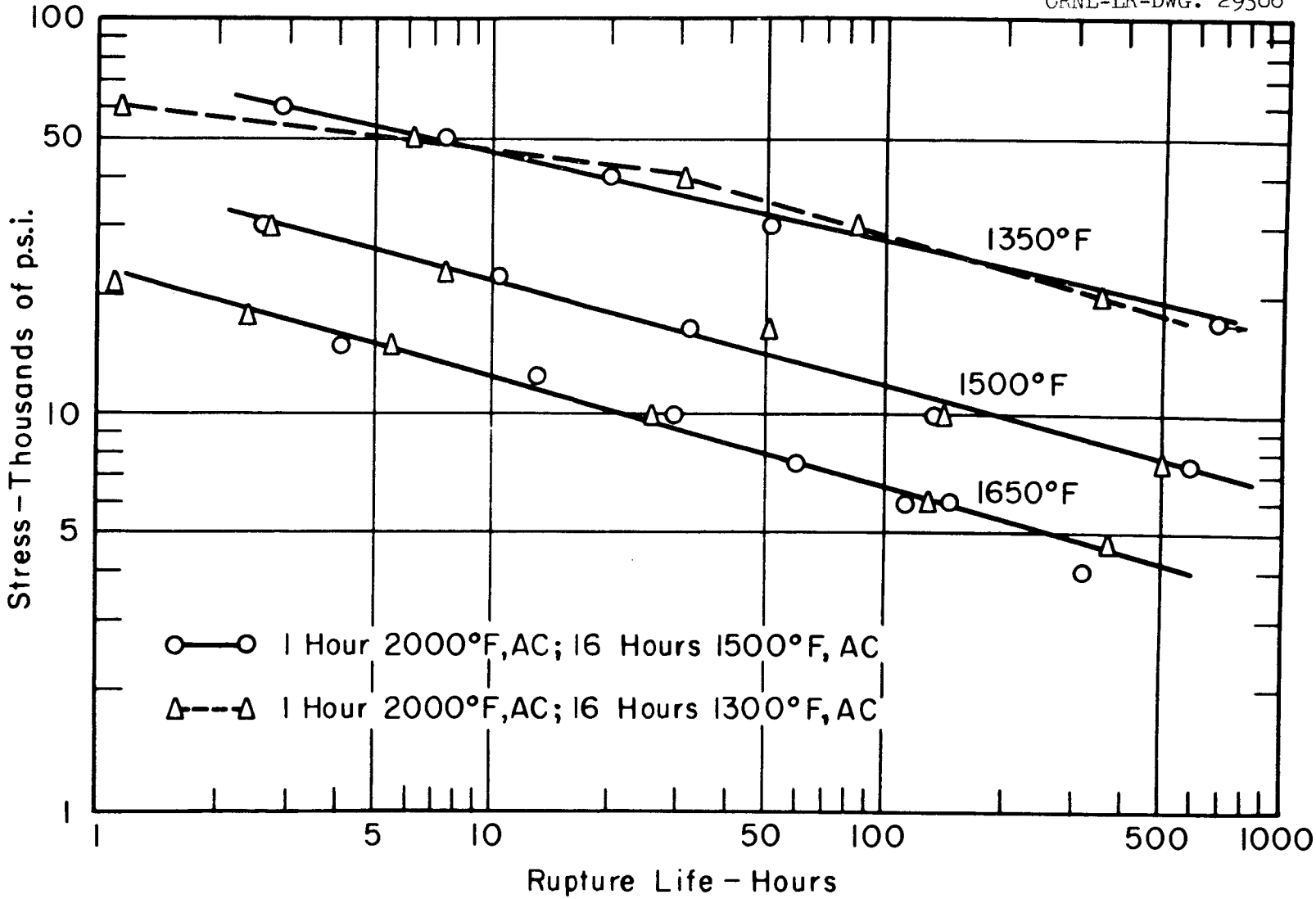

FIG. 4 – STRESS RUPTURE DATA FOR ALLOY INOR 4

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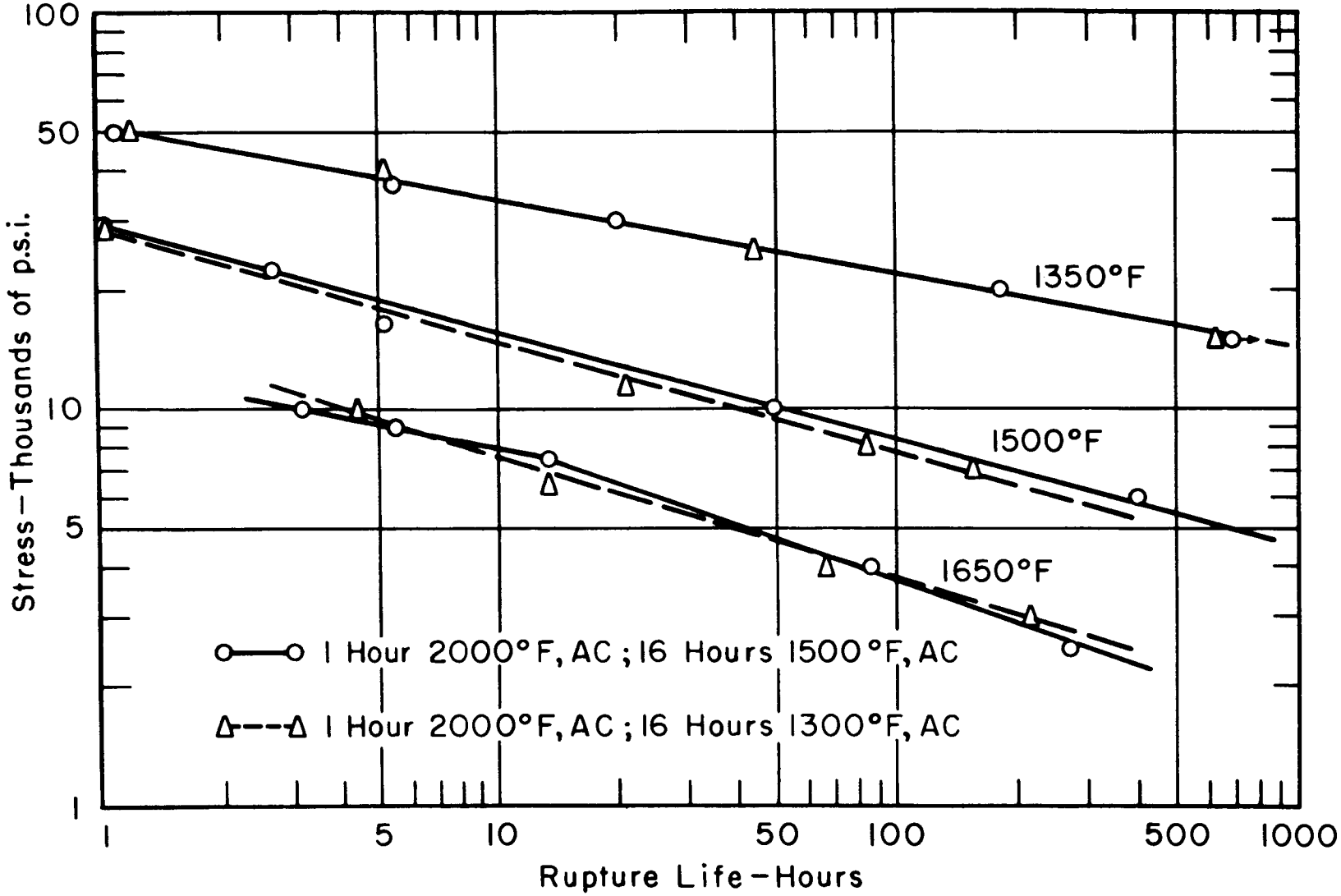

