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FINAL REPORT ON DEVELOPMENT AND TESTING OF NICKEL - MOLYBDENUM ALLOYS

F. C. Monkman, Jr.
N. J. Grant
C. F. Floe

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New England Materials Laboratory, Inc.

FINAL REPORT ON DEVELOPMENT AND TESTING OF NICKEL - MOLYBDENUM ALLOYS

F. C. Monkman, Jr.
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INTRODUCTION

The purpose of this investigation was to determine the effect of vacuum melting and variations in composition on the ductility, mechanical and stress-rupture properties of nickel-molybdenum alloys. Nickel base compositions alloyed primarily with molybdenum are mainly used for their high resistance to chemical corrosion. However, such alloys also have good high temperature properties which are intermediate between the iron and the cobalt-base alloys. Nickel-molybdenum alloys are, therefore, of considerable importance in certain applications when oxidation resistance is not a prime consideration.

PROCEDURE AND RESULTS

Five vacuum-melted and cast alloys were obtained from Utica Drop Forge Company as one inch diameter rods (Alloys 1 through 5). In addition, a length of 3/8 inch diameter commercial Hastalloy B was obtained from the Haynes-Stellite Company for comparison purposes (Alloy 6). The compositions of these alloys are listed in Table I.

The vacuum melted alloys were further forged to 3/8 inch round rod. It was found necessary to forge the thirty and the thirty-six per cent molybdenum alloys at 2250°F to prevent cracking. The other three alloys were forged at a maximum temperature of 2100°F. After forging, all of the alloys were solution treated at 2000°F for one half hour and air cooled. In addition to this condition, two heat treatments were investigated; (a) one half hour at 1850°F, air cooled; (b) one half hour at 1850°F, oil quenched, followed by sixteen hours aging at 1500°F.

Stress rupture tests were conducted on the six alloys in the three different conditions at 1350°, 1500°, and 1650°F. Stresses were chosen to give rupture lives from one to five hundred hours. The values of stress, rupture life, elongation, and reduction in area were measured for each test and are listed in Tables III through IX. Plots of log stress versus log rupture life are presented in Figures 1 through 6, and are summarized at each of the testing temperatures in Figures 7, 8, and 9. A best straight line was drawn through the rupture life values and a dotted line was drawn through the values of the heat treated specimens where they differed significantly from the values of the solution treated specimens.

The stress for 1000 hour rupture life, obtained by extrapolation, for each alloy in the solution treated condition, is listed in Table II, and presented graphically in Figure 17. The ductility of the 100 hour rupture life is also given in this last figure.

Tensile tests were conducted at room temperature in duplicate, and the tensile strengths, yield strengths (0.2 per cent offset), final elongations and reductions in area are tabulated in Table IX. Moduli were also measured, however, the variation found was within experimental error. Tensile tests were also conducted at room temperature on the alloys after they had been exposed 100 hours at 1500°F, and these values are listed in Table X. Hardness measurements were also made on each alloy, since generally hardness and tensile strength are approximately proportional to one another. The hardness values are listed in Table IX, and are presented in Figure 18.

Metallographic samples were prepared from each of the alloys in the three different heat treated conditions, and from stress-rupture specimens having a rupture life of about 100 hours at each test temperature. These are presented in Figures 11 through 16. From these photomicrographs, it was possible to determine the initial microstructure and to follow structural changes which took place during testing. For the purpose of discussing and understanding the structural changes which took place in these alloys, the nickel-molybdenum phase diagram by R. M. Parke, published in the Metals Handbook, is reproduced in Figure 10.

DISCUSSION

17.3% Mo Alloy

From Figure 1, it is seen that the stress-rupture properties of this alloy were decreased when it was heat treated at 1850°F after a solution treatment at 2000°F. (Compare the solid curve for the solution treated values with the dotted curve for the heat treated values.) The photomicrographs (Figure 11) indicate that this double heat treatment resulted in grain growth, including abnormal grain growth. This phenomena has been found to occur in other nickel base alloys[1] which have been solution treated and reheated to a high temperature, which in some cases was as low as 1500°F. The strains incurred in cooling from 2000°F appear to have been sufficient to cause abnormal grain growth when this alloy was reheated to 1850°F. The grain boundary thickening observed in these photomicrographs is due to the etching characteristics of the solution used.

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(1) J. Freeman, University of Michigan, Progress Report to NACA, 1954.

The tensile strength was found to decrease about fifty per cent with either the 16 or the 100 hour aging treatment at 1500°F. In addition, there was a decrease in ductility but without any significant variation in hardness (Table IX and X and Figure 18).

Metallographic examination showed that these specimens failed by intercrystalline fracture. The precipitation of a second phase can be ruled out inasmuch as neither the phase diagram (Figure 10) nor the photomicrographs of this alloy (Figure 11) indicate any precipitation. The tensile specimens were machined after the 16 hour aging treatment at 1500°F, therefore the embrittlement cannot be attributed to surface effects such as notches or oxidation. The specimens aged 100 hours at 1500°F were aged after machining, however, metallographic examination showed no oxide penetration at the grain boundaries or evidence of excessive surface oxidation.

21.0% Mo Alloy

Heat treating to 1850°F after the solution treatment had little or no effect on the stress rupture properties of this alloy (Figure 2). The photomicrographs (Figure 12) showed some grain growth and also that beta had precipitated at the grain boundaries at 1350°F. This is not in accordance with the phase diagram for this composition and temperature, however, since the rupture specimens were not quenched from the testing temperature, the beta may have precipitated out during cooling. Also, when the rupture specimen fails, the furnace automatically drops about 100°F, so beta may have been formed at this lower temperature.

Again the tensile strength and ductility of this alloy were severely reduced by aging at 1500°F; but again there was only a slight increase in hardness (Table IX and X). The fractures were intercrystalline and there was no metallographic evidence of precipitation or oxide penetration.

25.6% Mo Alloy

In the case of this alloy, heat treating to 1850°F had a detrimental effect on the stress rupture properties at 1350° and 1500°F, and no effect at 1650°F (Figure 3). The photomicrographs (Figure 13) show that the heat treatment had little effect on the initial microstructure. Precipitation of the beta phase occurred at the lower two temperatures, while at 1650°F the alloy consisted of a single solid solution (alpha). The exact relationship between the decrease in properties and the change in microstructure is not clearly understood, but a difference in the amount, distribution, or size of the beta precipitate may have affected the stress rupture properties significantly at 1350° and 1500°F.

Again, the tensile strength and ductility were reduced by aging at 1500°F, even though the hardness increased (Table IX and X, Figure 18). The latter appeared to be due to the precipitation of beta, while the cause of the embrittlement could not be determined from metallographic studies.

29.8% Mo Alloy

The stress rupture properties of this alloy were improved by heat treating to 1850°F (Figure 4). As in the case of the 25.6% Mo alloy, this is probably related to the subsequent precipitation, however, the photomicrographs (Figure 14) did not show any significant differences between the solution treated structure and the heat treated structures. From the nature of the precipitates, it appeared that gamma and beta were formed from alpha at all three testing temperatures in varying amounts. It is interesting to observe the banded nature of the precipitate. This was not caused by chemical segregation in the alloys, but most likely it was caused by the stress on the specimen during testing. As was mentioned previously, these are not necessarily the equilibrium phases at the testing temperatures since the rupture specimens were not quenched. Furthermore, equilibrium may not have been reached in the system during testing.

Aging at 1500°F embrittled this alloy to such an extent that the tensile tests failed in the threads where there are stress concentrations. The hardness increased from R_A 60 to 69, probably from the formation of gamma and beta at 1500°F (Figures 10 and 14).

36.0% Mo Alloy

Heat treating to 1850°F also increased the stress rupture properties of this alloy. Again it is thought that this is related to the precipitation of the various phases during testing. The photomicrographs of this alloy (Figure 15) show that the 1850°F treatment caused an agglomeration of the delta phase (Figure 10) and the 1850°F treatment followed by 16 hours aging at 1500°F resulted in the formation of gamma plus delta. This, then, is apparently beneficial to the high temperature strength. It is interesting to note that the longest rupture test at 1350°F is significantly stronger than predicted by the extrapolation of the curve. This strengthening is probably associated with the transformation of alpha to gamma during testing.

The embrittlement of the tensile specimens again occurred after aging at 1500°F, causing the aged specimens of this alloy to fail in the threads. In addition, the hardness increased from 60 R_A to 69, probably due to the precipitation of gamma and delta from the alpha phase (Figure 10).

Hastalloy B

Heat treating at 1850°F was found to have little or no effect on the stress rupture properties of this alloy (Figure 6). Gamma appears to have precipitated out of the alpha solid solution at 1350°, while at 1500° and 1650°F the structure appears to remain alpha plus delta (Figure 16).

The tensile strength was found to be insensitive to the 1850°F heat treatment and the aging treatments at 1500°F (Table IX). No embrittlement was found to occur in this alloy after aging at 1500°F, even though it was observed in the five vacuum melted alloys.

COMPARISON OF THE ALLOYS

The log stress - log rupture life curves for each of the alloys are summarized in Figures 7, 8, and 9 for 1350°, 1500°, and 1650°F, respectively. A clearer picture of the effect of composition is obtained by considering the strength values at 1000 hours as a function of composition. The strength values were obtained by extrapolating the log stress - log rupture life curves as a straight line, and are summarized in Table II, and presented in Figure 17. In this figure it can be seen that at 1650°F there is only a slight increase in strength over the whole composition range. This can be related to the microstructures at this temperature. The phase diagram (Figure 10) and the photomicrographs of these alloys indicate that the alloys consisted of an alpha solid solution with the 36 per cent molybdenum alloy having a small amount of delta.

At 1500°F, Figure 17 indicates that the strength increased fairly linearly up to the 29.8 per cent molybdenum alloy and then increased sharply in the 36.0 per cent molybdenum alloy. However, the strength of the 29.8 per cent molybdenum alloy could be raised by heat treating (see Table II) so that both the 29.8 and the 36.0 per cent molybdenum alloys were stronger than the other alloys. This appears to be the case at 1350°F also, and can be related to the phase diagram and microstructures of the alloys. According to the phase diagram (Figure 10) the 29.8 and the 36.0 per cent molybdenum alloys should decompose to beta plus gamma and gamma plus delta phases, respectively, at 1350° and 1500°F. This appears to have happened or to be in the process of taking place in the microstructures of the 100 hour stress rupture specimens of these alloys (Figures 14 and 15).

The summary of the stress rupture plots at the three testing temperatures (Figures 7, 8, and 9) show that the commercial Hastalloy B alloy was much stronger than any of the vacuum melted alloys at 100 and 1000 hours. From Table I it can be seen that the Hastalloy

B alloy contained significant amounts of iron, chromium, cobalt, manganese, silicon, and vanadium, which probably accounts for the higher rupture strength values of the commercial alloy. The microstructure of this alloy was considerably different than that of the 25.6 and the 29.8 per cent molybdenum alloy which contained about the same amount of nickel and molybdenum. The minor constituents in the Hastalloy B alloy appear to have stabilized the microstructure (Figure 16) and prevented many of the phase changes which took place in the comparable vacuum melted compositions (Figures 14 and 15).

The high temperature ductility, as approximated by the elongation of the 100 hour rupture tests (Figure 17) decreases at approximately the 26 per cent molybdenum composition at 1350° and 1500°F. A similar decrease at about this composition is seen in the reduction in area values (Tables IX and X).

The photomicrographs of the 25.6 per cent molybdenum alloy show that beta was precipitated as practically a continuous phase at 1350° and 1500°F, which would account for the reduced ductility in this composition range. The ductility of the Hastalloy B alloy was comparable to or better than that of the vacuum melted alloys (Table VIII).

The tensile strength, yield strength, and hardness values of the vacuum melted alloys increased with molybdenum content as is shown in Figure 18. The room temperature ductility increased up to the 29.8 per cent molybdenum alloy and then decreased slightly in the 36.0 per cent molybdenum alloy, which contains a precipitate of delta. The tensile strength, yield strength, and hardness values of the Hastalloy B alloy were comparable to the values of the other alloys, however, the severe embrittlement observed in the vacuum melted alloys was not found in the Hastalloy B alloy for comparable treatments. The cause of this embrittlement was not determined, however, such possibilities as precipitation, oxidation, or surface effects are considered unimportant. Since the Hastalloy B alloy did not exhibit embrittlement, it would be important to investigate the effect of small additions of such alloying elements as iron, vanadium, cobalt, chromium, manganese, and silicon.

CONCLUSIONS

The following results have been obtained in this investigation:

1. Abnormal grain growth may take place in these alloys if they are reheated to a high temperature following solution treating.

2. The room temperature tensile strength, yield strength, hardness and ductility increase with increasing molybdenum content in the alpha solid solution phase. The latter two properties are diminished with the precipitation of delta.

3. Exposure at 1500°F embrittled the vacuum melted alloys; the embrittlement could not be attributed to a phase precipitation, oxidation, or surface effects.

4. Embrittlement was not observed in the Hastalloy B alloy and may be due to the additional alloying elements in this alloy (iron, cobalt, vanadium, manganese, chromium, silicon).

SUGGESTIONS FOR FURTHER INVESTIGATIONS

To complete the study of the properties of vacuum melted nickel-molybdenum alloys, it would be necessary to determine the effects of the additional alloying elements found in the Hastalloy B composition (iron, chromium, cobalt, vanadium, manganese, silicon).

It should be possible to determine from such a study the cause of the embrittlement in the vacuum melted alloys aged at 1500°F, and the effect of such alloys on the high temperature strength.

Table I

Composition of the Alloys in this Investigation

Alloy	% Mo	% Ni	% C	% S	% O	% N	Others
1	17.3	bal	0.02	0.002	0.003	<0.0005	
2	21.0	bal	0.02	0.002	0.004	<0.0005	
3	25.6	bal	0.02	0.002	0.002	<0.0005	
4	29.8	bal	0.02	0.002	0.002	<0.0005	
5	36.0	bal	0.01	0.002	0.003	<0.0005	
Hastalloy B	27.2	bal	0.03	0.005	-	-	0.68 % Cr 4.50 % Fe 0.41 % Si 0.36 % Co 0.63 % Mn 0.34 % V 0.0008 % P

Table II

Summary of Stress for 1000 Hour Rupture Life Values for the Alloys in the Solution Treated Condition (1/2 Hour 2000° F. A. C.)

% Mo	1350°F	1500°F	1650°F
17.3	4,400 psi	2,400 psi	1,000 psi
21.0	5,900	2,800	1,700
25.6	6,200	3,600	2,400
29.8	10,000 13,500*	3,700 5,500*	2,100 2,900*
36.0	9,000 16,000*	5,500 8,000*	1,400 2,600*
Hastalloy B	21,000	11,000	6,000

*By extrapolation of the rupture lives of the heat-treated specimens.