FIG 5.- STRESS RUPTURE DATA FOR ALLOY INOR 5

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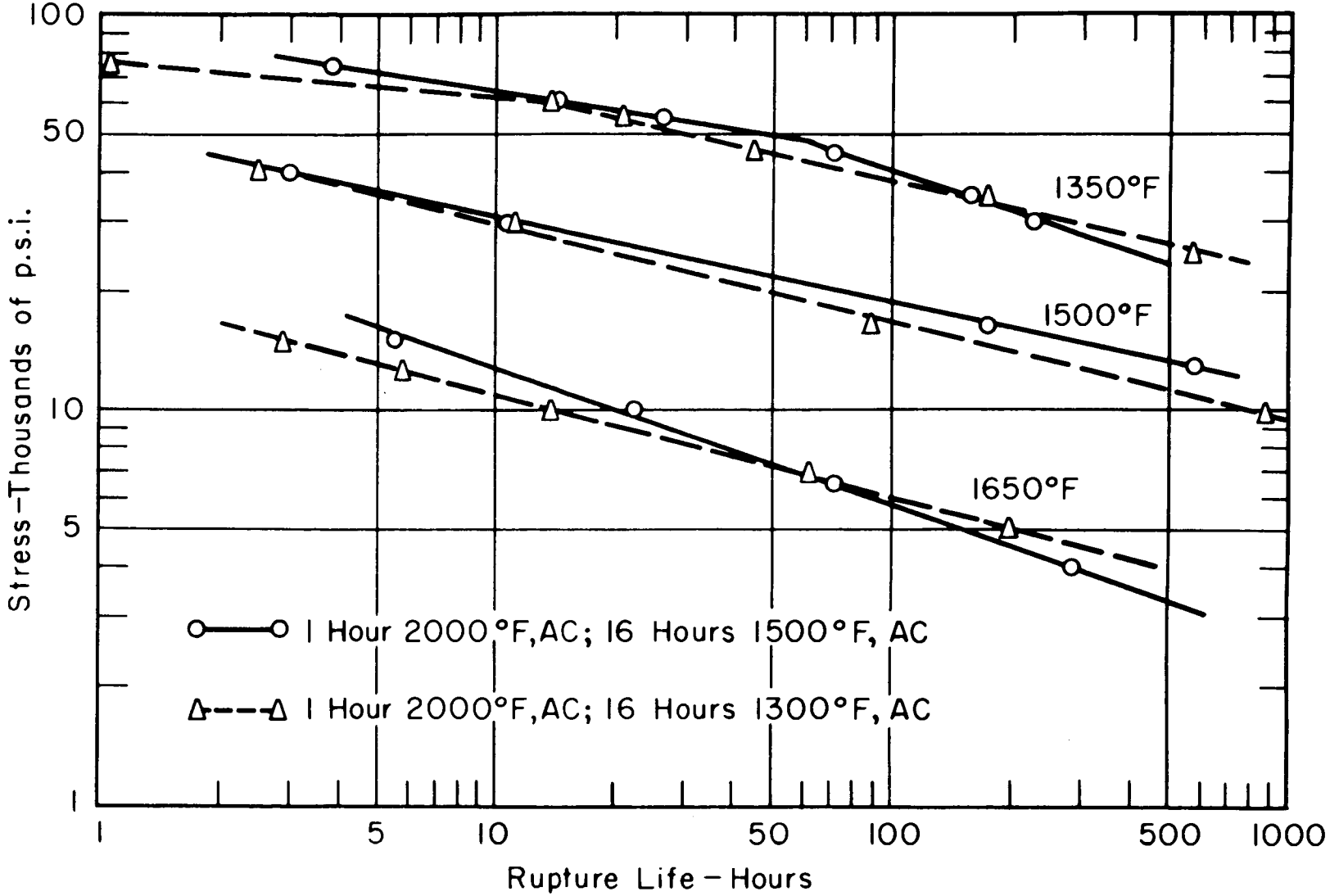

FIG. 6 - STRESS RUPTURE DATA FOR ALLOY INOR 6

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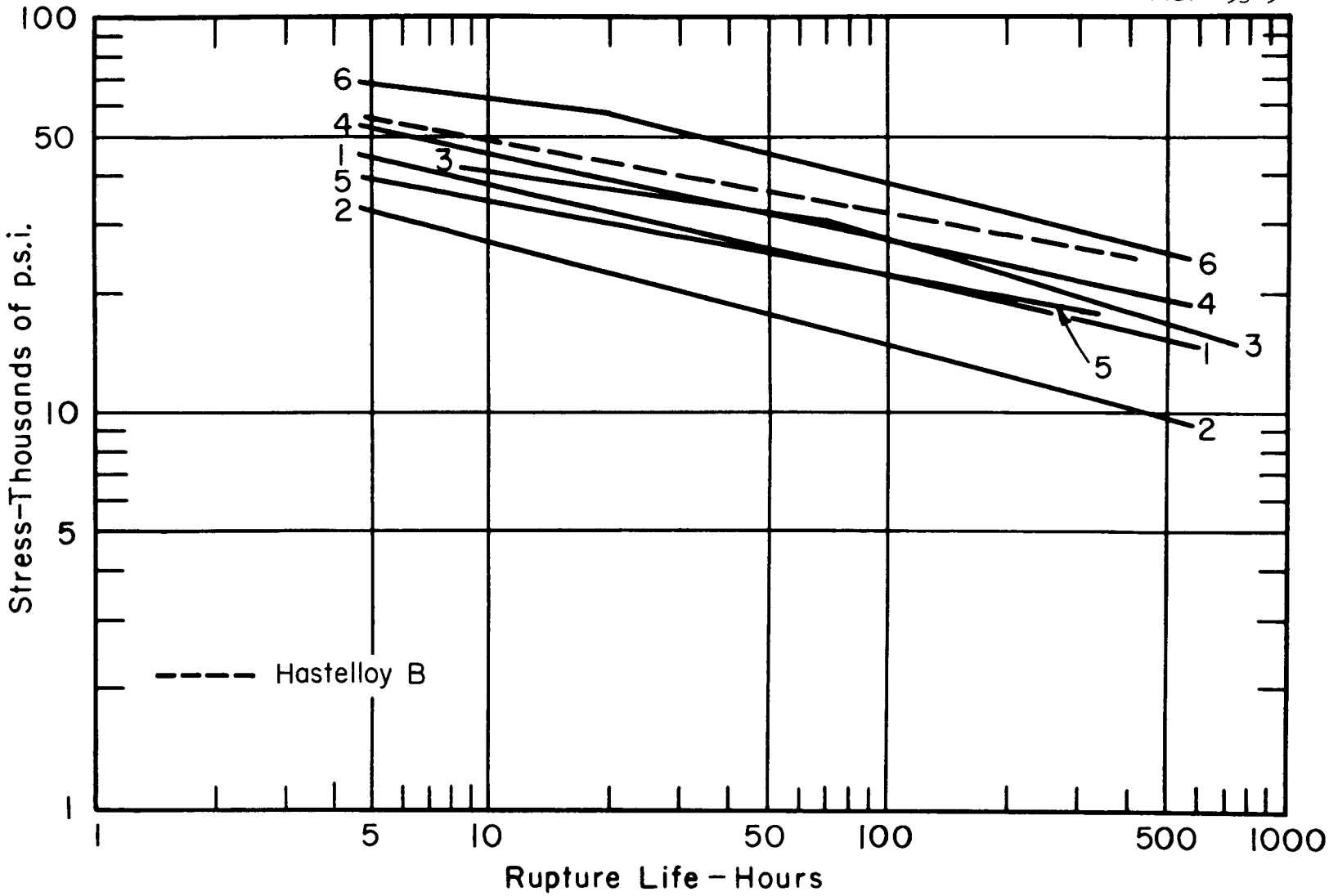

FIG. 7 - SUMMARY PLOT OF STRESS RUPTURE DATA AT 1350°F

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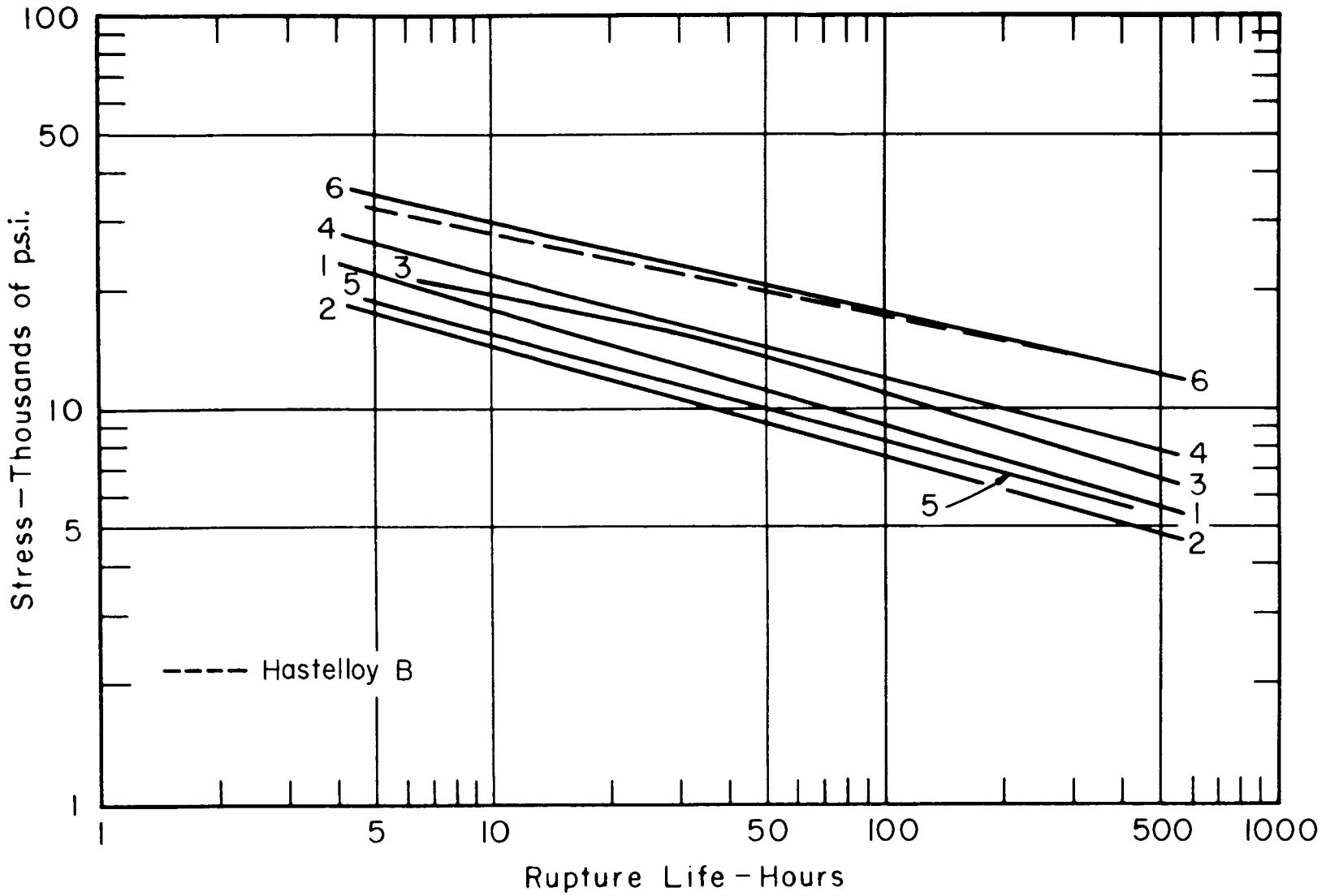

FIG. 8 – SUMMARY PLOT OF STRESS-RUPTURE DATA AT 1500°F

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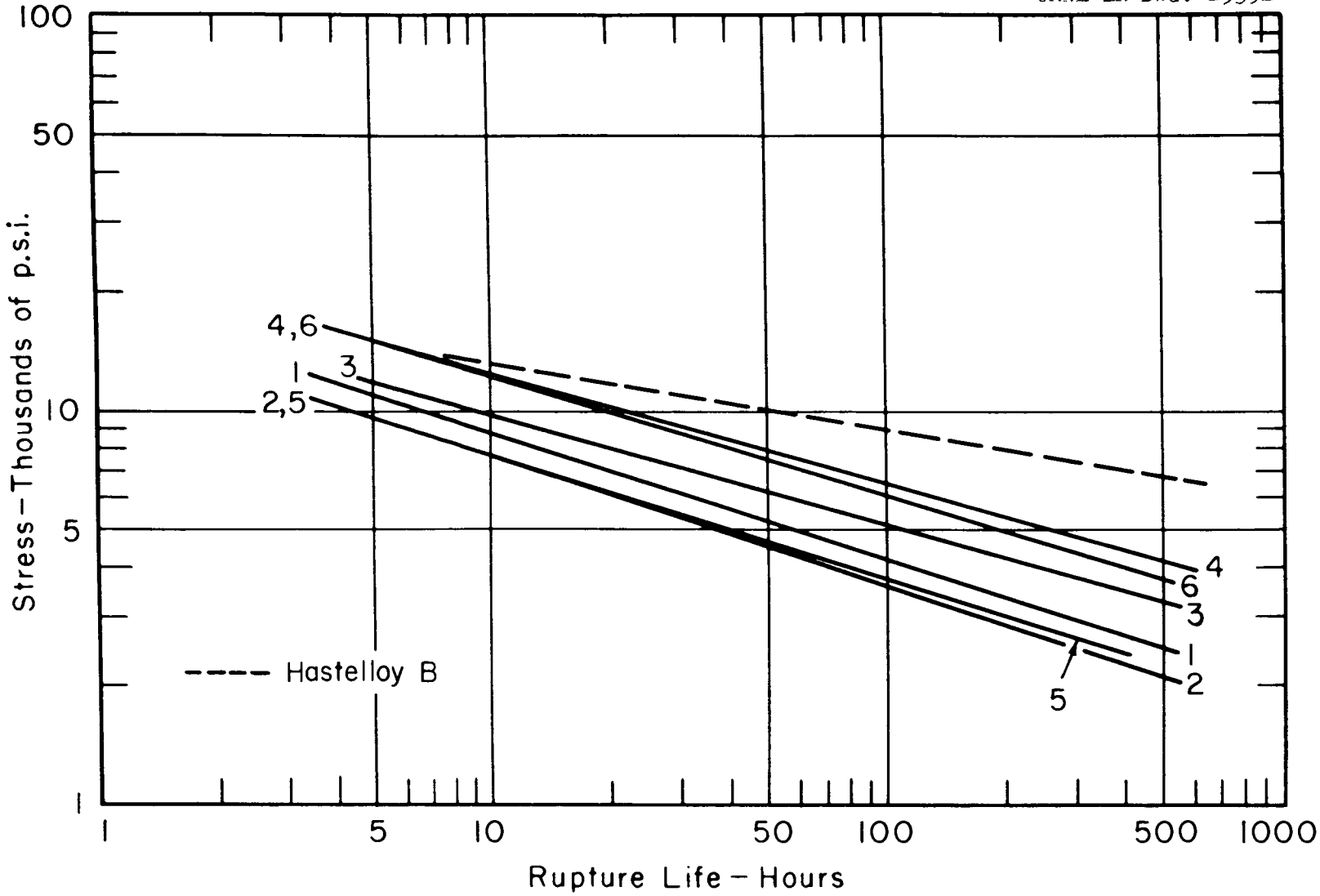

FIG. 9-SUMMARY PLOT OF STRESS-RUPTURE DATA AT 1650°F

The stress for 1000-hr rupture life was obtained by extrapolation of these plots, and these values are listed in Table IX. Values of elongation for 100-hr rupture life, shown in Table X, were obtained by interpolation.

Room-temperature tensile tests were conducted in duplicate for each alloy in the conditions of heat treatment indicated above. In addition, duplicate tests were made on test specimens of each alloy and each heat treatment after an embrittlement treatment consisting of heating without load for 100 hr at 1500°F and air-cooling. Data on tensile strength, yield strength (0.2% offset), elongation, and reduction of area are given in Tables XI and XII.

In order to observe the structural changes occurring during heat treatment and testing, metallographic specimens were prepared from each alloy in each of the above heat treatments and from stress-rupture bars which had approximately 100-hr rupture life for each of the three test temperatures.

DISCUSSION OF RESULTS

Room-Temperature Tensile Data

The tensile properties of alloys INOR-1 and INOR-2 are comparable to those of commercial Hastelloy B, even though the latter has considerably higher molybdenum content. The addition of 5% Cr (INOR-2) brings the tensile properties of the 16% Mo alloy up to those of the 20% Mo composition. Neither of these alloys showed response to aging for 16 hr at 1500°F.

Alloy INOR-3, containing 1% Al and 1.6% Ti, gave no increase in yield or tensile strength after the 1500°F aging treatment, presumably due to overaging at this temperature. However, aging at 1300°F resulted in moderate increases in yield and tensile strength with only a slight decrease in ductility. With a higher aluminum content (INOR-4 containing 2% Al and 1.7% Ti), there was a marked increase in yield and tensile strength after each of the aging treatments. Elongation and reduction of area values were still comparable to those for Hastelloy B.

The addition of 0.1% C, 2.7% W, and 2.2% Cb at the 13% Mo level (INOR-5) resulted in no significant increase in strength for either of the aging treatments while showing somewhat lower ductility values.

TABLE IX

SUMMARY OF EXTRAPOLATED VALUES OF STRESS FOR 1000-HR RUPTURE LIFE

Alloy	1350°F	1500°F	1650°F
(a) One hour at 2000°F, air-cooled			
INOR-1	12,000	4,000	2,000
INOR-2	7,700	3,600	1,700
(b) One hour at 2000°F, air-cooled; 16 hr at 1500°F, air-cooled			
INOR-1	14,000	5,300	2,000
INOR-2	8,600	4,100	1,700
INOR-3	14,000	5,200	2,700
INOR-4	16,600	6,500	3,400
INOR-5	14,200	4,500	1,600
INOR-6	18,500	11,400	2,600
(c) One hour at 2000°F, air-cooled; 16 hr at 1300°F, air-cooled			
INOR-3	13,000	5,600	2,700
INOR-4	14,800	6,500	3,400
INOR-5	14,200	4,100	1,800
INOR-6	22,500	9,500	3,300
(d) Hastelloy B	21,000	11,000	6,000

TABLE X

SUMMARY OF INTERPOLATED VALUES OF ELONGATION AT 100-HR RUPTURE LIFE

Alloy	1350°F	1500°F	1650°F
(a) One hour at 2000°F, air-cooled			
INOR-1	18%	13%	17%
INOR-2	6%	14%	20%
(b) One hour at 2000°F, air-cooled; 16 hr at 1500°F, air-cooled			
INOR-1	18%	19%	19%
INOR-2	11%	12%	20%
INOR-3	5%	19%	9%
INOR-4	1%	5%	11%
INOR-5	22%	26%	32%
INOR-6	5%	8%	20%
(c) One hour at 2000°F, air-cooled; 16 hr at 1300°F, air-cooled			
INOR-3	5%	15%	21%
INOR-4	2%	6%	8%
INOR-5	16%	28%	32%
INOR-6	7%	11%	24%
(d) Hastelloy B	20%	39%	24%

TABLE XI

ROOM-TEMPERATURE TENSILE DATA FOR ALLOYS IN THIS INVESTIGATION

Alloy	Tensile Strength, psi	Yield 0.2% Offset	Elongation %	Reduction of Area, %
(a) One hour at 2000°F, air-coooled				
INOR-1	131,700	57,800	55	67
	131,200	78,600	50	66
INOR-2	130,000	57,200	50	61
	133,500	62,200	50	57
(b) One hour at 2000°F, air-cooled; 16 hr at 1500°F, air-cooled				
INOR-1	129,200	56,700	54	64
	132,700	58,300	55	64
INOR-2	129,600	54,000	50	60
	130,900	57,200	50	60
INOR-3	127,200	57,800	65	61
	125,700	56,500	67	63
INOR-4	168,400	114,200	44	60
	168,300	109,800	42	59
INOR-5	134,000	61,600	43	48
	134,600	62,500	43	44
INOR-6	158,700	97,900	45	51
	163,500	102,400	45	53
(c) One hour at 2000°F, air-cooled; 16 hr at 1300°F, air-cooled				
INOR-3	140,800	70,400	59	63
	140,000	69,800	55	65
INOR-4	168,200	113,200	41	56
	166,000	113,500	42	55
INOR-5	135,600	66,400	43	48
	134,800	62,500	45	48
INOR-6	161,300	97,800	46	60
	166,700	105,600	43	57

TABLE XII

ROOM-TEMPERATURE TENSILE DATA AFTER EMBRITTLEMENT TREATMENT OF 100 HR AT 1500°F

Alloy	Tensile Strength, psi	Yield 0.2% Offset	Elongation %	Reduction of Area, %
(a) One hour at 2000°F, air-cooled				
INOR-1	128,200	57,600	57	66
	128,200	58,200	58	67
INOR-2	130,700	55,200	53	61
	131,800	55,900	54	59
(b) One hour at 2000°F, air-cooled; 16 hr at 1500°F, air-cooled				
INOR-1	125,500	56,400	59	68
	125,600	54,800	58	66
INOR-2	130,300	56,700	51	60
	130,400	56,700	52	64
INOR-3	121,200	47,800	71	67
	120,400	47,200	68	66
INOR-4	164,200	102,400	42	59
	164,200	100,500	43	60
INOR-5	133,700	61,600	45	51
	132,000	59,700	45	51
INOR-6	155,200	91,600	38	40
	154,700	89,300	39	38
(c) One hour at 2000°F, air-cooled, 16 hr at 1300°F, air-cooled				
INOR-3	124,200	52,200	69	69
	124,300	70,500	74	69
INOR-4	165,500	102,800	45	60
	166,500	104,300	41	60
INOR-5	133,000	61,500	47	49
	131,600	57,700	48	48
INOR-6	157,000	92,200	39	37
	157,000	92,300	39	38

Alloy INOR-6 containing 5% Cr with 1.2% Al and 1.7% Ti (i.e, alloy INOR-3 with 5% Cr added) showed significant response to aging both at 1300 and at 1500°F. The possible stabilization of the aging reaction at 1500°F by the addition of 5% Cr is also indicated by the stress-rupture data to be discussed later.