Table III

Stress Rupture Data on the 17.3% Mo Alloy

Temp., °F	Stress psi	% Red., of Area	% Elong.	Rupture Life, Hrs.
	1. 2000°F, 1/2 hr., A. C. (Code 1)			
1350	40,000	8	7	0
1350	35,000	4	6	0
1350	25,000	2	9	0.3
1350	20,000	0	3	1.1
1350	15,000	0	3	4.3
1350	12,000	0	4	16.7
1350	10,000	1	9	73.7
1350	6,740	2	8	144.8
1350	5,500	1	6	211.3
1500	20,000	2	3	0.4
1500	18,000	1	1	0.4
1500	10,000	6	17	7.5
1500	7,000	2	9	11.8
1500	7,000	1	3	7.0
1500	5,000	3	10	35.9
1500	3,500	6	16	283.8
1650	10,000	1	7	0.6
1650	7,000	2	7	*
1650	6,500	4	10	2.5
1650	5,000	2	7	8.7
1650	4,000	2	9	10.3
1650	3,000	2	8	27.3

*Obstruction by chain

	2. 2000°F, 1/2 hr., A. C., 1850°F 1/2 hr., A. C. (Code 11)			
1350	15,000	0.5	8.5	1.8
1350	12,000	0	9.0	17.4
1350	10,000	0	2.0	12.9
1350	7,000	0	7.0	55.0
1350	6,000	1.0	1.0	90.2
1500	12,000	0	9.0	1.2
1500	8,000	5.0	8.0	5.4
1500	4,000	4.5	9.0	30.7
1650	7,000	1.0	1.0	0.9
1650	5,000	0	8.0	3.6
1650	3,500	2.5	10.0	21.0

Table III (continued)

Temp., °F	Stress psi	% Red., of Area	% Elong.	Rupture Life, Hrs.
3. 2000°F, 1/2 hr., A. C., 1850°F 1/2 hr. O. Q., 16 hrs. 1500°F (Code 12)				
1350	15,000	1	6	3.2
1350	10,000	1	10	27.6
1350	7,000	2	9	87.0
1350	5,000	1	9	246.5
1500	9,000	2	10	3.2
1500	6,000	0	6	10.3
1500	4,000	1	8	37.9
1500	3,500	2	2	36.0
1650	6,000	2	4	1.7
1650	4,000	2	12	9.8
1650	3,000	1	11	2.2

Table IV

Stress Rupture Data on the 21.0% Mo Alloy

Temp., °F	Stress psi	% Red. of Area	% Elong.	Rupture Life, Hrs.
1. 2000°F, 1/2 hr. A.C. (Code 2)				
1350	20,000	6.7	18.0	175.1
1350	17,000	0	8.5	12.1
1350	15,000	2.2	7.8	30.8
1350	12,000	2.2	9.4	42.0
1350	9,000	0	9.0	166.4
1500	15,000	4.5	10.0	3.3
1500	12,000	3.5	11.4	7.2
1500	9,000	5.2	15.8	13.7
1500	7,500	3.0	11.0	227.9
1500	7,000	7.0	12.0	49.2
1500	5,000	7.5	15.4	140.2
1500	4,000	6.0	14.0	273.5
1650	10,000	7.5	14.0	2.1
1650	7,000	7.5	14.4	4.4
1650	5,000	5.7	9.6	22.6
1650	3,500	7.5	14.0	86.9
2. 2000°F, 1/2 hr., A. C., 1850°F 1/2 hr., A. C. (Code 21)				
1350	20,000	4	10	0.12
1350	15,000	broke in threads		14.8
1350	12,000	2	7	20.7
1350	9,000	broke in threads		141.1
1350	7,500	3	9	326.7
1500	10,000	2	8	10.3
1500	7,000	4	12	36.0
1500	5,000	3	10	139.5
1500	4,000	4	10	186.4
1650	7,000	4	11	5.2
1650	5,000	6	13	22.3
1650	4,000	4	10	63.0
1650	3,000	11	18	208.1
3. 2000°F, 1/2 hr., A.C. 1850°F, 1/2 hr., O.Q., 16 hrs., 1500°F (Code 22)				
1350	20,000	broke in threads		6.9
1350	15,000	0	5	11.7
1350	10,000	broke in threads		114.0
1350	9,000	1	9	127.6
1500	15,000	5	10	2.2
1500	10,000	6	12	12.8
1500	7,000	3	10	28.5
1500	5,000	4	14	122.8
1650	7,000	7	16	10.2
1650	5,000	4	9	12.0
1650	4,000	7	13	50.4
1650	3,500	8	15	63.7

Table V

Stress Rupture Data on the 25.6% Mo Alloy

Temp. °F	Stress psi	% Red. of Area	% Elong.	Rupture Life, Hrs.
1. 2000°F, 1/2 hr., A.C., (Code 3)				
1350	20,000	broke in threads		2.8
1350	15,000	1.0	1.1	14.6
1350	12,000	1.25	2.0	71.2
1350	12,000	1.0	2.1	38.3
1350	10,000	1.0	2.1	94.1
1350	8,000	2.0	5.0	234.9
1500	15,000	0.5	1.9	4.5
1500	10,000	2.0	5.0	14.5
1500	10,000	1.7	5.8	19.8
1500	7,500	1.25	4.5	49.3
1500	6,000	7.0	13.0	158.5
1500	5,000	7.0	20.0	287.7
1650	10,000	8.5	15.7	1.3
1650	7,500	8.0	14.0	8.8
1650	6,000	11.2	14.0	30.6
1650	5,000	8.0	16.3	54.7
1650	4,000	broke in threads		98.2
1650	3,000	13.0	18.6	325.7
2. 2000°F, 1/2 hr., A.C., 1850°F, 1/2 hr., A. C. (Code 31)				
1350	15,000	1.5	4.5	12.0
1350	12,000	2.0	5.0	17.1
1350	9,000	broke in threads		55.6
1350	7,000	2.0	8.0	236.6
1500	12,000	2.0	7.0	4.4
1500	8,000	1.5	4.5	32.7
1500	6,000	1.0	9.8	78.9
1500	4,500	2.0	9.0	213.8
1650	9,000	2.5	9.5	3.3
1650	8,000	2.0	7.7	7.7
1650	5,000	4.5	12.2	59.2
1650	3,500	5.5	11.3	33.7
1650	3,500	8.0	16.0	261.3
3. 2000°F, 1/2 hr., A. C., 1850°F, 1/2 hr., O. Q., 16 hrs. 1500°F (Code 32)				
1350	17,000	1	5	5.4
1350	15,000	1	3	47.9
1350	12,000	1	6	56.0
1350	9,000	1	8	153.0
1500	12,000	1	4	9.9
1500	8,000	2	6	51.5
1500	6,000	2	7	133.9
1650	9,000	10	18	8.5
1650	7,000	13	21	67.4
1650	5,000	11	19	73.2
1650	3,500	9	15	178.3

Table VI

Stress Rupture Data on the 29.8% Mo Alloy

Temp. °F	Stress psi	% Red. of Area	% Elong.	Rupture Life, Hrs.
1. 2000°F, 1/2 hr., A. C. (Code 4)				
1350	40,000	4	10	59.7
1350	38,400	1	8	69.8
1350	30,000	5	6	99.7
1350	20,000	9	13	170.8
1350	15,000	16	19	425.6
1500	20,000	3	5	44.1
1500	15,000	9	8	64.0
1500	12,000	13	14	93.1
1500	10,000	12	14	127.9
1500	7,500	19	20	245.4
1500	6,000	13	19	354.2
1650	10,000	24	29	15.5
1650	7,000	11	16	27.2
1650	5,000	8	12	77.9
1650	4,000	16	26	167.5
1650	3,000	13	22	319.1
2. 2000°F, 1/2 hr., A.C., 1850°F, 1/2 hr., A. C. (Code 41)				
1350	45,000	broke in threads		15.0
1350	40,000	2.2	10.5	89.8
1350	30,000	4.7	11.5	174.1
1350	17,000	15.0	21.0	622.1
1350	20,000	13.0	18.7	319.4
1500	30,000	1.2	3.0	22.0
1500	20,000	3.5	18.4	55.5
1500	14,000	9.0	14.0	163.6
1500	10,000	11.0	17.2	226.5
1650	12,000	19.0	32.0	14.2
1650	7,000	14.0	20.0	74.1
1650	5,000	17.5	25.0	180.5
1650	4,000	15.0	24.0	392.7
3. 2000°F, 1/2 hr., A. C., 1850°F, 1/2 hr., O.Q. 16 hrs. 1500°F (Code 42)				
1350	45,000	2	7	33.0
1350	40,000	1	6	50.8
1350	20,000	8	18	391.3
1500	30,000	1	8	13.3
1500	20,000	7	15	35.6
1500	10,000	13	19	198.8
1650	12,000	14	23	14.2
1650	7,000	16	26	58.4
1650	7,000	17	27	64.3
1650	5,000	12	19	177.6

Table VII

Stress Rupture Data on the 36.0% Mo Alloy

Temp., °F	Stress, psi	% Red., of Area	% Elong.	Rupture Life, Hrs.
1. 2000°F, 1/2 hr. A. C. (Code 5)				
1350	50,000	5	11	7.7
1350	40,000	8	11	9.8
1350	30,000	7	15	31.4
1350	25,000	9	15	47.1
1350	15,000	17	27	189.7
1350	12,000	12	20	737.9
1500	25,000	12	17	5.5
1500	20,000	17	21	7.4
1500	15,000	23	36	20.6
1500	12,000	18	30	44.4
1500	10,000	18	30	119.4
1500	7,000	14	20	514.5
1650	15,000	8	11	0.4
1650	10,000	26	37	13.0
1650	7,500	24	36	22.4
1650	5,000	28	38	30.8
1650	4,000	23	35	105.4
1650	3,000	broke in threads		79.9
1350	20,000	13	18	79.1
2. 2000°F, 1/2 hr. A. C., 1850°F, 1/2 hr. A. C. (Code 51)				
1350	50,000	broke in threads		14.5
1350	40,000	3	8	30.8
1350	30,000	3	9	96.5
1350	20,000	5	12	466.3
1500	25,000	6	13	18.3
1500	20,000	8	14	30.2
1500	15,000	7	17	111.1
1500	10,000	broke in threads		337.4
1650	15,000	8	14	12.3
1650	10,000	14	20	25.4
1650	6,000	9	16	201.0
1650	3,500	11	21	289.8
3. 2000°F, 1/2 hr. A. C., 1850°F, 1/2 hr., O. Q., 16 hrs. 1500°F (Code 52)				
1350	50,000	broke in threads		0
1350	40,000	broke in threads		0.5
1350	35,000	7	17	27.7
1350	30,000	7	14	54.4
1350	20,000	broke in threads		205.1
1500	25,000	9	20	8.4
1500	20,000	8	17	28.5
1500	12,000	15	25	138.1
1650	10,000	27	40	33.3
1650	6,000	21	38	63.1
1650	3,500	24	40	268.9

Table VIII

Stress Rupture Data on Hastalloy B

Temp., °F	Stress, psi	% Red., of Area	% Elong.	Rupture Life, Hrs.
1. 2000°F, 1/2 hr., A. C. (Code 6)				
1350	50,000	7	18	5.7
1350	45,000	7	12	15.0
1350	40,000	12	15	37.6
1350	30,000	11	21	121.2
1350	25,000	11	17	307.8
1500	30,000	27	31.5	5.9
1500	25,000	27	30	14.6
1500	20,000	30	38	45.5
1500	17,000	34	40	126.9
1500	15,000	31	42	220.4
1650	20,000	34	30	1.4
1650	15,000	35	25	4.5
1650	12,000	24	30	25.3
1650	10,000	18	26	70.9
1650	7,000	18	17	263.4
2. 2000°F, 1/2 hr. A. C., 1850°F 1/2 hr. A. C. (Code 61)				
1350	50,000	10	19	1.7
1350	40,000	15	27	23.2
1350	35,000	20	30	52.5
1350	30,000	15	30	135.7
1500	30,000	29	44	10.0
1500	20,000	34	53	47.5
1500	15,000	34	49	222.9
1650	20,000	37	45	2.6
1650	15,000	31	31	9.9
1650	12,000	37	52	39.5
1650	10,000	31	45	85.2
1650	8,000	24	33	184.4
3. 2000°F, 1/2 hr., A. C., 1850°F 1/2 hr. O. Q., 16 hrs. 1500°F (Code 62)				
1350	50,000	12	20	8.7
1350	40,000	17	29	39.3
1350	35,000	16	23	67.9
1350	30,000	16	23	148.6
1350	25,000	16	24	243.9
1500	25,000	34	50	17.7
1500	20,000	36	46	62.6
1500	15,000	34	43	178.9
1650	15,000	37	42	10.2
1650	12,000	36	41	30.1
1650	10,000	29	38	67.6
1650	8,000	23	29	189.4

Table IX

Mechanical Tests on the Alloys

Alloy (% Mo)	Tensile Strength	Yield Strength psi (0.2% offset)	Red. of Area %	Elong. %	R_A
		2000°F 1/2 hr. A. C.			
17.3 (Code 1)	106,000	53,000	53.8	45.5	52.0
	110,000	54,000	51.5	42.3	
21.0 (Code 2)	125,000	60,000	70.8	41.6	54.5
	130,000	60,000	52.2	40.6	
25.6 (Code 3)	140,000	68,000	71.6	41.8	56.0
	136,000	67,000	70.6	51.5	
29.8 (Code 4)	140,000	68,000	70.2	50.5	60.0
	143,000	70,000	70.8	46.5	
36.0 (Code 5)	155,000	77,000	50.1	37.8	60.0
	150,000	76,000	50.3	38.3	
Hastalloy B (Code 6)	135,000	64,500	58.5	42.0	59.5
	137,000	64,000	54.8	41.1	
		2000°F 1/2 hr. A. C., 1850°F 1/2 hr. A. C.			
17.3 (Code 11)	110,000	44,000	57.7	46.0	52.0
	113,000	50,000	54.8	43.3	
21.0 (Code 21)	125,000	64,000	73.6	37.1	53.0
	120,000	53,000	76.4	48.4	
25.6 (Code 31)	126,000	60,000	57.8	50.9	58.0
	134,000	69,000	69.7	46.3	
29.8 (Code 41)	138,000	65,000	68.4	54.0	59.5
	138,000	69,000	69.4	49.7	
36.0 (Code 51)	151,000	76,000	49.2	41.4	63.0
	151,000	77,000	47.8	37.1	
Hastalloy B (Code 61)	138,000	72,000	54.7	39.8	60.5
	135,000	70,000	53.5	42.2	
		2000°F 1/2 hr. A. C., 1850°F, 1/2 hr. O. Q., 16 hrs. 1500°F, A. C.			
17.3 (Code 12)	50,400	48,000	2.5	2.06	51.5
	50,200	49,000	2.5	2.76	
21.0 (Code 22)	72,000	52,000	8.5	9.90	57.0
	75,000	53,000	8.2	4.93	
25.6 (Code 32)	60,000	none	broke in thread		66.0
	75,000	none	broke in thread		
29.8 (Code 42)	58,000	none	broke in thread		69.0
	55,000	none	broke in thread		
36.0 (Code 52)	broke in thread (2 specimens)				
Hastalloy B (Code 62)	135,000	66,000	45.7	34.7	57.0
	134,000	65,000	48.4	38.5	

Table X

Mechanical Tests on the Alloys Exposed 100 Hours at 1500°F

Alloy (% Mo)	Tensile Strength, psi	Yield Strength, psi (0.2% offset)	Red. of Area %	Elong. %
		2000°F, 1/2 hr. A. C.		
17.3 (Code 1)	52,000	40,000	9.0	4.4
	55,000	39,000	7.7	3.5
21.0 (Code 2)	65,000	45,000	11.9	7.0
	71,000	45,000	7.7	4.10
25.6 (Code 3)	90,000	65,000	9.9	0.73
	88,000	68,000	7.4	1.62
29.8 (Code 4)	70,000	broke in threads		
	75,000	broke in threads		
36.0 (Code 5)	48,000	broke in threads		
	49,000	broke in threads		
Hastalloy B	73,000		28.8	24.6
(Code 6)	135,000	78,000	31.1	23.3
		2000°F, 1/2 hr. A. C., 1850°F 1/2 hr. A. C.		
17.3 (Code 11)	48,500	39,000	5.1	1.10
	53,000	38,000	6.4	0.49
21.0 (Code 21)	65,000	45,000	8.3	5.2
	80,000	46,000	14.4	4.1
25.6 (Code 31)	91,000	75,000	9.9	0.87
	95,000	78,000	2.5	0.29
29.8 (Code 41)	63,000	-	broke in threads	
	60,000	-	broke in threads	
36.0 (Code 51)	broke in threads (2 specimens)			
Hastalloy B	135,000	74,000	30.8	21.3
(Code 61)	132,000	73,000	26.1	23.2
		2000°F, 1/2 hr. A. C., 1850°F, 1/2 hr. O. Q., 16 hrs. 1500°F		
17.3 (Code 12)	40,500	38,000	7.5	1.80
	49,000	37,000	6.1	0.48
21.0 (Code 22)	70,000	42,000	13.0	5.68
	75,000	42,000	11.3	4.75
25.6 (Code 32)	93,000	73,000	5.0	0.98
	95,000	73,000	6.4	0.42
29.8 (Code 42)	78,000	broke in threads		
	75,000	broke in threads		
36.0 (Code 52)	broke in threads (2 specimens)			
Hastalloy B	123,000	65,000	21.6	17.7
(Code 62)	126,000	65,000	21.6	13.4

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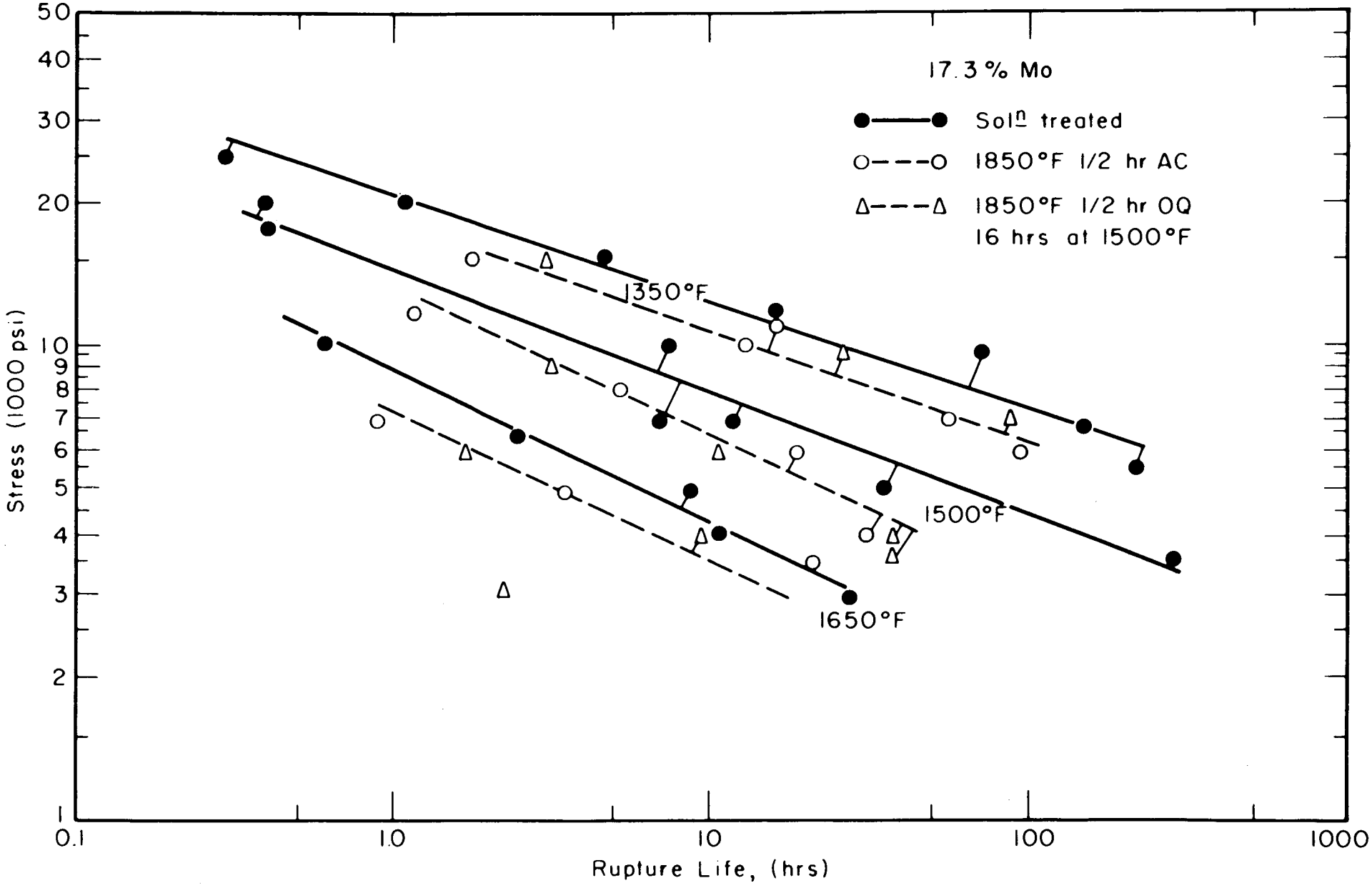

FIGURE 1 - STRESS RUPTURE DATA OF THE 17.3 % Mo ALLOY

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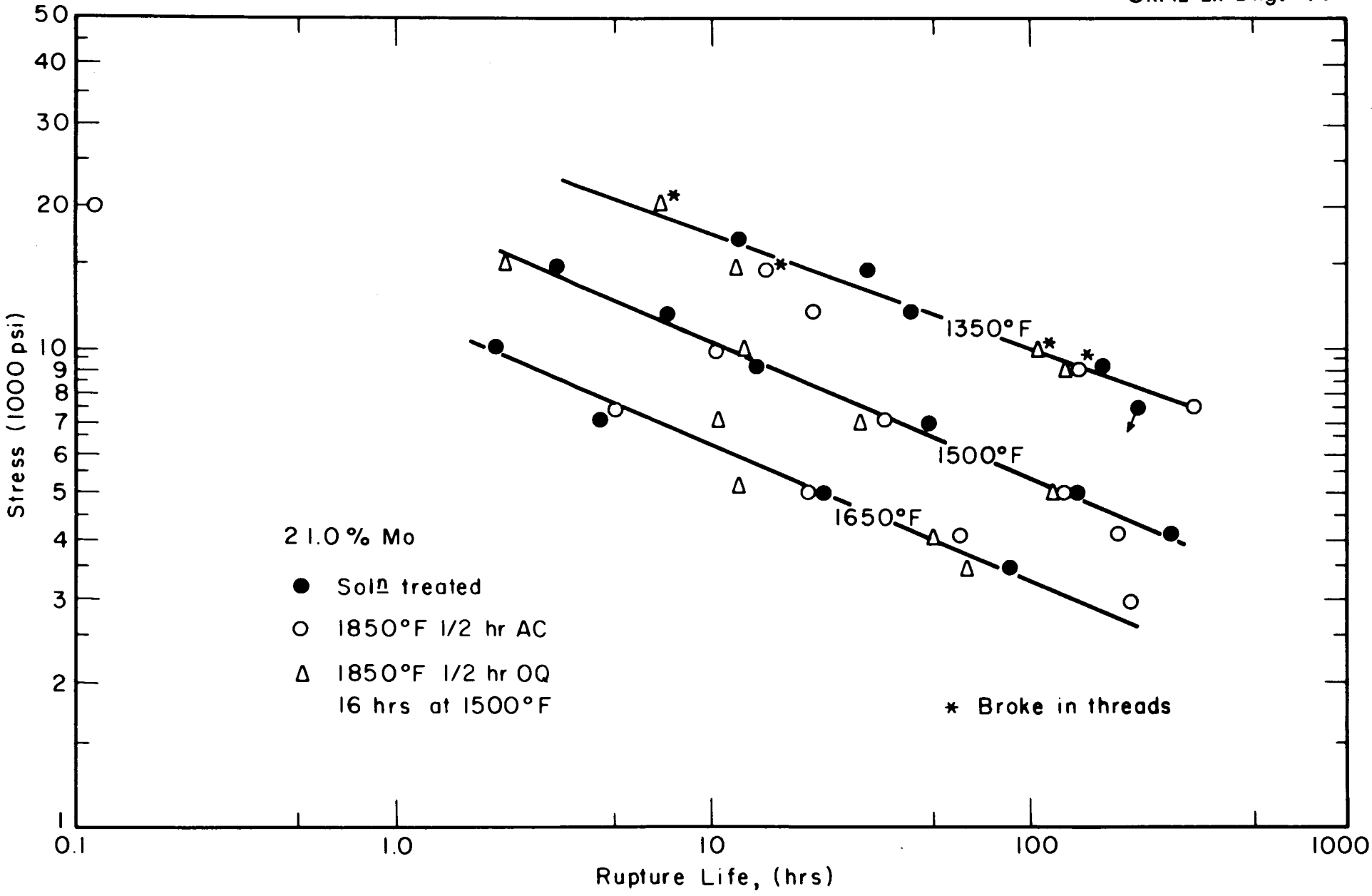