Embrittlement of Treatment

None of the alloys in this investigation showed the severe embrittlement previously observed in the simple nickel-molybdenum alloys after a treatment for 100 hr at 1500°F and air-cooled.

Alloys INOR-1 and INOR-2, without aging additions, showed no change in room-temperature tensile properties after the embrittlement treatment. Alloy INOR-3, which showed overaging after 16 hr at 1500°F, showed the expected decrease in yield and tensile strength after the embrittlement treatment at 1500°F, accompanied by an increase in ductility. With the higher aluminum content, alloy INOR-4, there was only a slight decrease in strength after the embrittlement treatment, indicating a relatively stable aging reaction. The 5% Cr addition in alloy INOR-6 had a similar stabilizing effect on the aging reaction. Alloy INOR-5, containing carbon, tungsten, and columbium, showed no significant change in room-temperature tensile properties after the 100-hr treatment as would be expected from its lack of response to the aging treatments.

Stress-Rupture Tests

Alloys INOR-1, INOR-2, and INOR-5, which showed no effective aging in room-temperature-test results, gave the lowest stress-rupture values over the entire range of testing temperatures and times. Test results for alloy INOR-2 indicate that chromium does not effectively replace molybdenum in these alloys for stress-rupture strength, particularly at the lower temperatures.

Alloy INOR-3, with the lower content of aging constituents, showed a slight improvement in rupture strength at each of the three test temperatures, with instabilities apparent at 1350 and 1500°F. There was substantially no differences in response to the two aging treatments.

The addition of 5% Cr in alloy INOR-6 resulted in a marked increase in rupture strength over that of alloy INOR-3 over the entire temperature range with some evidence of an instability only in the 1350°F tests. This resulted in an alloy showing stress-rupture properties superior to those of Hastelloy B at 1350°F. This superiorty was lost at 1500°F while at 1650°F the results were considerably below those of Hastelloy B.

Alloy INOR-4 with the higher aluminum content showed somewhat lower rupture values than INOR-6 at 1350 and 1500°F but retained a slightly higher strength at 1650°F particularly at the longer times.

Metallography

Figures 10 to 21 show the microstructure of these alloys after solution treatment and after stress-rupture failure, showing one view each for each different treatment represented by the specimen which failed in about 100 hr at each test temperature.

Figure 10 shows a relatively fine-grained structure with a small amount of second phase but free of any aging precipitation. Fractures were intercrystalline.

Figure 11, also of INOR-1, shows that there was a small amount of banding which was, however, slight.

Figures 12 and 13 are of INOR-2. Apparently, the substitution of chromium for molybdenum results in an increase in the quantity of second phase (presumably beta). The beta is in bands. The grain size is somewhat coarser than in INOR-1. Fractures were intercrystalline. No aging was evident.

Figures 14 and 15 are of INOR-3. The grain size is significantly coarser than in alloys 1 or 2. Both grain boundary and general precipitation are noted. At 1650°F overaging is complete and is evident at 1500°F. A strongly banded structure is evident. Fractures were intercrystalline.

Figures 16 and 17 are of INOR-4. A duplex grain size is clearly evident. Aging is much more general and overaging does not appear to take place at 1500°F too rapidly. Fractures are intercrystalline.

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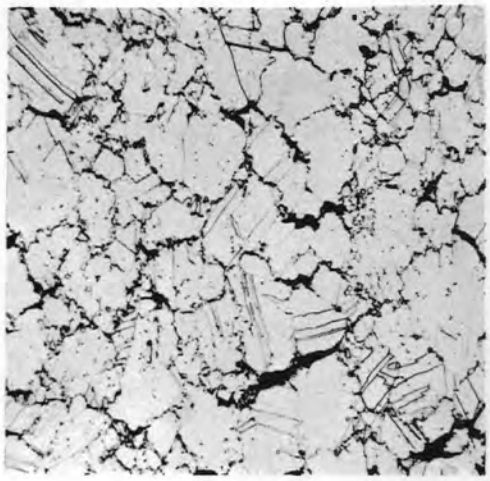
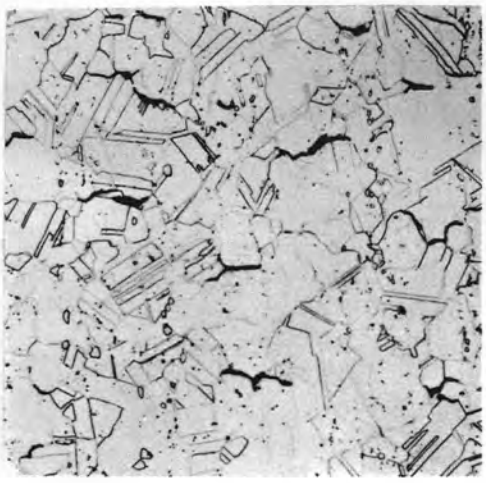
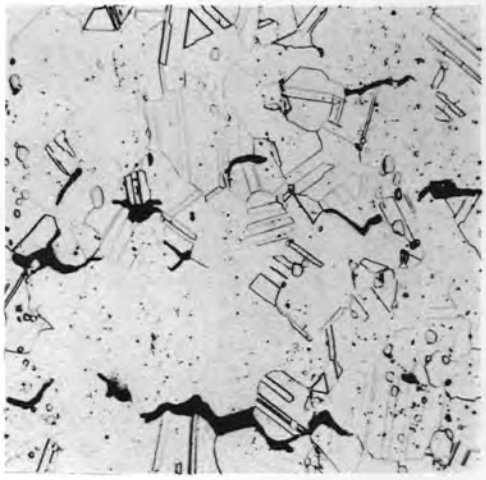
One hour at 2000°F, air-cooled.
As heat-treated.



25,000 psi at 1350°F.
Rupture life 85.2 hr.



7,500 psi at 1500°F.
Rupture life 124.9 hr.



4,000 psi at 1650°F.
Rupture life 99.7 hr.

Fig. 10 Photomicrographs of Alloy INOR-1 in the Solution-Treated Condition and After Stress-Rupture Testing as Indicated. Etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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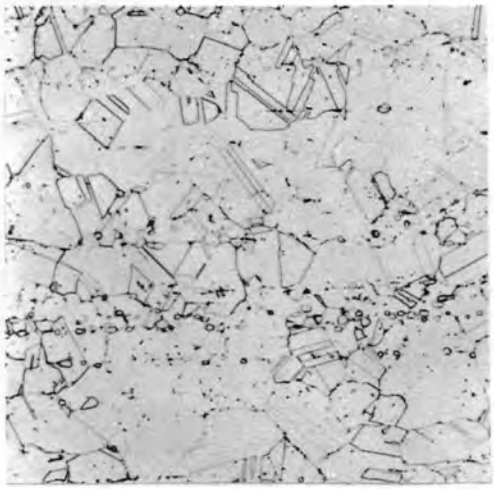
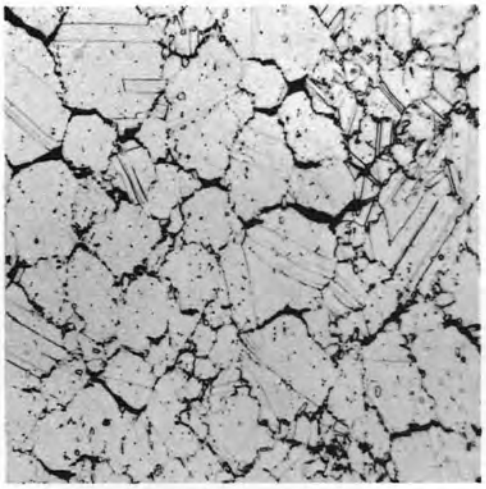
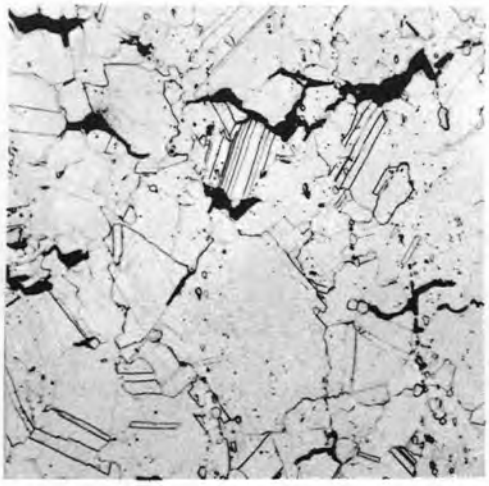


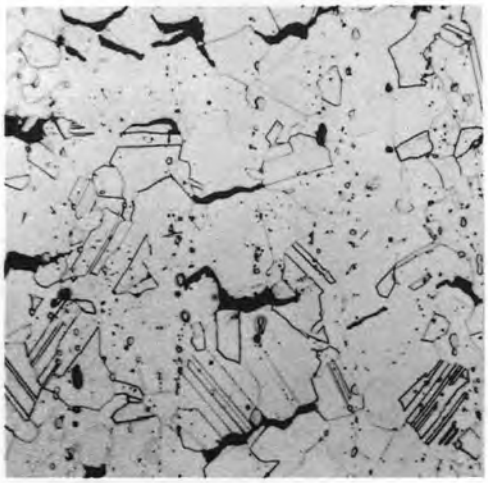
One hour at 2000°F, air-cooled.
Aged 16 hr at 1500°F, air-cooled.