FIGURE 2 - STRESS RUPTURE DATA OF THE 21.0 % Mo ALLOY

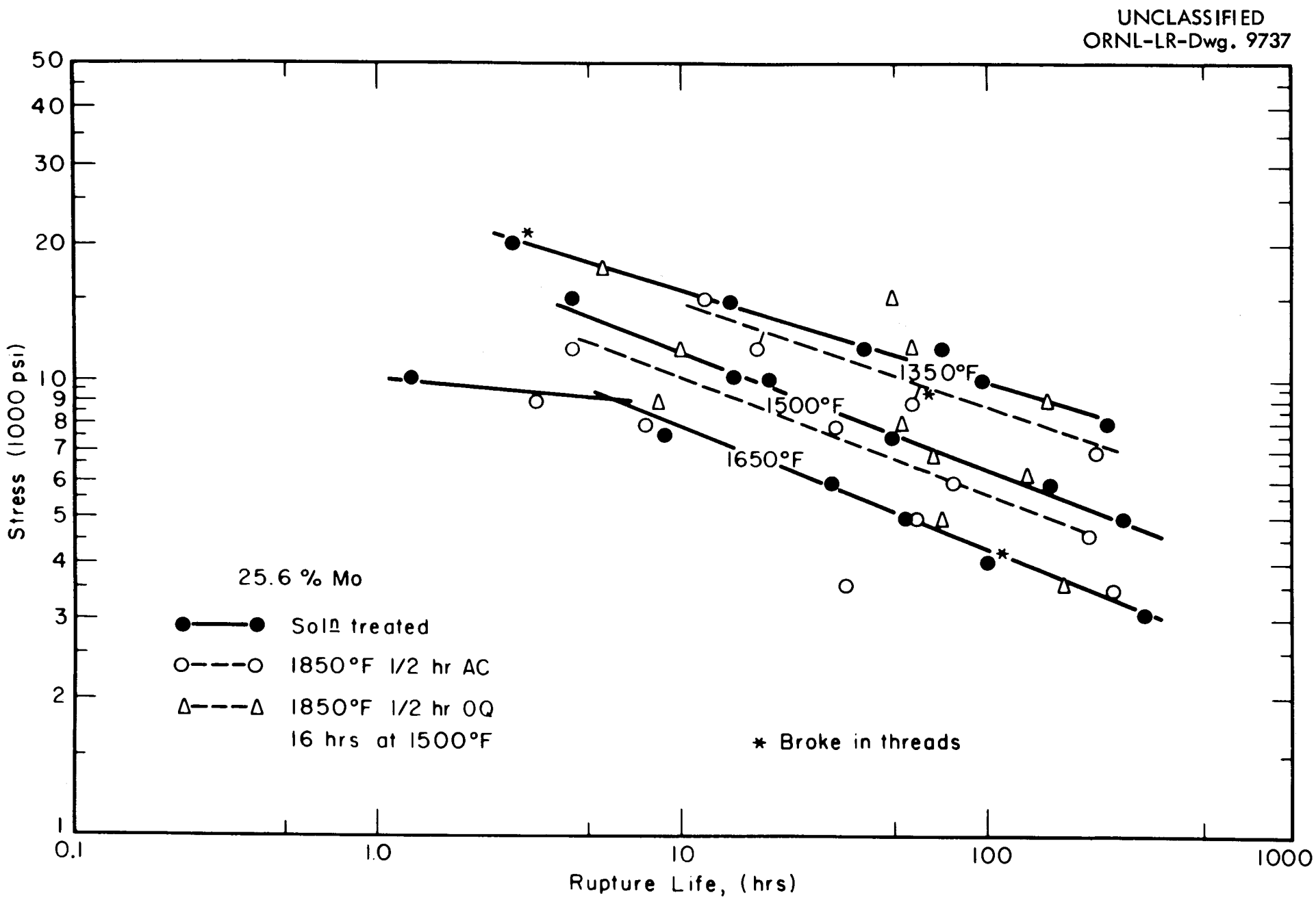

FIGURE 3 - STRESS RUPTURE DATA OF THE 25.6 % Mo ALLOY

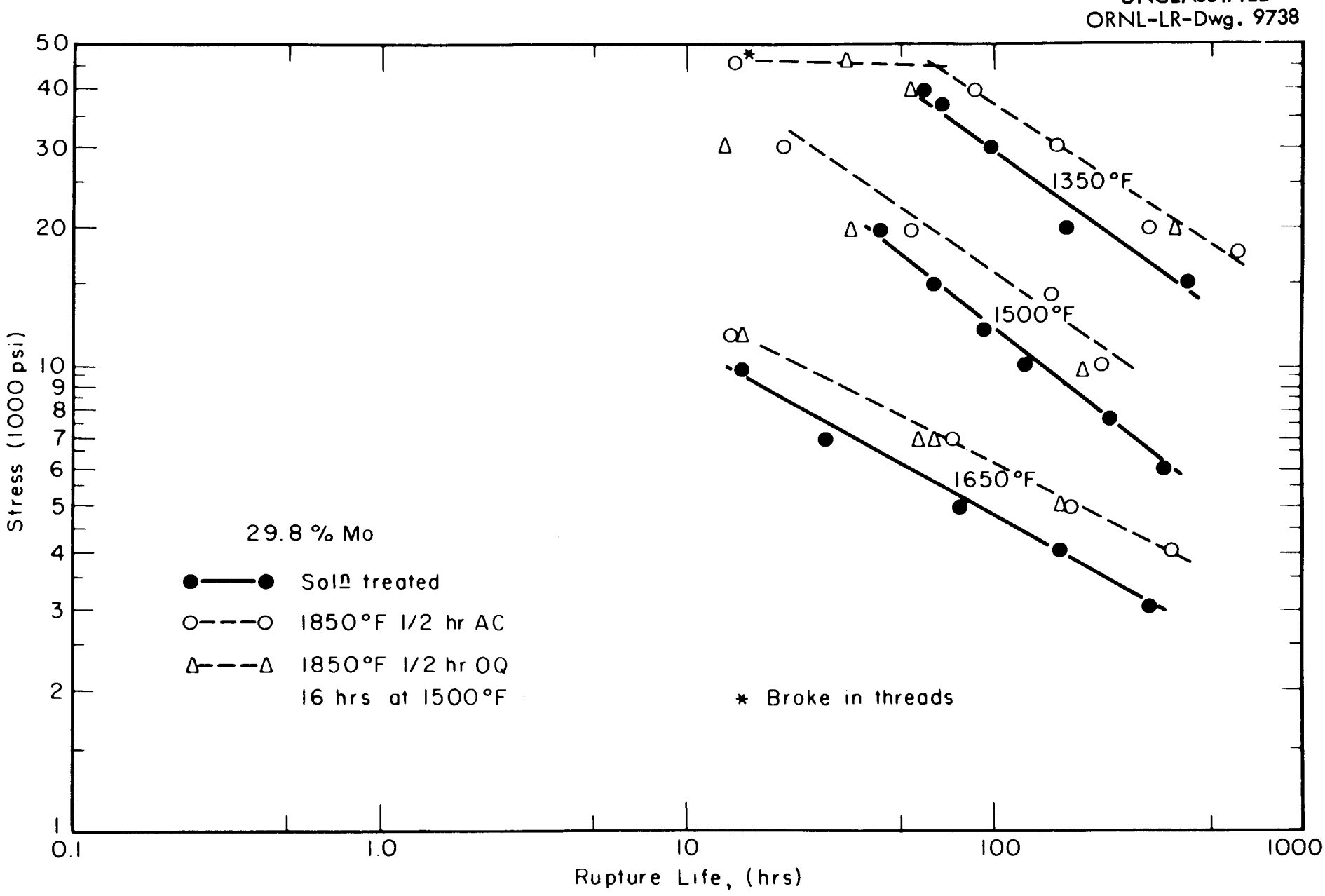

FIGURE 4 - STRESS RUPTURE DATA OF THE 29.8 % Mo ALLOY

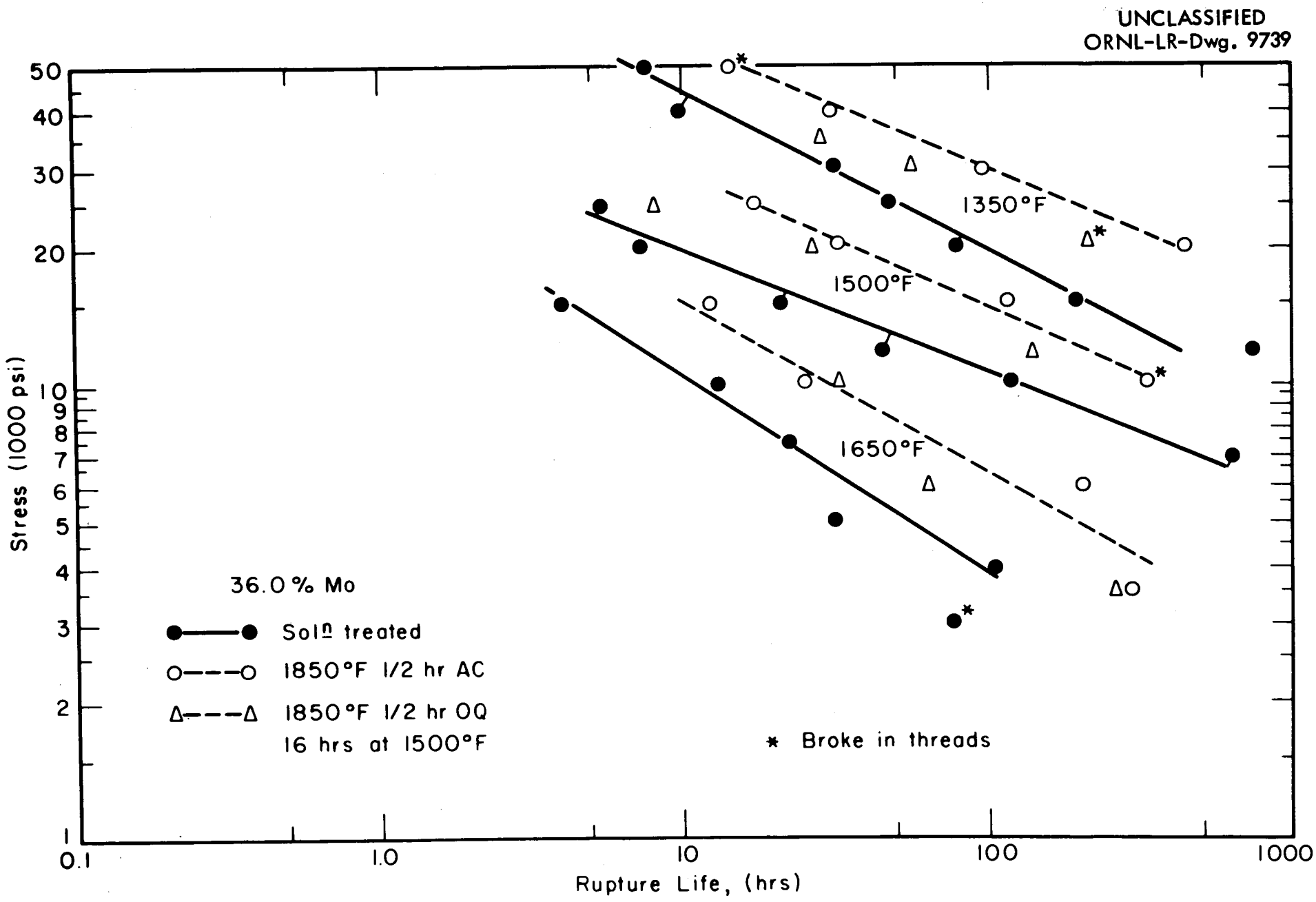

FIGURE 5 – STRESS RUPTURE DATA OF THE 36.0 % Mo ALLOY

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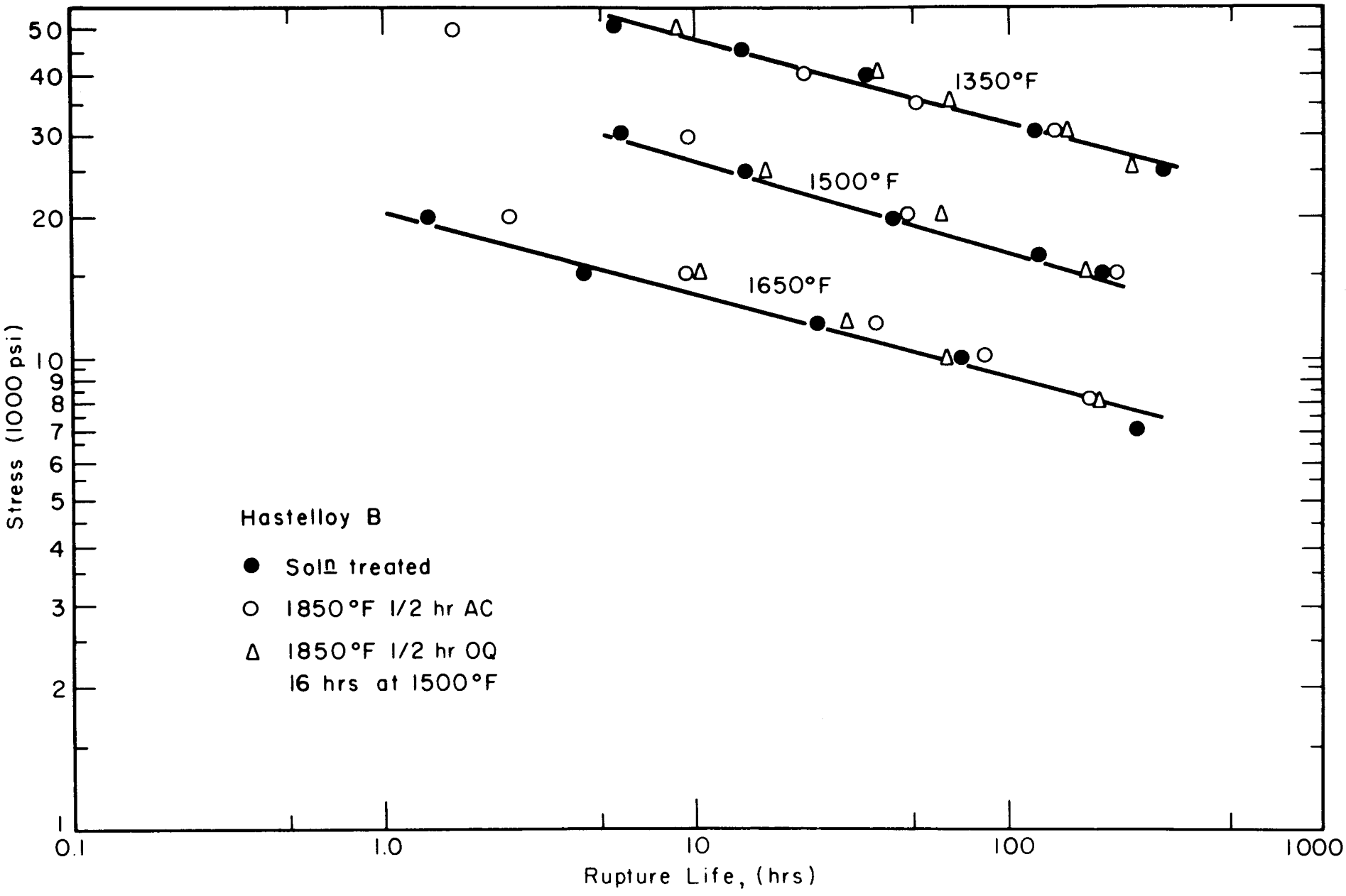

FIGURE 6 - STRESS RUPTURE DATA OF COMMERCIAL HASTELLOY B

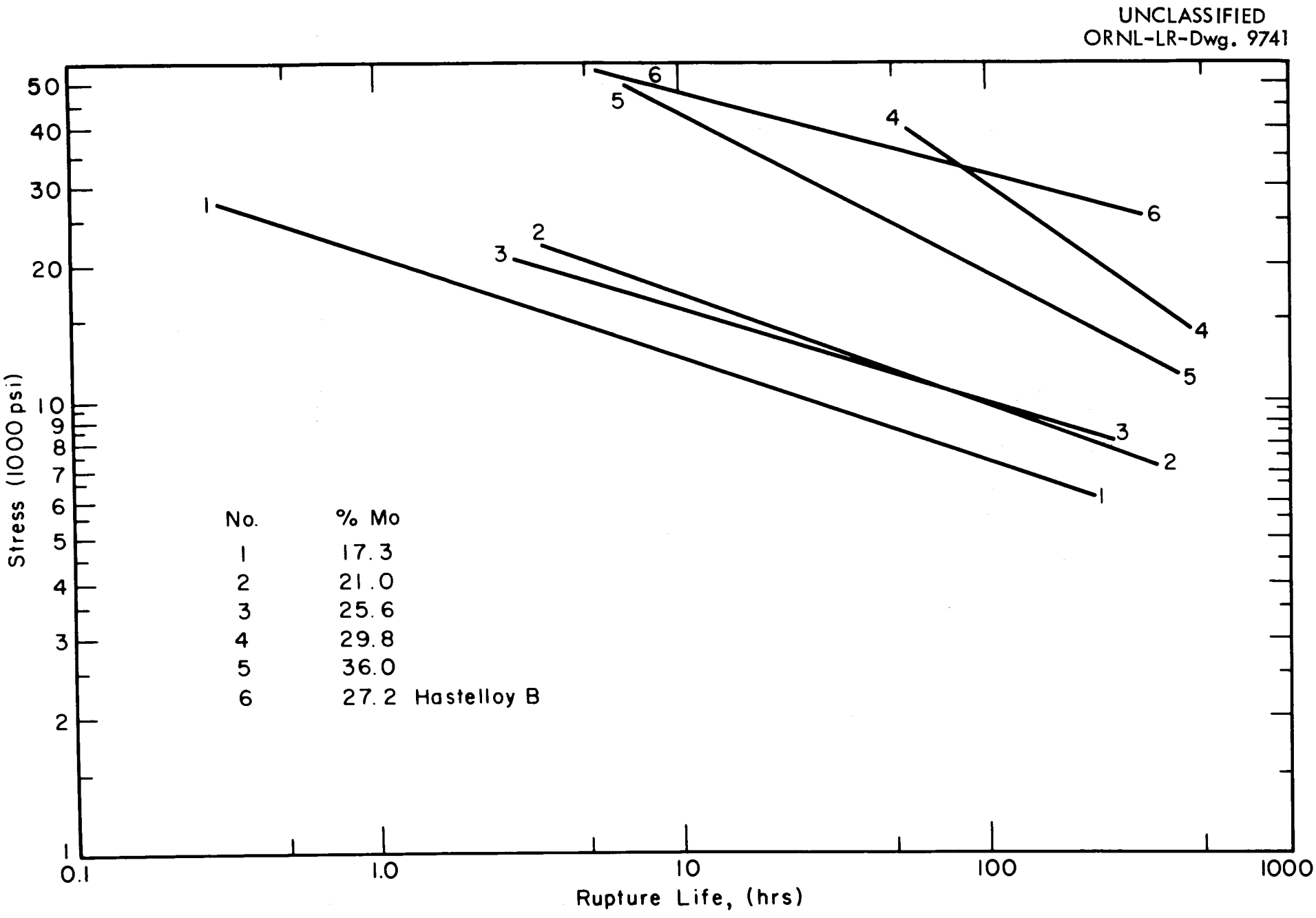

FIGURE 7 - SUMMARY PLOT OF STRESS RUPTURE DATA AT 1350°F

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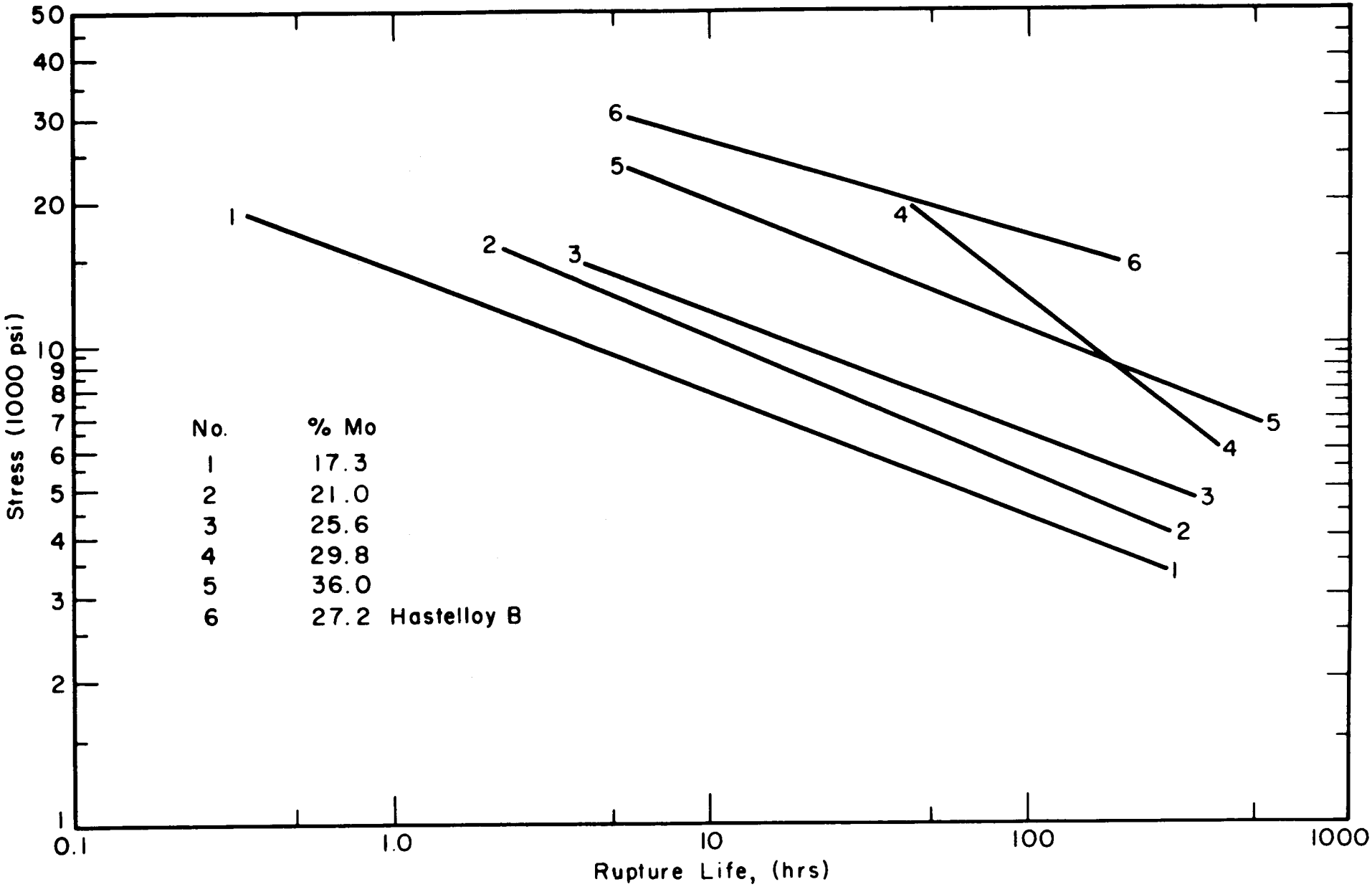

FIGURE 8 - SUMMARY PLOT OF STRESS RUPTURE DATA AT 1500°F

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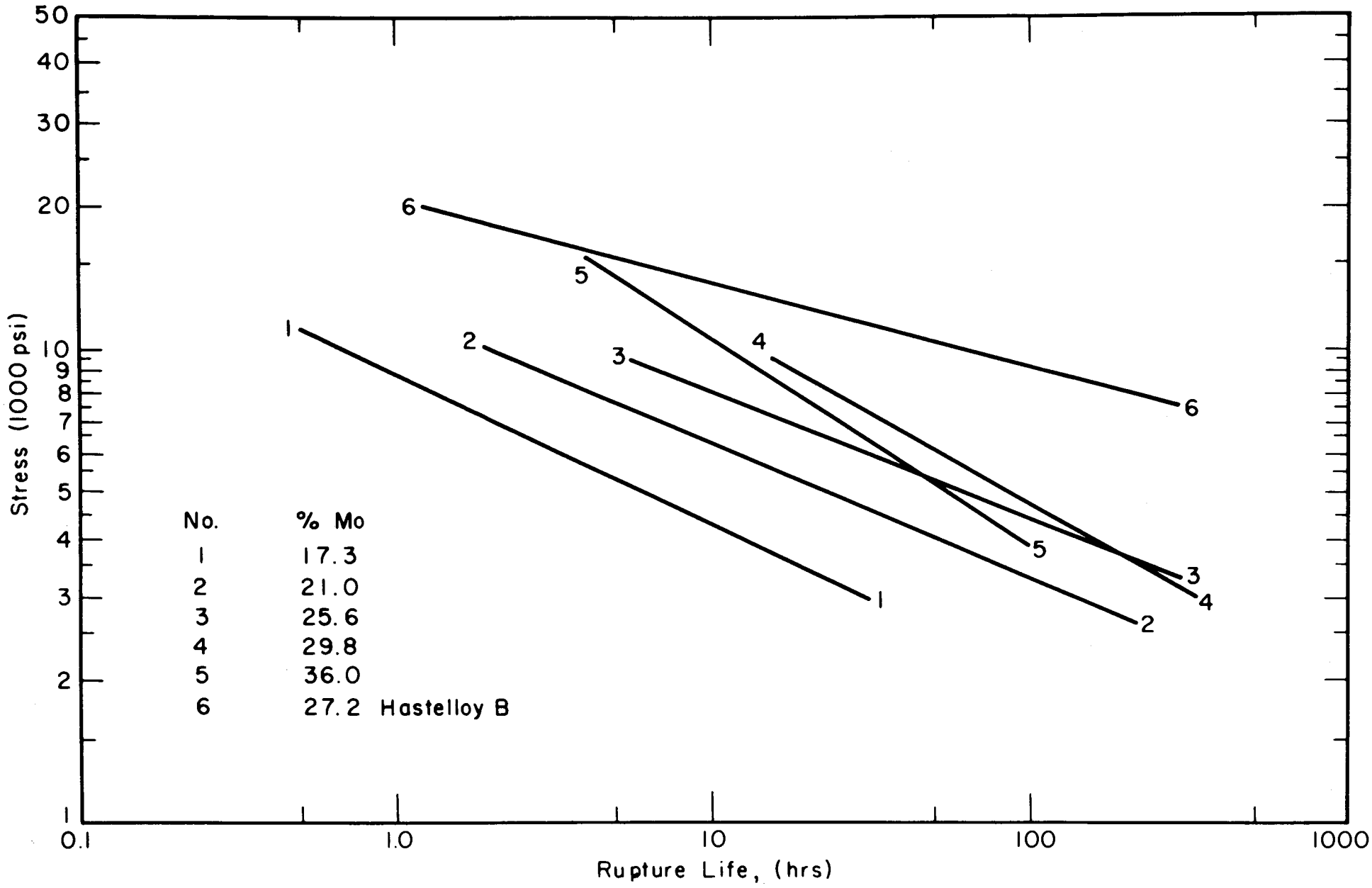

FIGURE 9 – SUMMARY PLOT OF STRESS RUPTURE DATA AT 1650°F

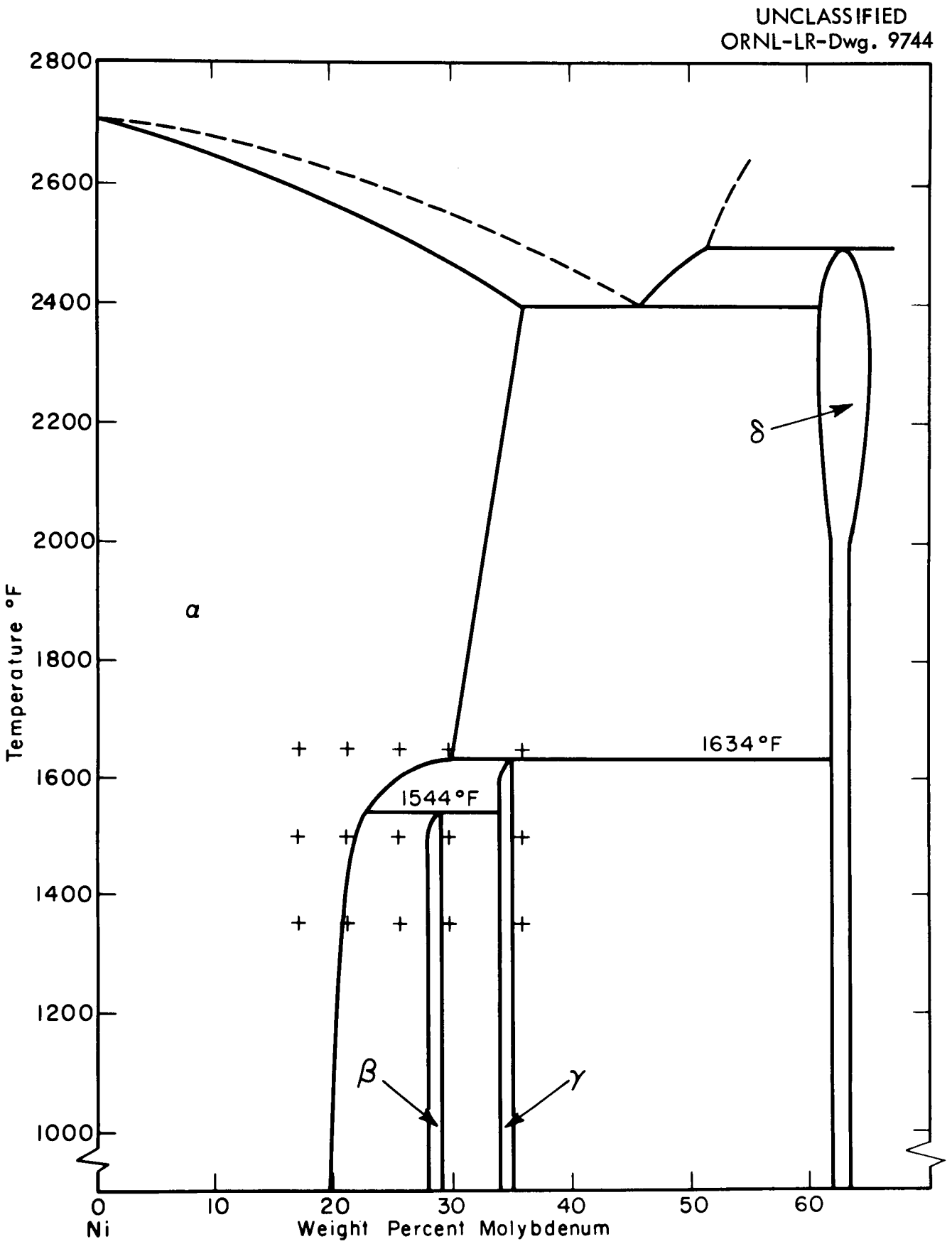

FIGURE 10 - MOLYBDENUM-NICKEL PHASE DIAGRAM BY R. M. PARKE

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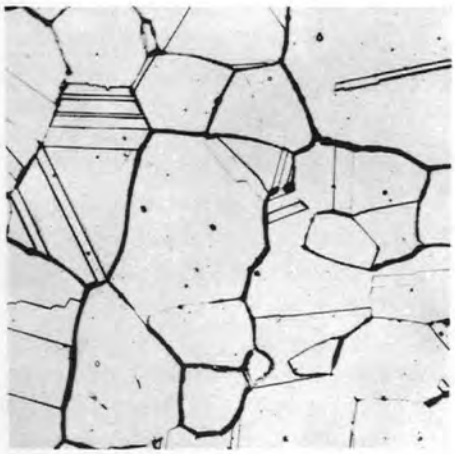
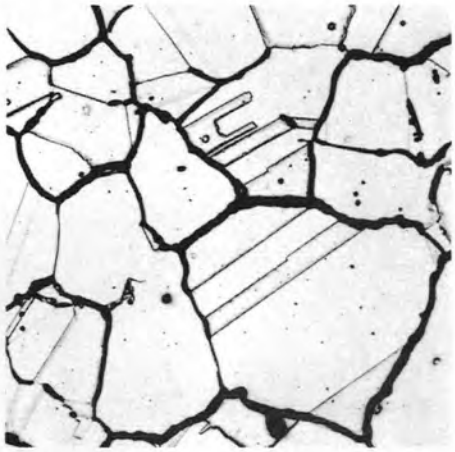
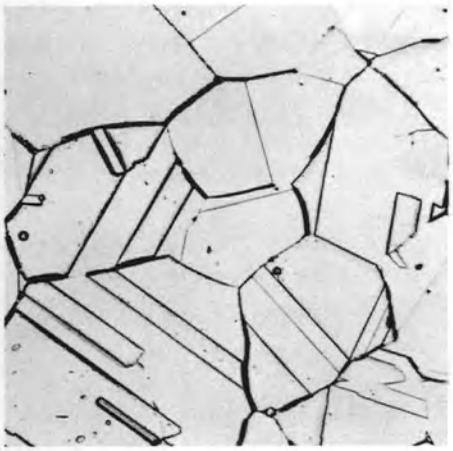


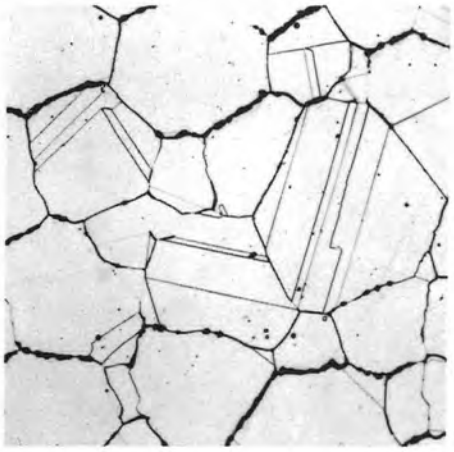
2000°F, 1/2 hr. A.C., 1850°F
1/2 hr. O. Q., 16 hr. 1500°F
Code 12



1350°F, 7,000 psi, 87 hrs.
Code 12

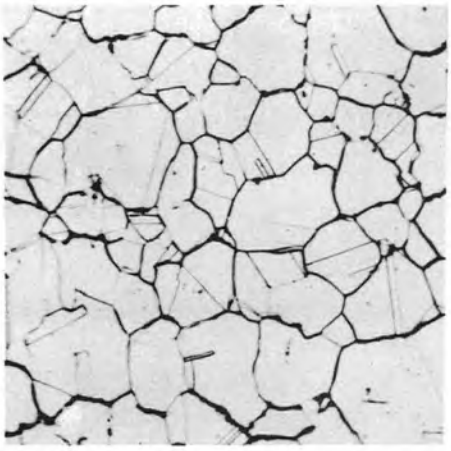


2000°F, 1/2 hr. A.C., 1850°F
1/2 hr. A. C., Code 11



1350°F, 6,000 psi, 90 hrs.
Code 11

2000°F, 1/2 hr. A. C. Code 1



1350°F, 6,740 psi, 145 hrs. Code 1

Figure 11. Photomicrographs of 17.3% Mo alloy, etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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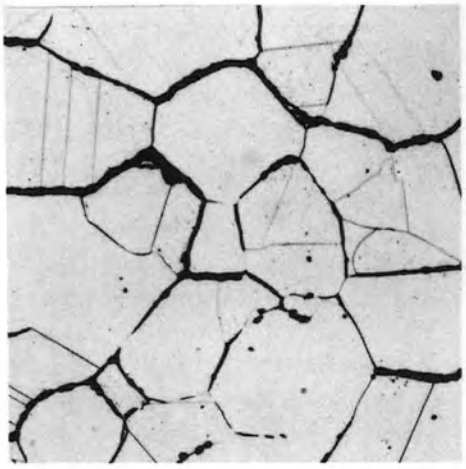
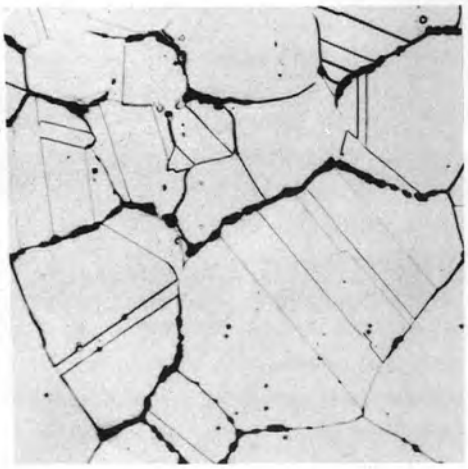
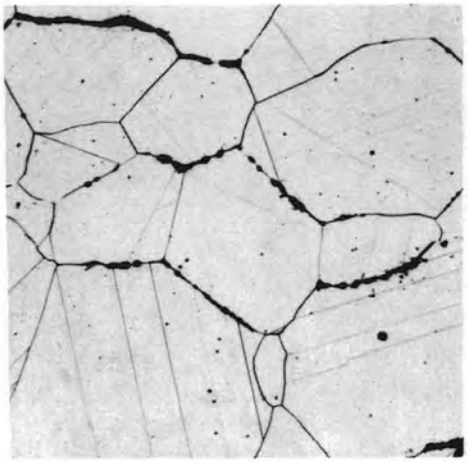


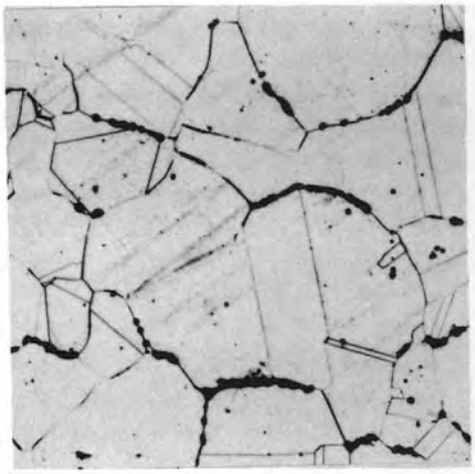
1500°F, 4,000 psi, 38 hrs.
Code 12



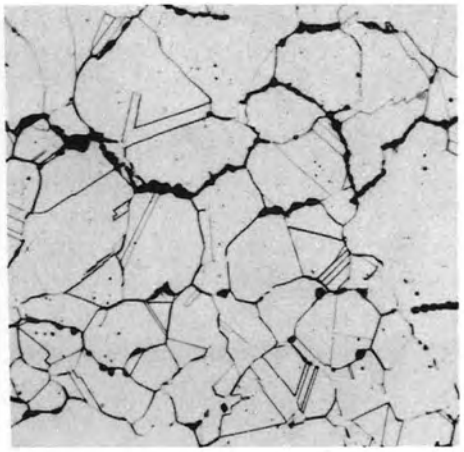
1650°F, 4,000 psi, 9.8 hrs.
Code 12



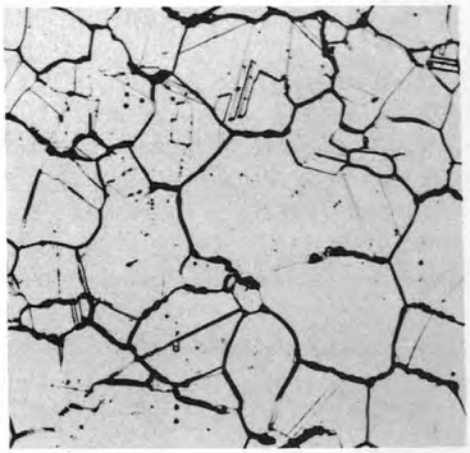
1500°F, 4,000 psi, 31 hrs.
Code 11



1650°F, 3,500 psi, 21 hrs.
Code 11



1500°F, 3,500 psi, 284 hrs.
Code 1



1650°F, 3,000 psi, 27 hrs.
Code 1

Fig. 11. (continued)