25,000 psi at 1350°F.
Rupture life 55.2 hr.



10,000 psi at 1500°F.
Rupture life 76.6 hr.



4,000 psi at 1650°F.
Rupture life 80 hr.

Fig. 11 Photomicrographs of Alloy INOR-1 in the Solution-Treated and Aged Condition, and After Stress-Rupture Testing as Indicated. Etched with 1/3 HCL, 1/3 HNO_3, 1/3 H_2O. 250X.

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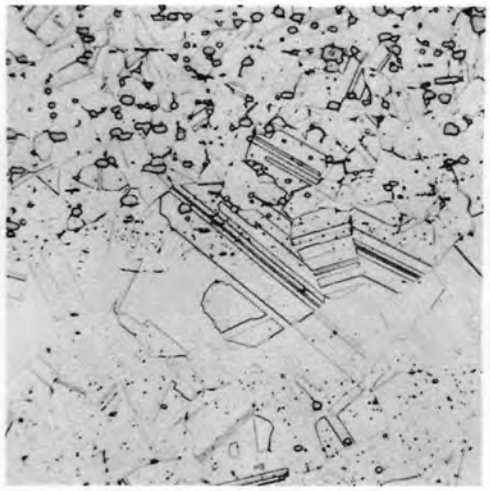
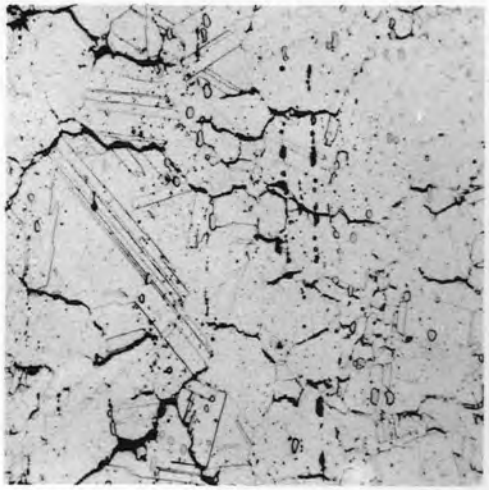
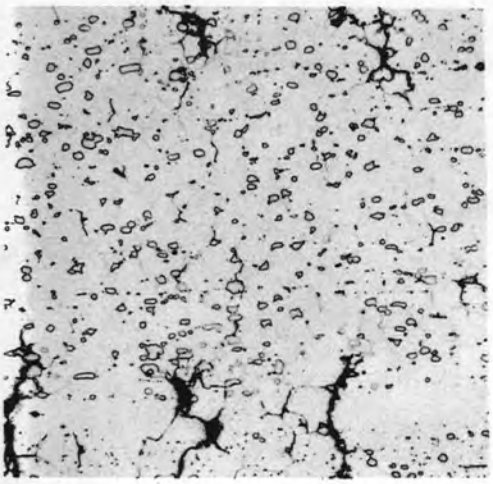


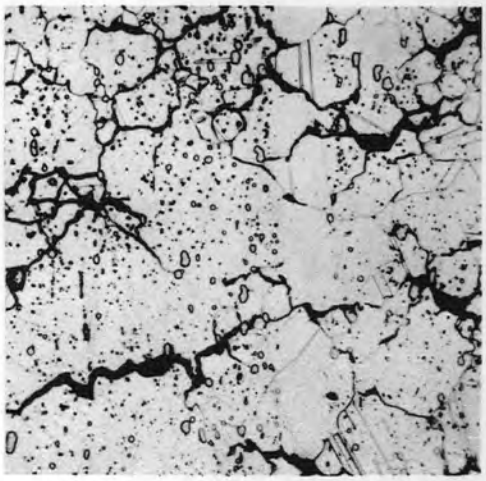
One hour at 2000°F, air-cooled.
As heat-treated.



15,000 psi at 1350°F.
Rupture life 112.7 hr.



5,550 psi at 1500°F.
Rupture life 135.2 hr.



4,000 psi at 1650°F.
Rupture life 64.2 hr.

Fig. 12 Photomicrographs of Alloy INOR-2 in the Solution-Treated Condition, and After Stress-Rupture Testing as Indicated. Etched with 1/3 HCL, 1/3 HNO_3, 1/3 H_2O. 250X.

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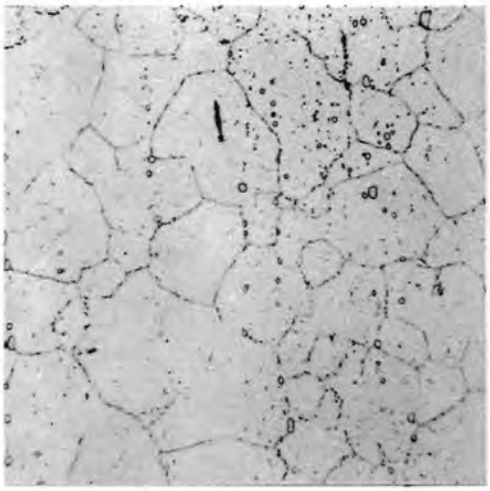
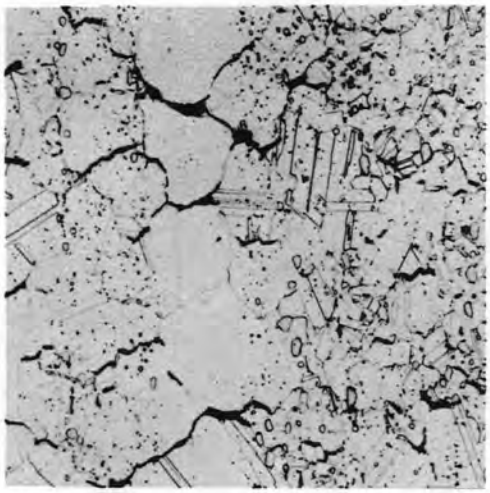
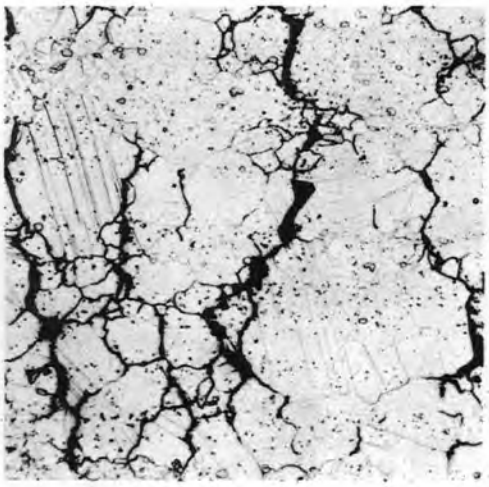


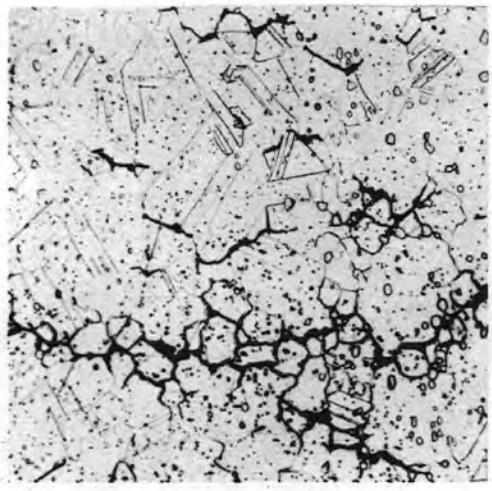
One hour at 2000°F, air-cooled.
Aged 16 hr at 1500°F, air-cooled.
As heat-treated.



15,000 psi at 1350°F.
Rupture life 187.1 hr.



10,000 psi at 1500°F.
Rupture life 35.9 hr.



4,000 psi at 1650°F.
Rupture life 64.7 hr.