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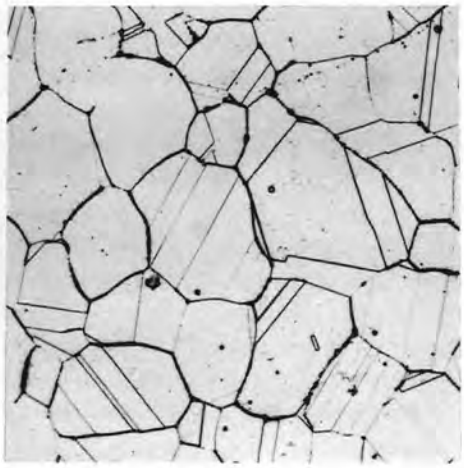
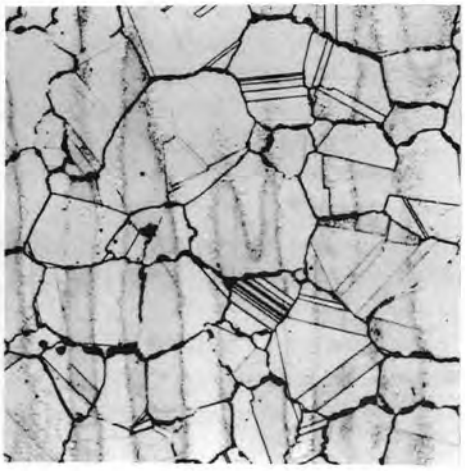
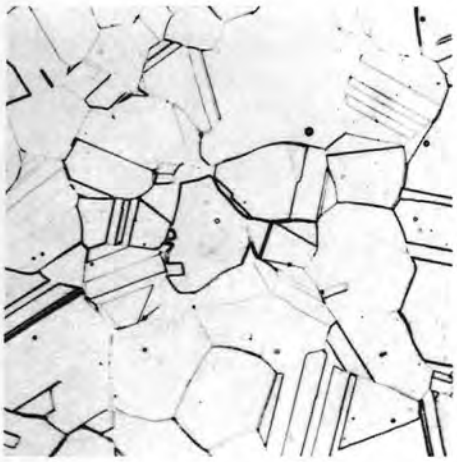


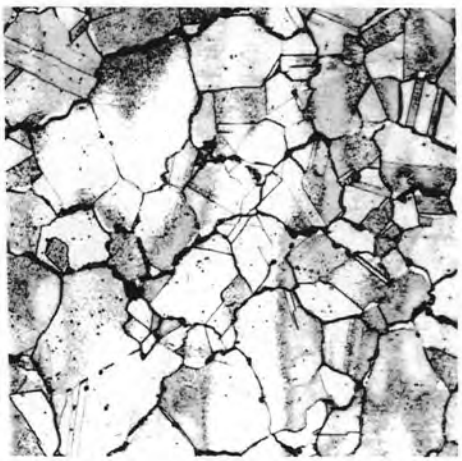
2000°F, 1/2 hr. A. C., 1850°F
1/2 hr. O. Q. 16 hrs., 1500°F
Code 22



1350°F, 9,000 psi, 128 hrs.
Code 22

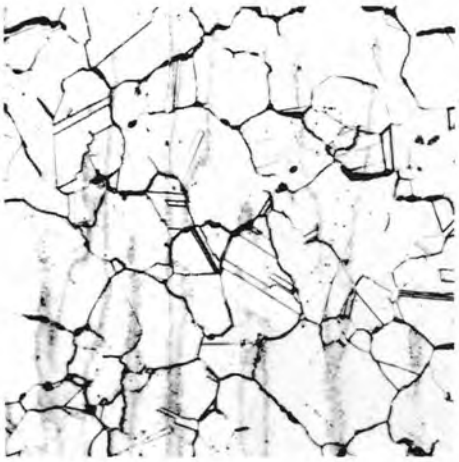


2000°F, 1/2 hr. A. C., 1850°F
1/2 hr. A. C., Code 21



1350°F, 7,500 psi, 327 hrs.
Code 21

2000°F, 1/2 hr., A. C. Code 2



1350°F, 9,000 psi, 166 hrs. Code 2

Figure 12. Photomicrographs of 21.0% Mo alloy, etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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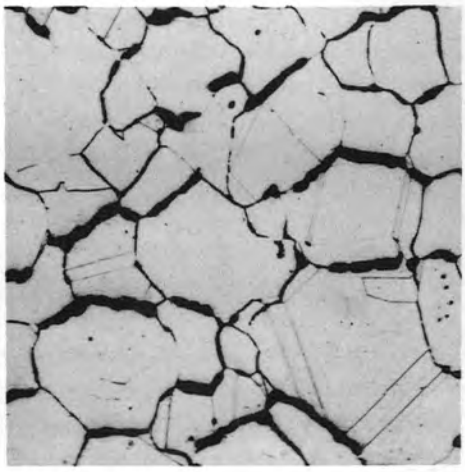
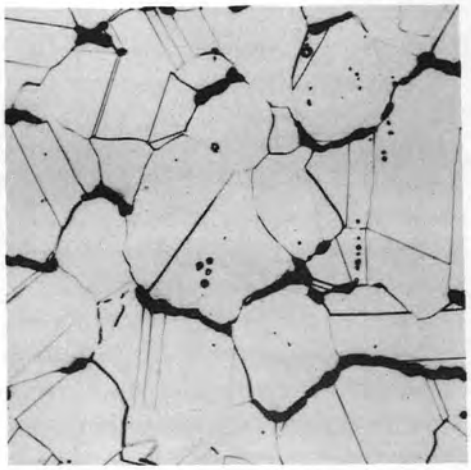
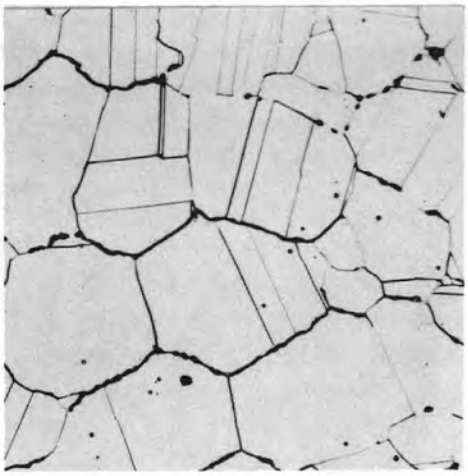
PHOTO 15458



1500°F, 5,000 psi, 123 hrs.
Code 22

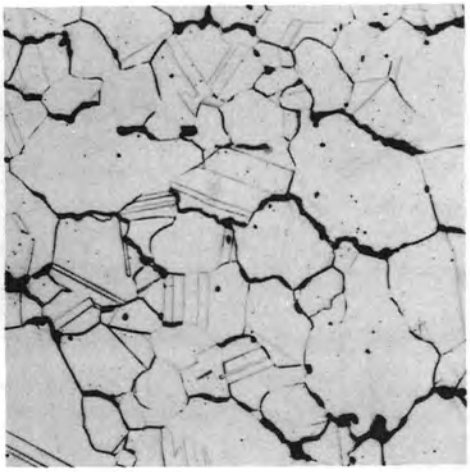


1650°F, 3,500 psi, 64 hrs.
Code 22

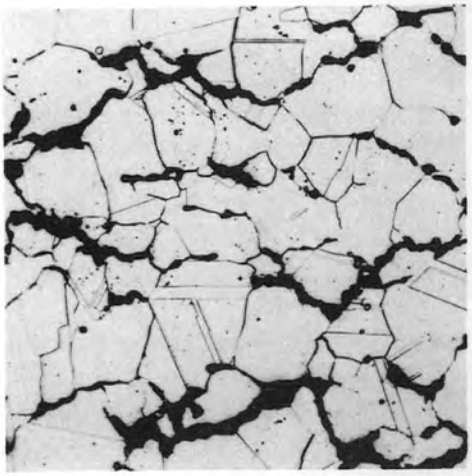


1500°F, 5,000 psi, 140 hrs.
Code 21

1650°F, 4,000 psi, 63 hrs.
Code 21



1500°F, 5,000 psi, 140 hrs.
Code 2



1650°F, 3,500 psi, 87 hrs.
Code 2

Fig. 12. (continued)

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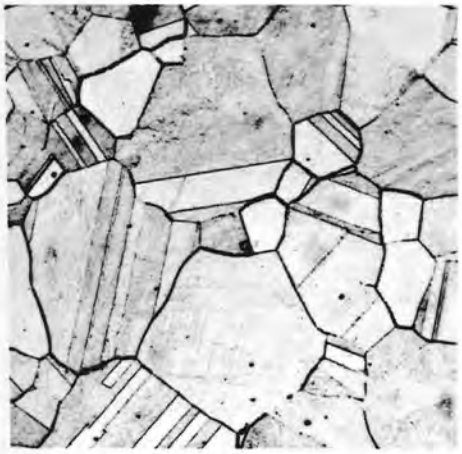
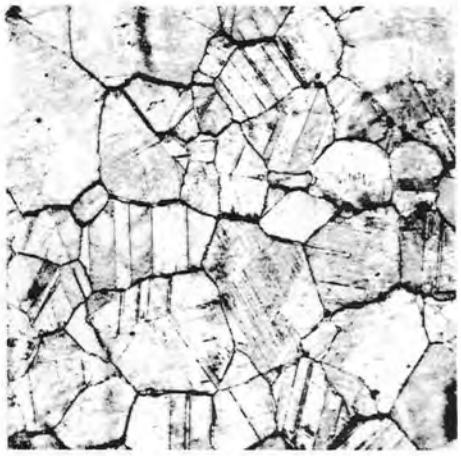
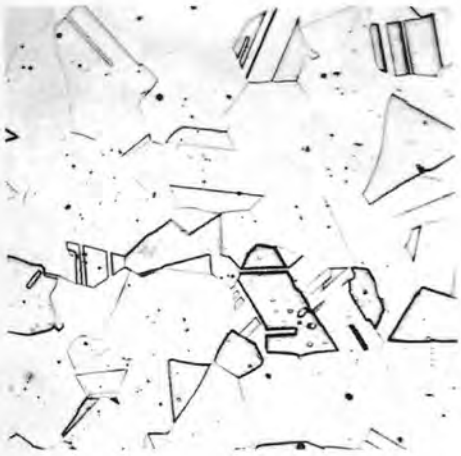


2000°F, 1/2 hr. A. C., 1850°F 1/2 hr., O. Q., 16 hrs. 1500°F, Code 32



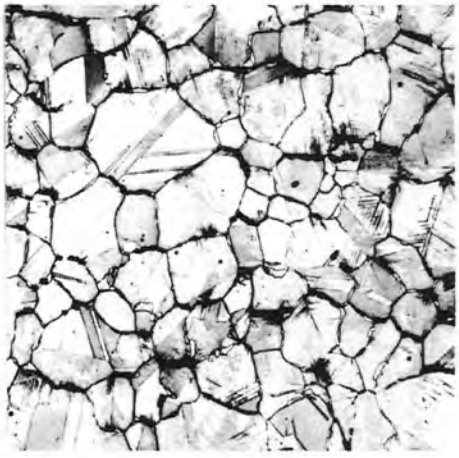
1350°F, 9,000 psi, 153 hrs. Code 32



2000°F, 1/2 hr., A. C., 1850°F 1/2 hr. A. C., Code 31

1350°F, 7,000 psi, 237 hrs. Code 31

2000°F, 1/2 hr. A. C., Code 3



1350°F, 8,000 psi, 235 hrs. Code 3

Figure 13. Photomicrographs of 25.6% Mo alloy, etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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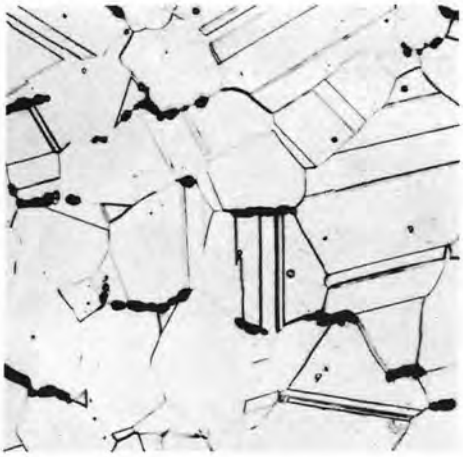
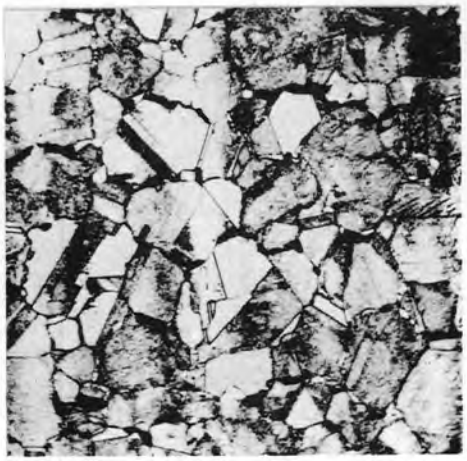
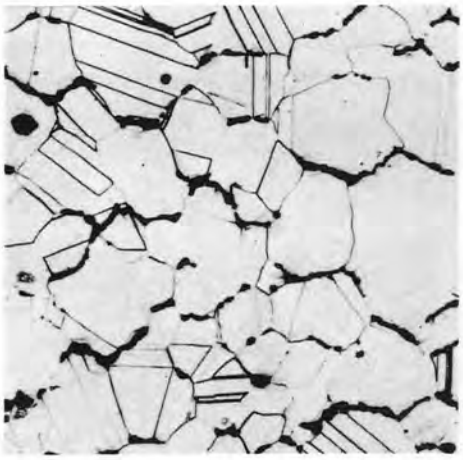
1500°F, 6,000 psi, 134 hrs.
Code 32



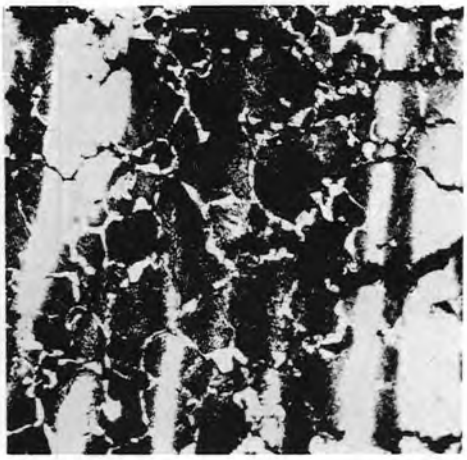
1650°F, 3,500 psi, 178 hrs.
Code 32



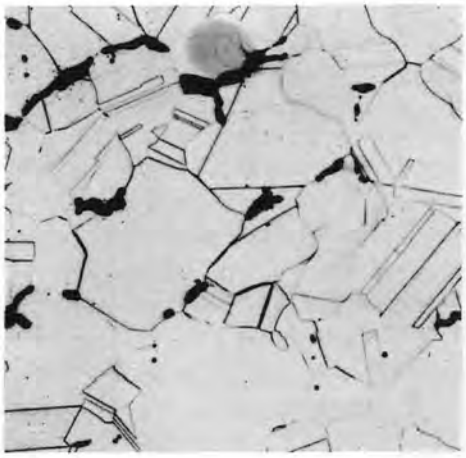
1500°F, 4,500 psi, 214 hrs.
Code 31



1650°F, 3,500 psi, 261 hrs.
Code 31



1500°F, 5,000 psi, 288 hrs.
Code 3



1650°F, 3,000 psi, 326 hrs.
Code 3

Fig. 13. (continued)

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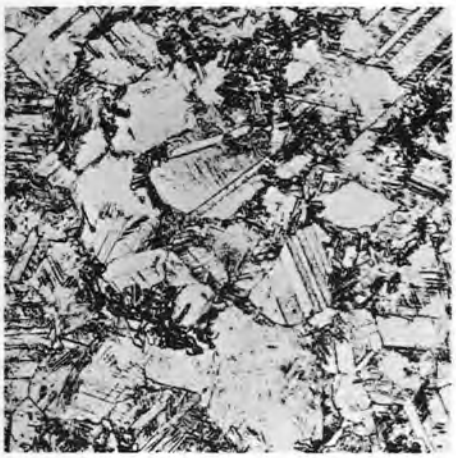
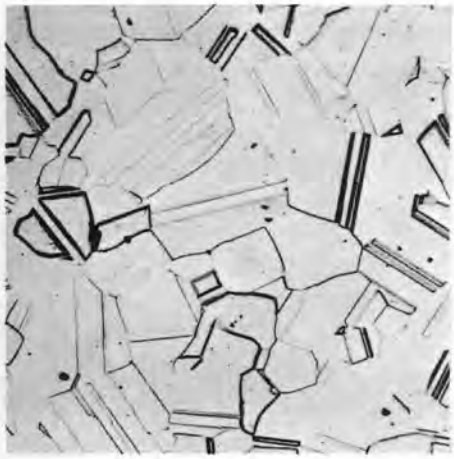


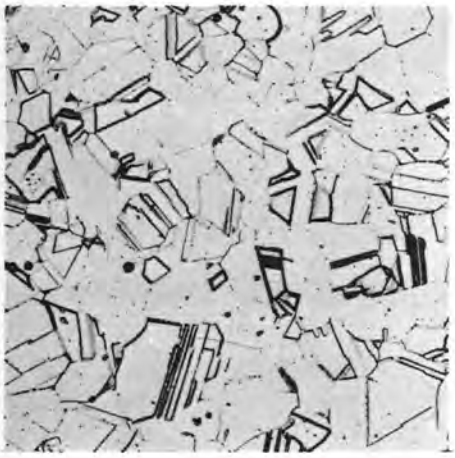
2000°F, 1/2 hr. A. C., 1850°F 1/2 hr. O. Q., 16 hrs. 1500°F, Code 42

1350°F, 20,000 psi, 391 hrs. Code 42

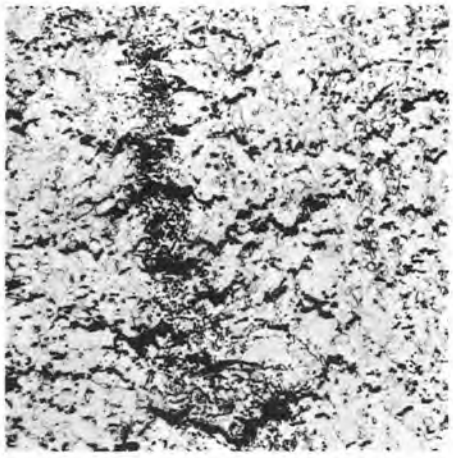


2000°F, 1/2 hr. A. C., 1850°F 1/2 hr. A. C., Code 41

1350°F, 30,000 psi, 174 hrs. Code 41



2000°F, 1/2 hr., A. C. Code 4



1350°F, 20,000 psi, 171 hrs., Code 4

Figure 14. Photomicrographs of 29.8% Mo alloy, etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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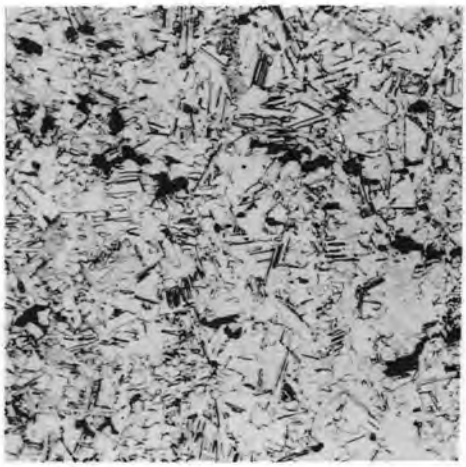
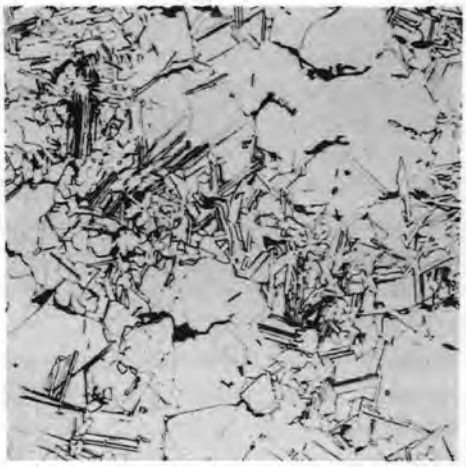
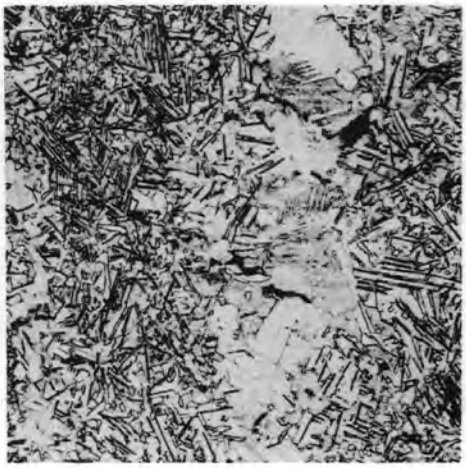


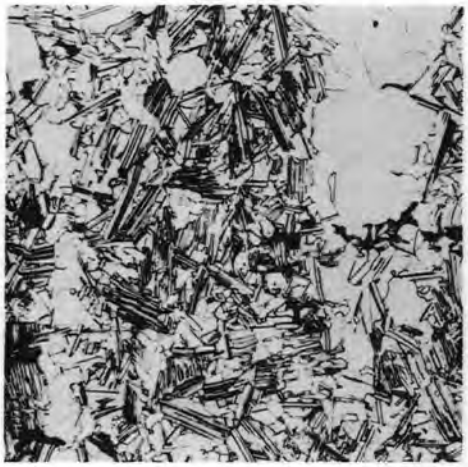
1500°F, 10,000 psi, 199 hrs.
Code 42



1650°F, 5,000 psi, 178 hrs.
Code 42

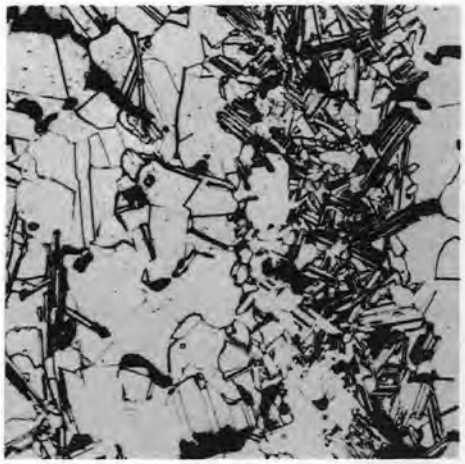


1500°F, 14,000 psi, 164 hrs.
Code 41



1650°F, 5,000 psi, 181 hrs.
Code 41

1500°F, 10,000 psi, 128 hrs.
Code 4



1650°F, 4,000 psi, 168 hrs.
Code 4

Fig. 14. (continued)

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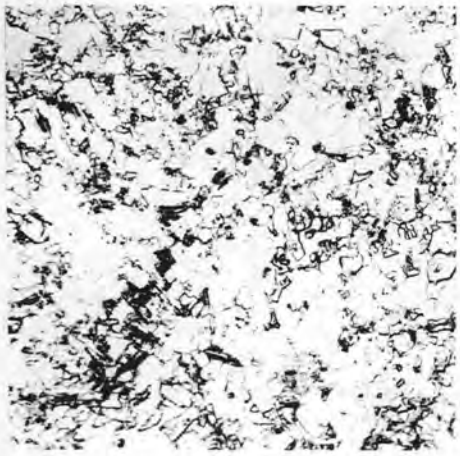
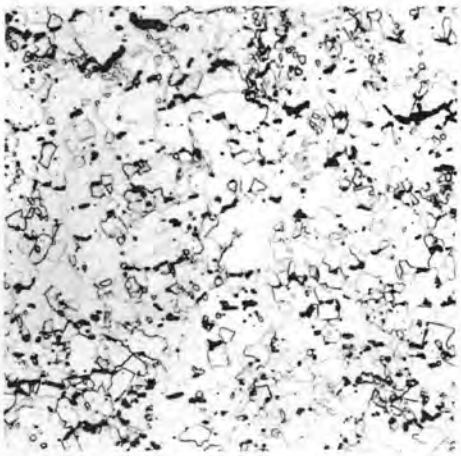
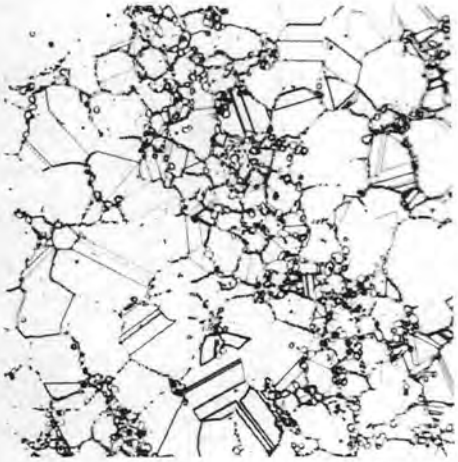


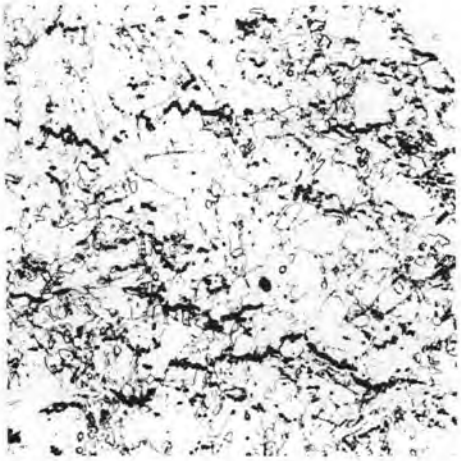
2000°F, 1/2 hr. A. C., 1850°F
1/2 hr. O. Q., 16 hrs. 1500°F
Code 52



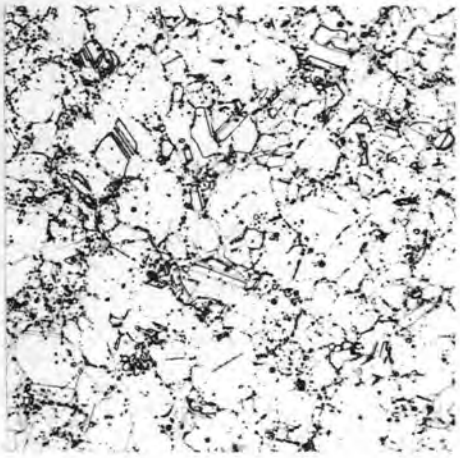
1350°F, 20,000 psi, 205 hrs.
Code 52



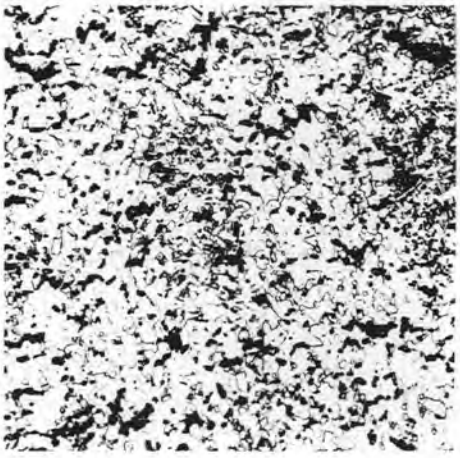
2000°F, 1/2 hr., A. C. 1850°F
1/2 hr. A. C., Code 51



1350°F, 30,000 psi, 97 hrs.
Code 51



2000°F, 1/2 hr. A. C., Code 5



1350°F, 15,000 psi, 190 hrs. Code 5

Figure 15. Photomicrographs of 36.0% Mo alloy, etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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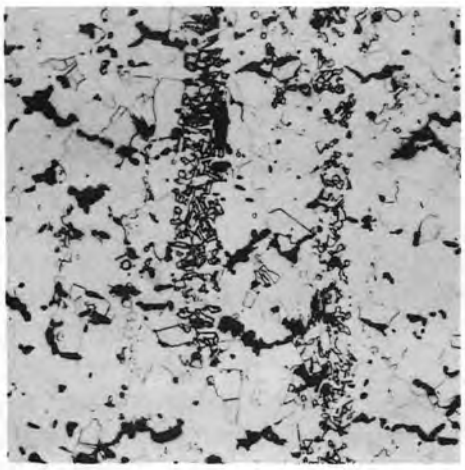
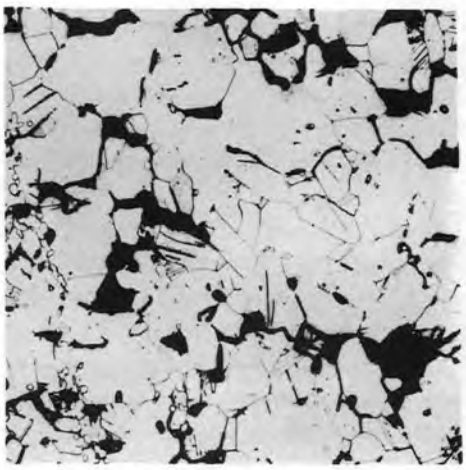
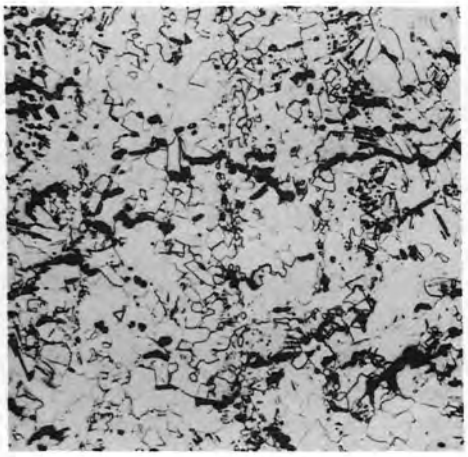


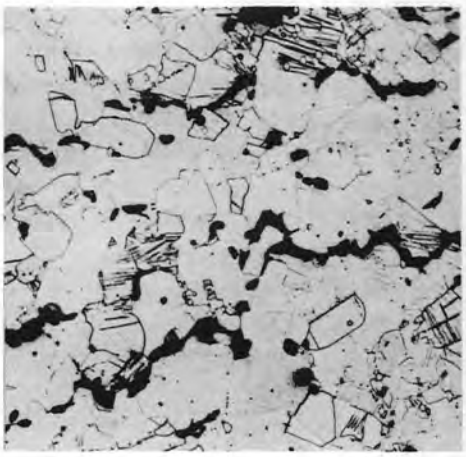
1500°F, 12,000 psi, 138 hrs.
Code 52



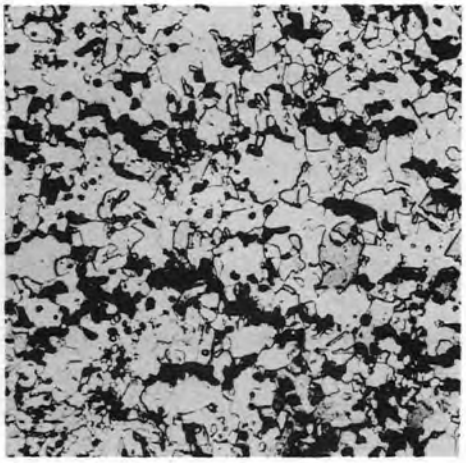
1650°F, 3,500 psi, 269 hrs.
Code 52



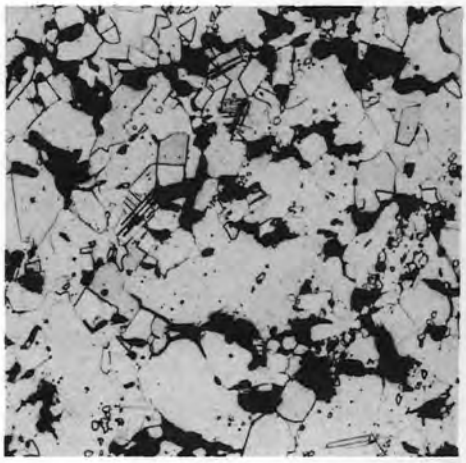
1500°F, 15,000 psi, 111 hrs.
Code 51



1650°F, 6,000 psi, 201 hrs.
Code 51



1500°F, 10,000 psi, 119 hrs.
Code 5



1650°F, 4,000 psi, 105 hrs.
Code 5

Fig. 15. (continued)