Fig. 13 Photomicrographs of Alloy INOR-2 in the Solution-Treated and Aged Condition, and After Stress-Rupture Testing as Indicated. Etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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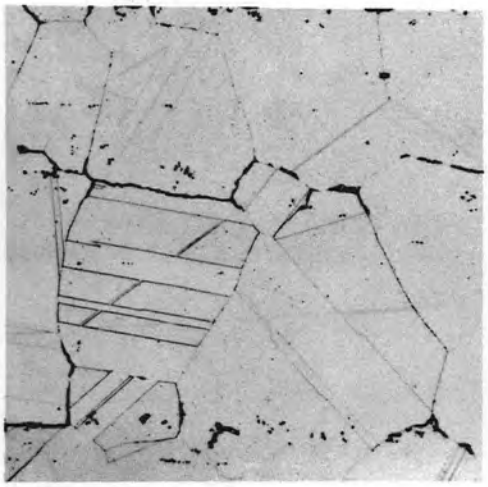
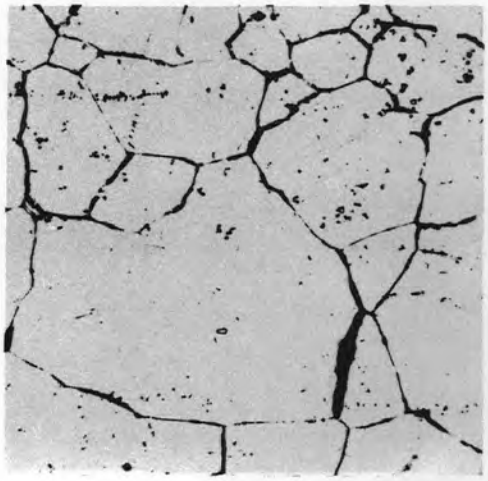
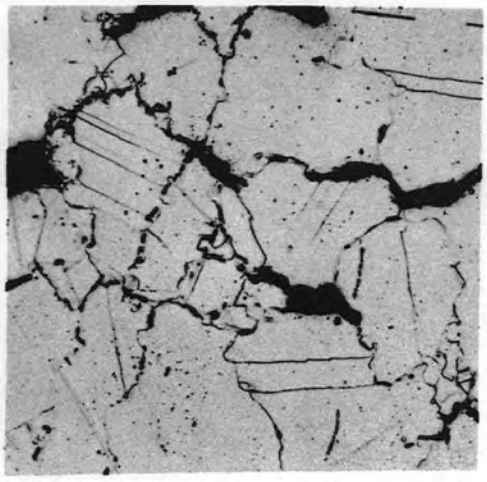


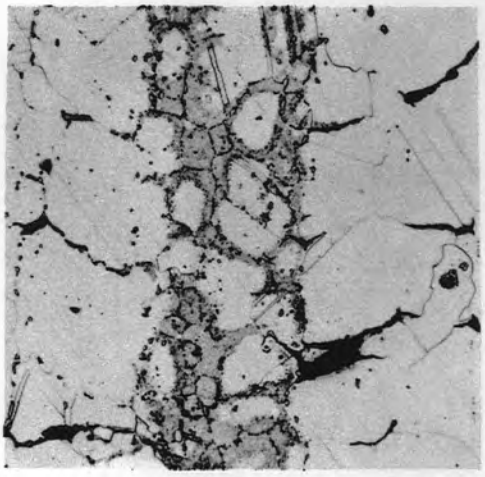
One hour at 2000°F, air-cooled.
Aged 16 hr at 1500°F, air-cooled.
As heat-treated.



30,000 psi at 1350°F.
Rupture life 80.9 hr.



10,000 psi at 1500°F.
Rupture life 92.9 hr.



5,000 psi at 1650°F.
Rupture life 97.1 hr.

Fig. 14 Photomicrographs of Alloy INOR-3 Solution-Treated and Aged at 1500°F, as Heat-Treated and After Stress-Rupture Testing as Indicated. Etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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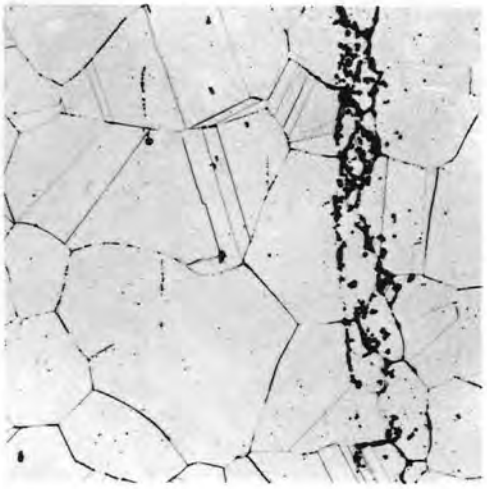
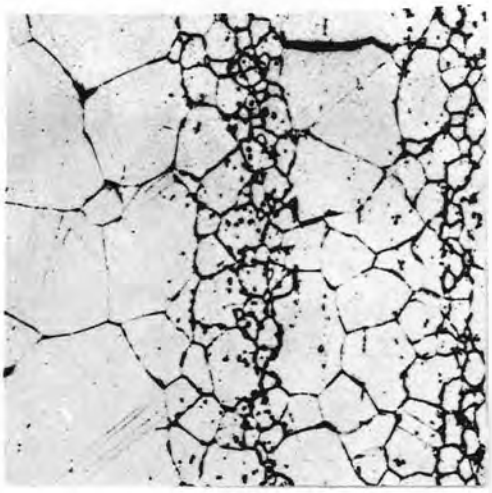
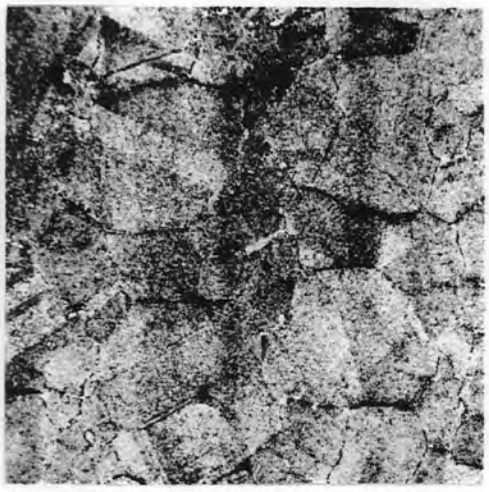


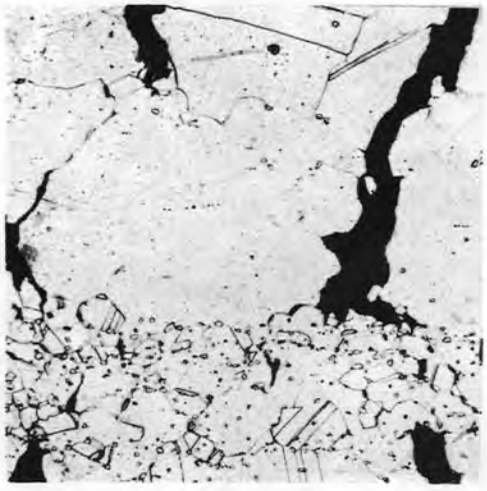
One hour at 2000°F, air-cooled.
Aged 16 hr at 1300°F, air-cooled.
As heat-treated.



30,000 psi at 1350°F.
Rupture life 69.1 hr.



10,000 psi at 1500°F.
Rupture life 172.8 hr.



5,000 psi at 1650°F.
Rupture life 116.6 hr.

Fig. 15 Photomicrographs of Alloy INOR-3 Solution-Treated and Aged at 1300°F, as Heat-Treated and After Stress-Rupture Testing as Indicated. Etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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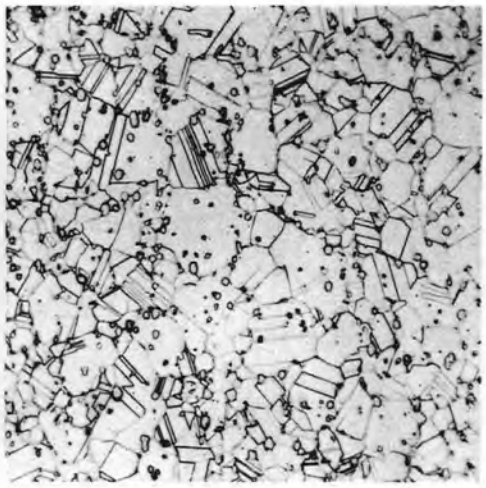
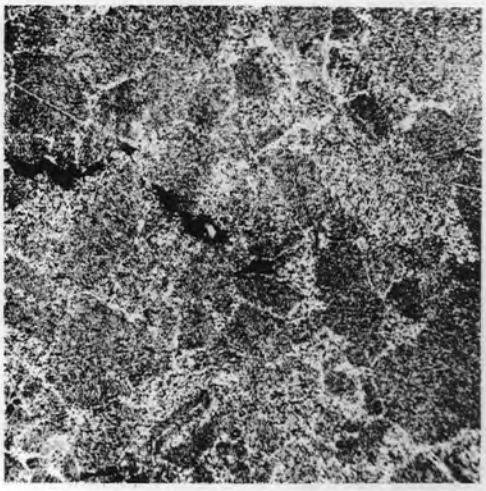
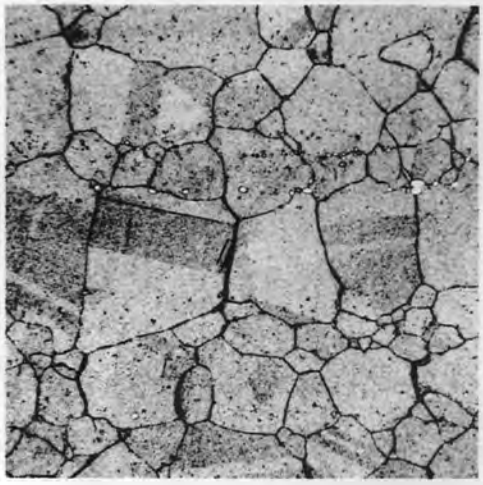


One hour at 2000°F, air-cooled.
Aged for 16 hr at 1500°F, air-cooled
As heat-treated.



30,000 psi at 1350°F.
Rupture life 50.6 hr.

10,000 psi at 1500°F.
Rupture life 130.8 hr.



6,000 psi at 1650°F.
Rupture life 113.6 hr.