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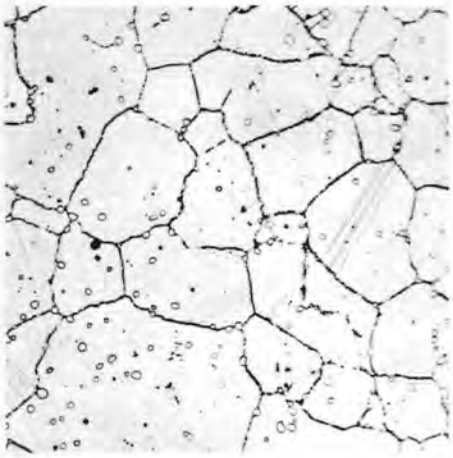
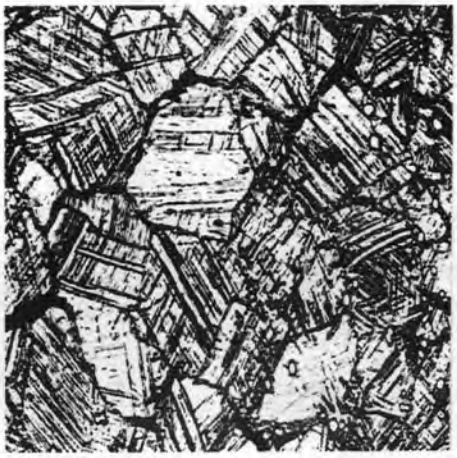
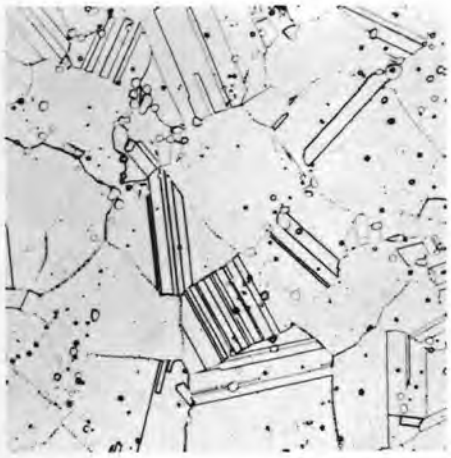


2000°F, 1/2 hr. A. C., 1850°F
1/2 hr. O. Q., 16 hrs, 1500°F
Code 62

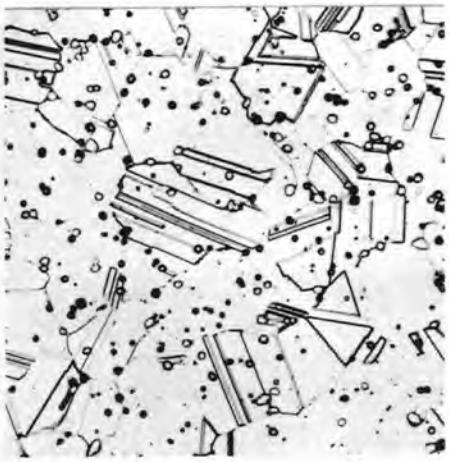


1350°F, 30,000 psi, 149 hrs.
Code 62



2000°F, 1/2 hr. A. C., 1850°F
1/2 hr. A. C. Code 61

1350°F, 30,000 psi, 136 hrs.
Code 61



2000°F, 1/2 hr. A. C. Code 6

1350°F, 30,000 psi, 121 hrs. Code 6

Figure 16. Photomicrographs of Hastelloy B, etched with 1/3 HCl, 1/3 HNO_3, 1/3 H_2O. 250X.

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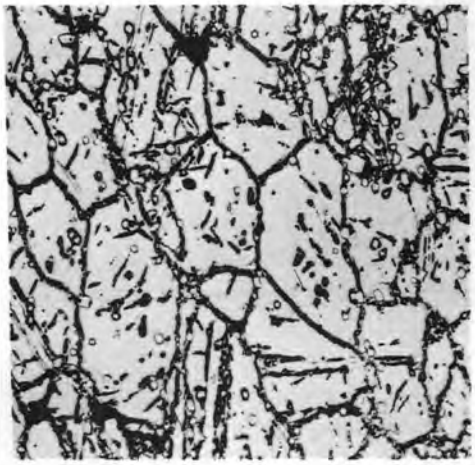
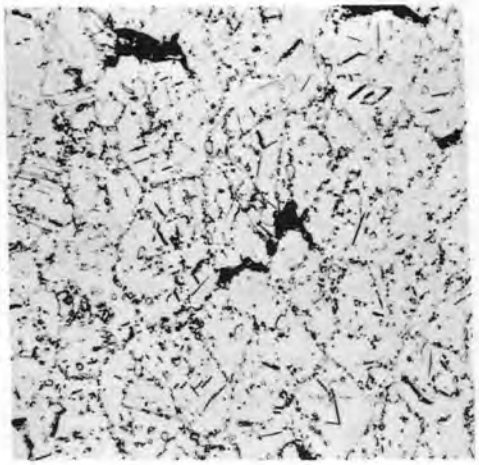
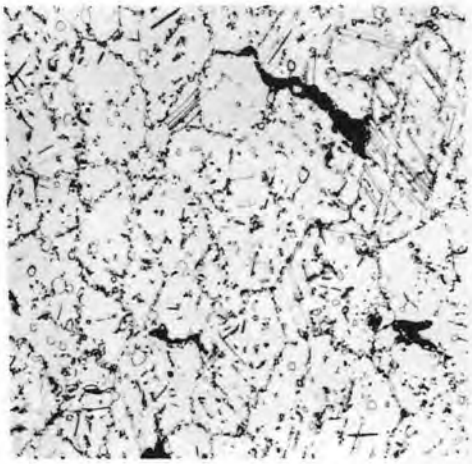


1500°F, 15,000 psi, 179 hrs.
Code 62

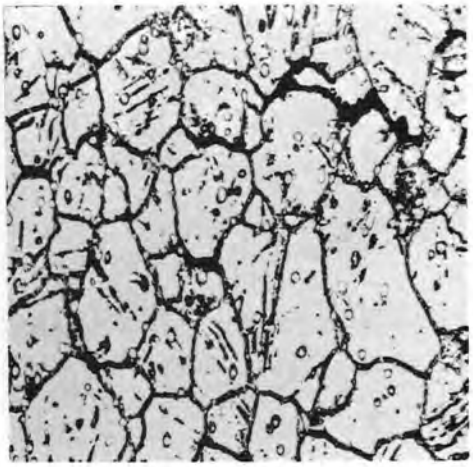


1650°F, 8,000 psi, 189 hrs.
Code 62

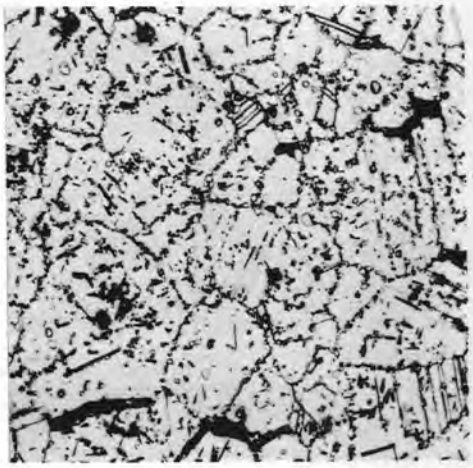
1500°F, 15,000 psi, 223 hrs.
Code 61



1650°F, 8,000 psi, 184 hrs.
Code 61



1500°F, 17,000 psi, 127 hrs.
Code 6



1650°F, 7,000 psi, 263 hrs.
Code 6

Fig. 16. (continued)

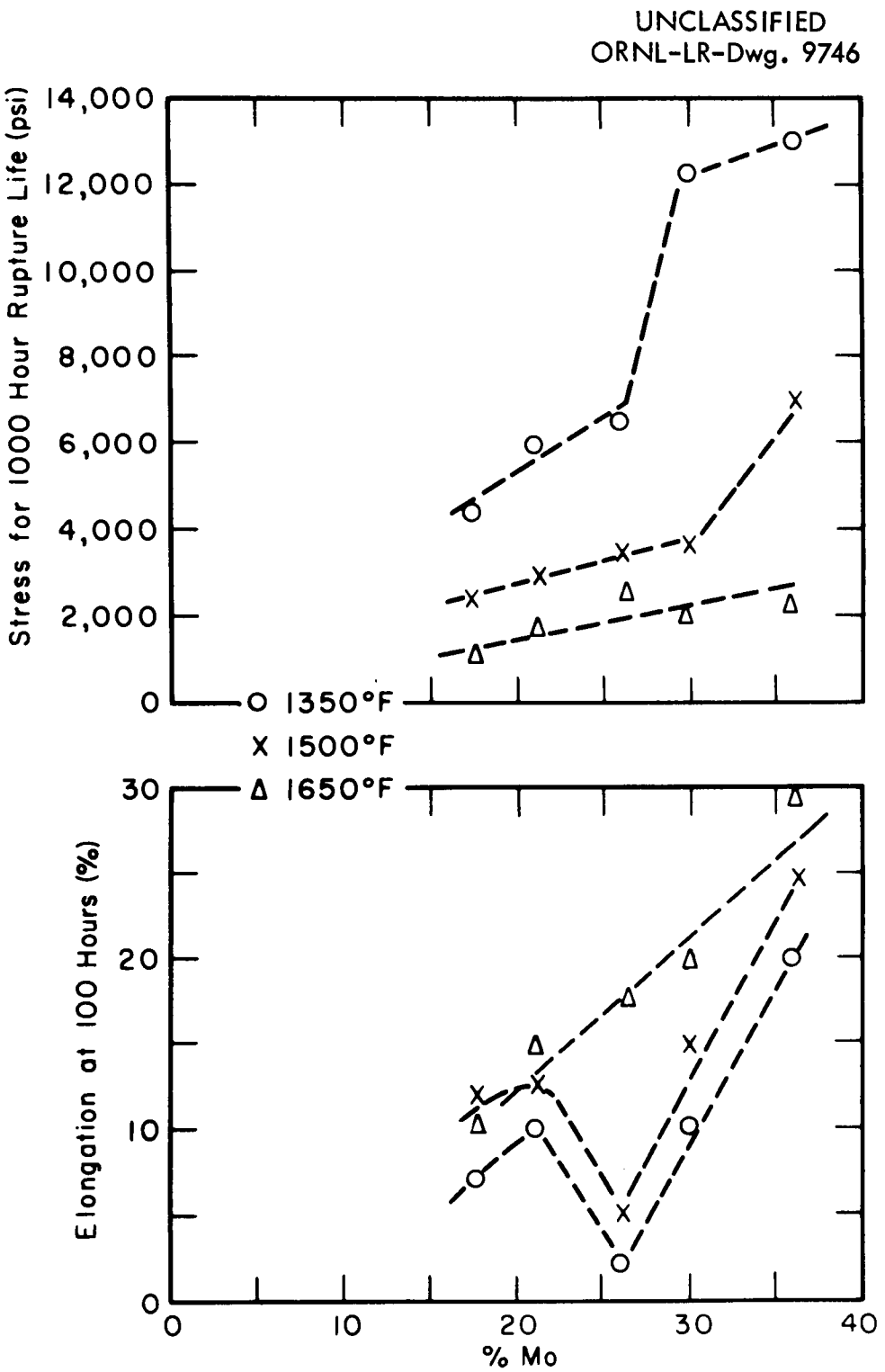


FIGURE 17 – HIGH TEMPERATURE STRENGTH AND DUCTILITY AS A FUNCTION OF COMPOSITION

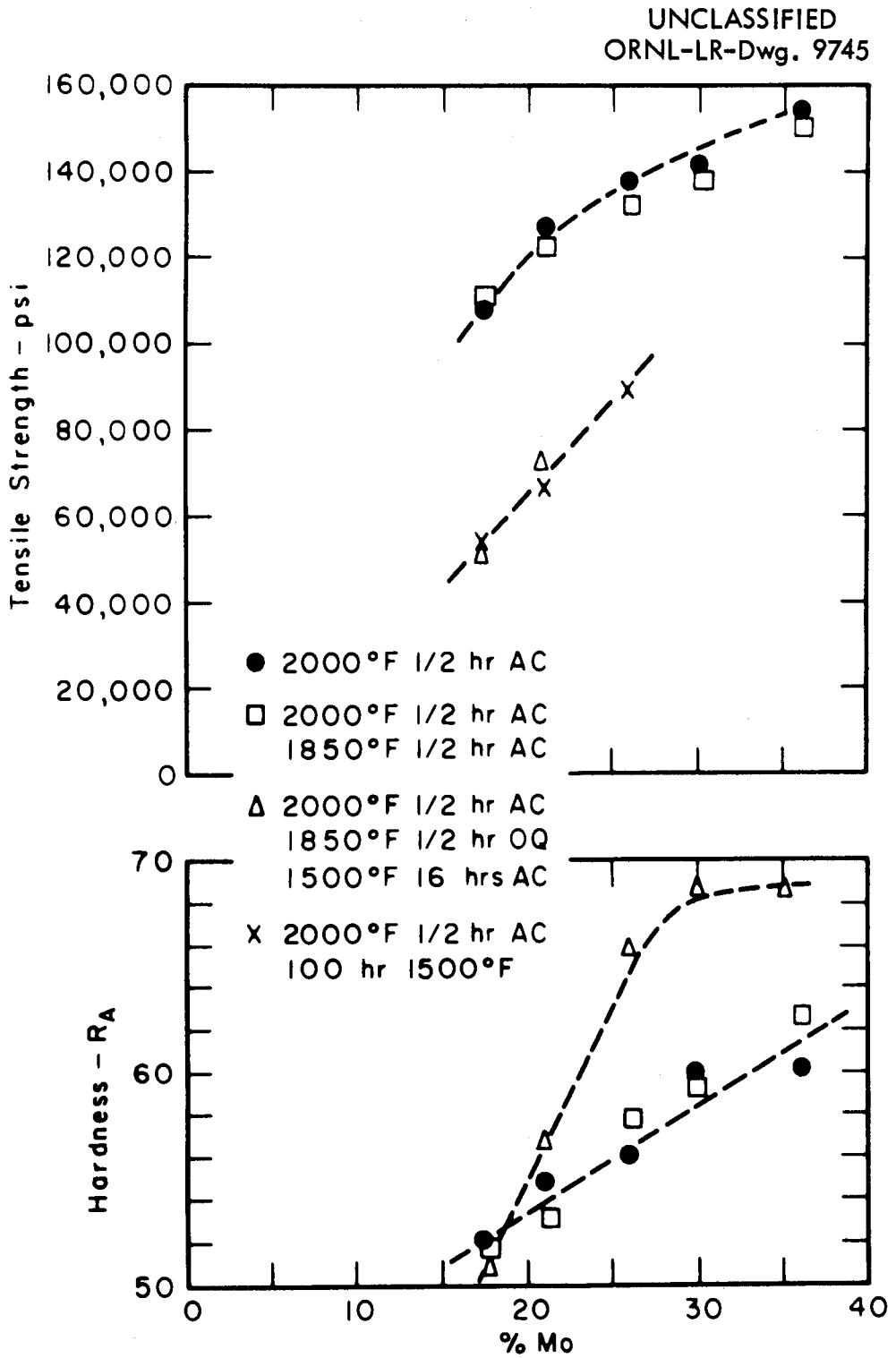


FIGURE 18 - TENSILE STRENGTH AND HARDNESS AS A FUNCTION OF COMPOSITION