Fig. 16 Photomicrographs of Alloy INOR-4 Solution-Treated and Aged at 1500°F, as Heat-Treated and After Stress-Rupture Testing as Indicated. Etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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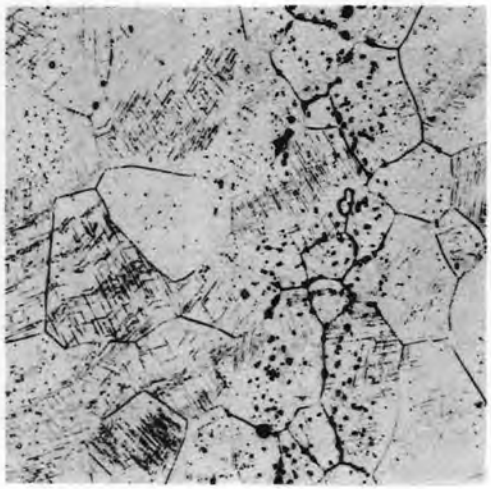
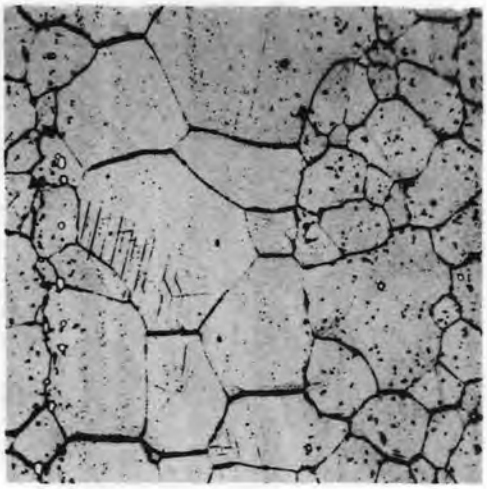
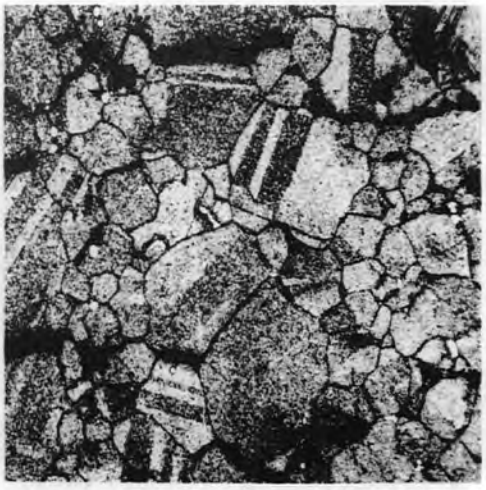


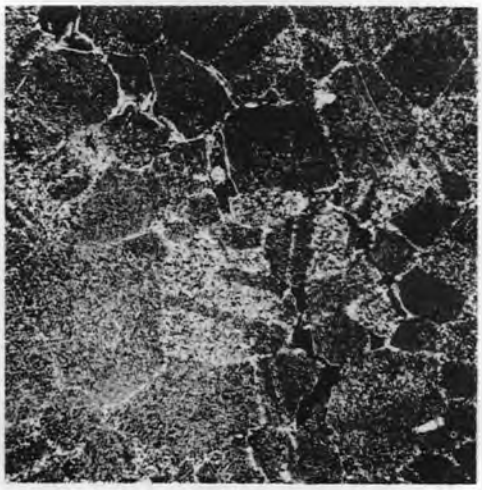
One hour at 2000°F, air-cooled.
Aged 16 hr at 1300°F, air-cooled.
As heat-treated.



40,000 psi at 1350°F.
Rupture life 30.9 hr.



10,000 psi at 1500°F.
Rupture life 142 hr.



5,000 psi at 1650°F.
Rupture life 127.6 hr.

Fig. 17 Photomicrographs of Alloy INOR-4 Solution-Treated and Aged at 1300°F, as Heat-Treated and After Stress-Rupture Testing as Indicated. Etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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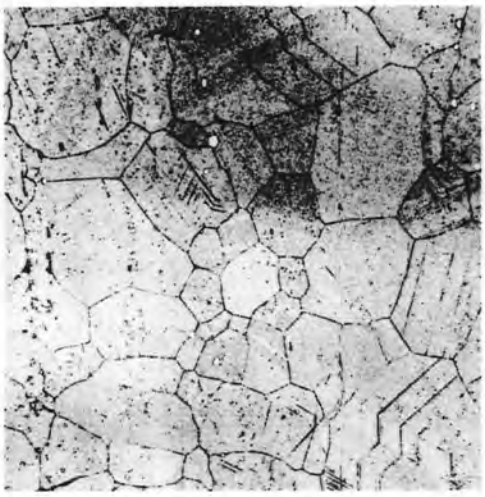
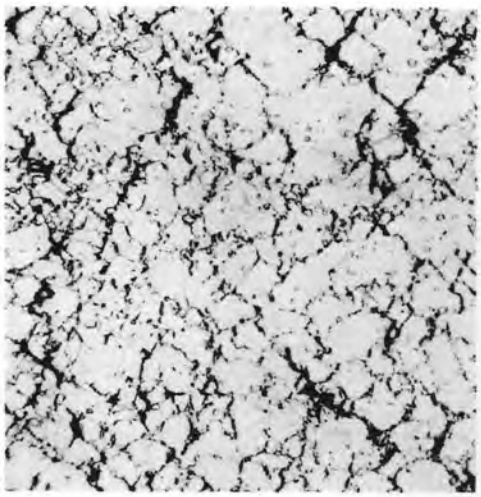
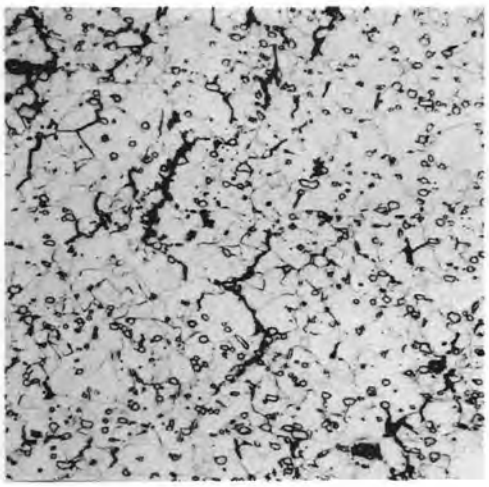
PHOTO 43507



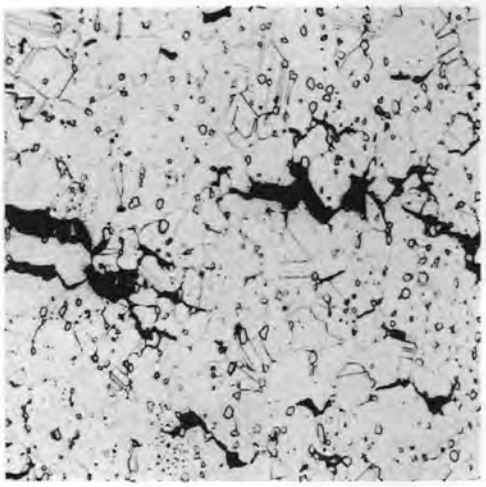
One hour at 2000°F, air-cooled.
Aged 16 hr at 1500°F, air-cooled.
As heat-treated.



20,000 psi at 1350°F.
Rupture life 183 hr.



10,000 psi at 1500°F.
Rupture life 49.4 hr.



4,000 psi at 1650°F.
Rupture life 86.1 hr.

Fig. 18 Photomicrographs of Alloy INOR-5 Solution-Treated and Aged at 1500°F, as Heat-Treated and After Stress-Rupture Testing as Indicated. Etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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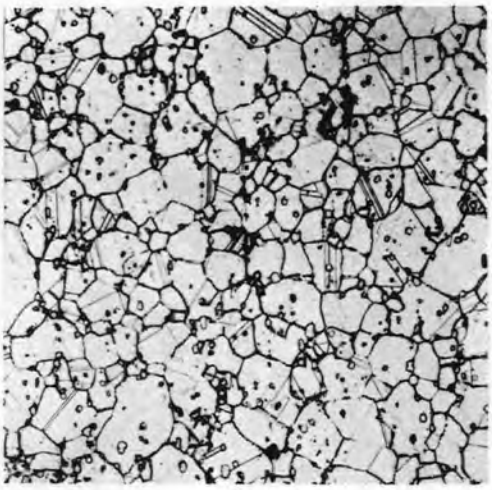
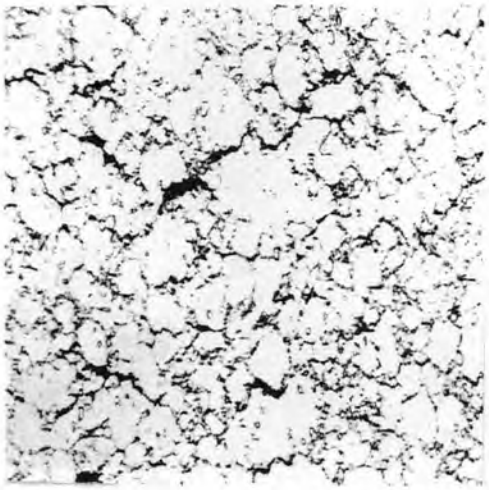
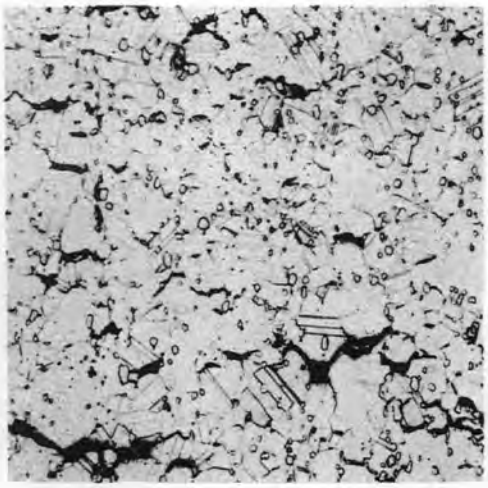
PHOTO 43508



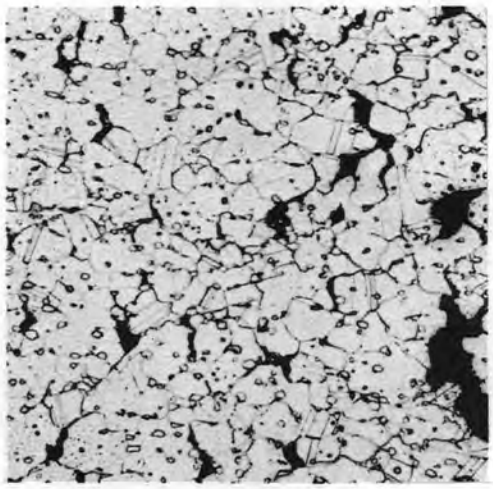
One hour at 2000°F, air-cooled.
Aged 16 hr at 1300°F, air-cooled.
As heat-treated.



25,000 psi at 1350°F.
Rupture life 44.3 hr.



7,000 psi at 1500°F.
Rupture life 157.4 hr.



4,000 psi at 1650°F.
Rupture life 66.2 hr.

Fig. 19 Photomicrographs of Alloy INOR-5 Solution-Treated and Aged at 1300°F, as Heat-Treated and After Stress-Rupture Testing as Indicated. Etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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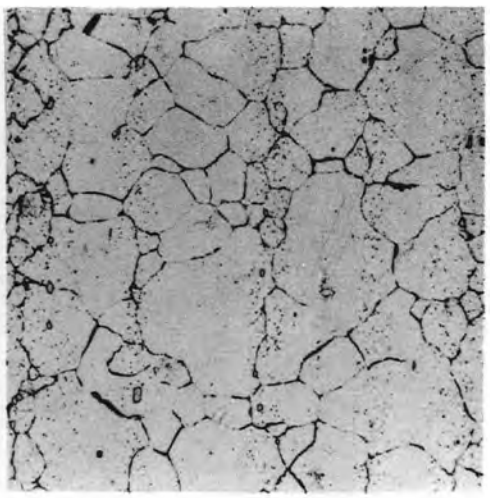
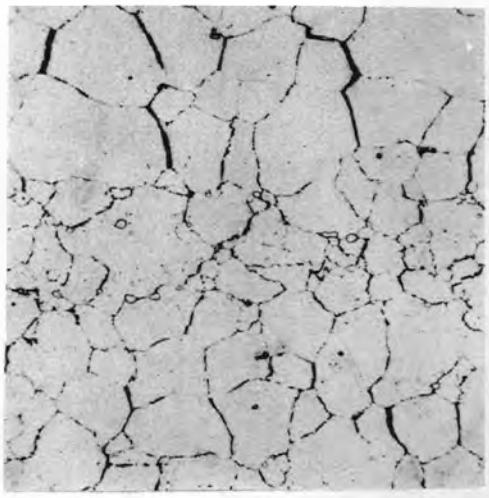
PHOTO 43509

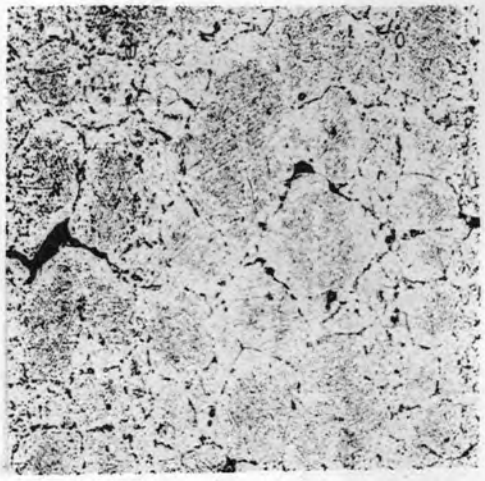


One hour at 2000°F, air-cooled.
Aged 16 hr at 1500°F, air-cooled.
As heat-treated.



45,000 psi at 1350°F.
Rupture life 71.1 hr.

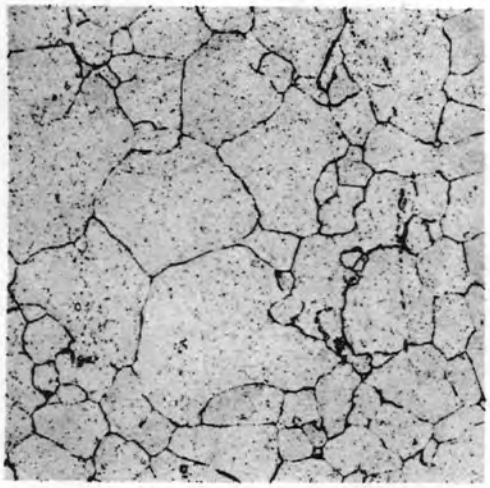
16,500 psi at 1500°F.
Rupture life 171.6 hr.



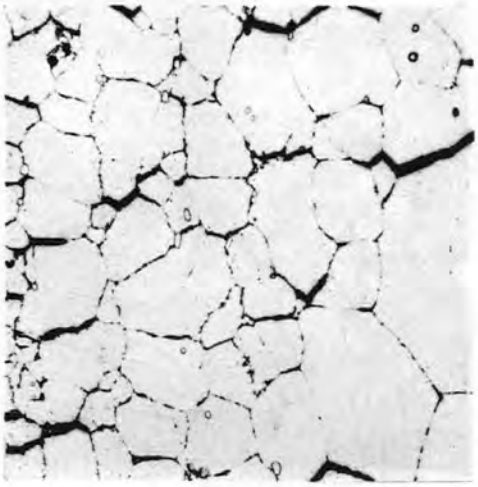
6,500 psi at 1650°F.
Rupture life 72.1 hr.

Fig. 20 Photomicrographs of Alloy INOR-6 Solution-Treated and Aged at 1500°F, as Heat-Treated and After Stress-Rupture Testing as Indicated. Etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

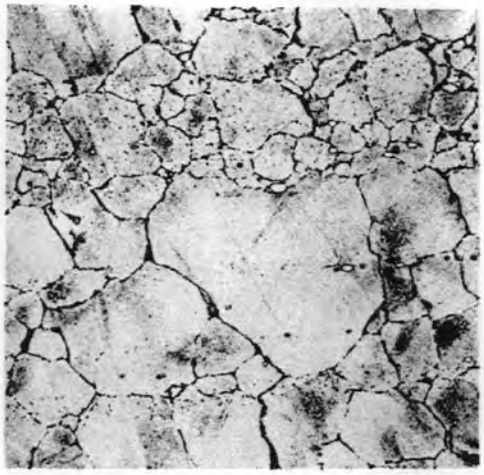
UNCLASSIFIED
PHOTO 43510



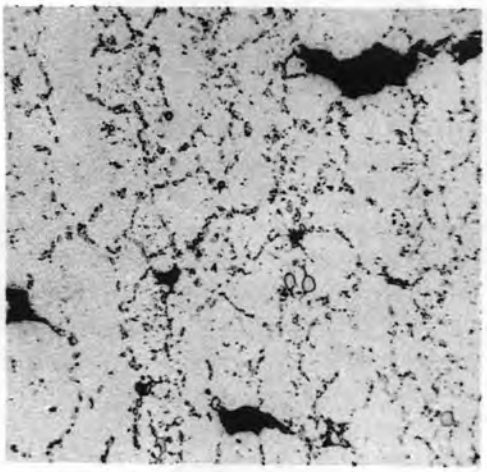
One hour at 2000°F, air-cooled.
Aged 16 hr at 1300°F, air-cooled.
As heat-treated.



35,000 psi at 1350°F.
Rupture life 73.6 hr.



16,500 psi at 1500°F.
Rupture life 88.8 hr.



5,000 psi at 1650°F.
Rupture life 150.2 hr.

Fig. 21 Photomicrographs of Alloy INOR-6 Solution-Treated and Aged at 1300°F, as Heat-Treated and After Stress-Rupture Testing as Indicated. Etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

Figures 18 and 19 are of INOR-5. This alloy is relatively fine-grained. Carbides are well distributed throughout the structure. No aging is evident. Fractures are all intercrystalline.

Figures 20 and 21 are of INOR-6. A duplex grain structure is evident. The aging reaction is more definite than in INOR-3, possibly due to the chromium addition. Overaging and coalesence are evident at 1650°F in Figs. 20 and 21. Fractures were intercrystalline.

From the strength values at high temperatures and the microstructures, it is quite clear that the benefits of aging due to titanium plus aluminum are not as great in the nickel-molybdenum alloys as in the nickel-chromium alloys such as the Nimonics, Inconel X-550, etc.

CONCLUSIONS

1. The addition of minor alloy elements is effective in eliminating the embrittlement in the vacuum-melted simple nickel-molybdenum alloys previously reported.

2. In the absence of aging additions, the addition of 5% Cr brings the room-temperature strength of the 16% Mo alloy up to that of the 20% Mo material. Chromium, however, does not effectively replace molybdenum with respect to rupture strength.

3. Addition of 1% Al and 1.6% Ti results in effective aging at 1300°F, but the alloy overages at 1500°F. The aging has only slight effect on stress-rupture properties in the range 1350 to 1650°F.

4. Increasing the aluminum content to 2% with 1.6% Ti results in a significant increase in the stability of the aging reaction with respect to both room-temperature and rupture properties, particularly at 1650°F.

5. At the lower aluminum content, the addition of 5% Cr results in a marked increase in the response and stability of the aging reaction with respect to both room-temperature properties and to stress-rupture properties in the range of 1350 to 1650°F. This is not as effective as the increased aluminum content at 1650°F.

6. No aging response was observed on addition of 0.1% C, 2.7% W, and 2.2% Cb.

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