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ELEVATED TEMPERATURE PROPERTIES OF Fe-Mo-B ALLOYS AND TYPE 434 STEEL

by

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A research program sponsored by the Climax Molybdenum Company of Michigan has been conducted at the University of Michigan. This program had as its objective the determination of the creep-rupture properties of several alloys out to times well in excess of 1000 hours. The materials investigated included Type 434 ferritic stainless steel and several Fe-Mo-B alloys.

The rupture properties of Type 434 (17Cr-1Mo) steel were evaluated at 900°, 1050° and 1200°F. The Fe-Mo-B alloys were divided into two types, cobalt-free alloys which were tested at 900°F, and complex alloys which were tested at 1200°F.

CONCLUSIONS

The rupture strength of the 17Cr-1Mo ferritic steel (Type 434) at 1200°F was similar to that of Type 430 (17Cr) steel At 900°F the 17Cr-1Mo alloy underwent an aging reaction during testing which significantly strengthened it. There is little doubt that this strengthening is associated with the so-called 475°C (885°F) embrittlement which can occur in high chromium ferritic steels.

The Fe-Mo-B alloys showed significant differences in level of strength with chemical composition. The compositional variations, however, were too numerous to allow the complete separation of the influence of the individual elements. In the cobalt-free Fe-Mo-B alloys, the high aluminum material had the most promising long time properties. In the complex alloys the highest levels of long time strength properties were obtained in vanadium-free alloys containing 5.7 percent cobalt.

EXPERIMENTAL MATERIAL AND PROGRAM

Two types of alloy were used in this investigation. The first alloy was Type 434 stainless steel. This material is classified as a ferritic stainless steel having a nominal composition of 17 percent chromium and 1 percent molybdenum, balance iron. Rupture tests on specimens from two different heats of the steel were conducted at 900°, 1050° and 1200°F. The machined specimens were received from the project sponsor.

The second class of alloys tested in this program were Fe-Mo-B materials. The reported chemical compositions of these materials were as follows:

Heat	Mo	Ni	Co	Zr	B	Al	C	V	Fe
170-3	4.8	2.2	2.0	.05	.015	.07	-	-	Bal.
170-4	4.8	2.2	5.7	.05	.015	.07	-	-	Bal.
170-5	4.8	2.2	5.7	.05	.048	.07	-	-	Bal.
170-6	4.8	2.2	5.7	.05	.048	.07	.05	0.40	Bal.
166-2	1.0	2.2	-	-	.015	.07	-	-	Bal.
166-4	1.0	3.0	-	.05	.015	.07	-	-	Bal.
166-6	1.0	3.0	-	.05	.015	1.50	-	-	Bal.
168A	1.0	0.5	-	-	.01	.07	-	0.1	Bal.
168B	1.0	1.0	-	-	.01	.07	-	0.1	Bal.
168C	1.0	1.5	-	-	.01	.07	-	0.1	Bal.
168D	1.0	2.0	-	-	.01	.07	.05	0.4	Bal.

The above tabulation separates the alloys into two groups by their compositional complexity. Creep-rupture tests were conducted on specimens from the first group at 1200°F. The test specimens were furnished by the sponsor. Screening tests were used to select the three most promising alloys from the second group of Fe-Mo-B materials. These three alloys were rupture tested at 900°F.

RESULTS AND DISCUSSION

Type 434 Steel

At the beginning of this investigation it was not recognized that high chromium steels could undergo a transformation in the region of 900°F. This transformation has been referred to in the literature as 475°C (885°F) embrittlement (Ref. 1). Aging at temperatures in the vicinity of 885°F has been shown to significantly increase the room temperature tensile strength of high chromium steels and simultaneously drastically reduce their ductility at ambient temperatures (Refs. 1, 2, 3). The exact nature of the transformation or aging reaction has not been established.

With this background in mind the results obtained on the Type 434 steel specimens are more readily understood. The results are shown in Table I. The 1050° and 1200°F rupture data follow expected trends with the exception of the 13,500 psi test at 1050°F which fractured in a very short time (Fig. 1). The results obtained at 900°F, however, were quite startling until it was recognized that the so-called 475°C embrittlement could occur. The rupture tests which were completed at this temperature were conducted under sufficiently high stresses to cause rupture in very short times (10 hours or less). It is assumed that in these cases the embrittling transformation had not progressed sufficiently far to strengthen the alloy before rupture occurred. If some critical amount of time at 900°F did pass then the transformation so enhanced the strength of the steel as to result in extremely long although undetermined rupture times.

The magnitude of the strengthening reaction can be emphasized by examination of the results obtained from specimen 434-10 (Table I). This specimen deformed approximately 11 percent on initial loading and during the first three days of the test. After this time, however, no significant creep was measured for the duration of the test (approximately 2600 hours).

Specimen 434-1 was tensile tested at 900°F after being exposed to different stresses ranging from 30,000 psi to 43,000 psi, for a total time of approximately 4000 hours. The complete history of this specimen is shown in Table II. The ultimate tensile strength of the specimen after the prolonged stressed exposure was 90, 500 psi as compared to the sponsor's reported ultimate strength at 900°F of 43, 800 psi. This specimen after tensile testing is shown in Figure 2a. The striking features of the structure were the numerous twins which formed in the sample. These twins were most pronounced near the fracture. There were, however, a number of twins in the threaded section of the specimen. In order to determine whether these twins formed during the stressed exposure or the tensile testing a second specimen (434-10) was examined. This specimen had been interrupted after exposure for 2690 hours at 900°F under a stress of 41, 000 psi. The microstructure of this specimen did not show any evidence of significant twinning (Fig. 2b). It is therefore assumed that the twinning formed during the tensile test. It is further assumed that it occurred as a result of the embrittling transformation (Ref. 3).

The microstructure of this steel shows the presence of numerous rod-shaped inclusions (Figs. 2a and 2b). These inclusions are very probably amorphous. It is considered unlikely that these particles contributed significantly to the strength of the steel.

No attempt had been made to estimate the rupture strength of this steel at 900°F. The reason for the scatter in the 1050°F data has not been determined and as a consequence no estimate of the rupture strength has been made at this temperature. At 1200°F, however, the rupture properties of Type 434 steel can be summed up as follows:

Stress for rupture in:		
50 hours	500 hours	1000 hours
7600 psi	5500 psi	5000 psi

These strengths are approximately the same as those reported for Type 430 steel (17Cr) in Reference 4.

Fe-Mo-B Alloys

Cobalt-Free Materials

The cobalt-free Fe-Mo-B alloys were rupture tested at 900°F, except for one heat (166-2) which was included with the complex alloys tested at 1200°F. A preliminary rupture test was run on each of the six heats of varying chemical composition to determine which of the experimental alloys had the most promising properties. Three heatswere selected and these materials were subjected to additional tests at 900°F. The results obtained from these tests and from the preliminary tests are reported in Table III. These data have been plotted in the form of stress-rupture time curves, which are shown in Figure 3.

The comparative rupture strengths of the alloys are shown in the following tabulation:

	Stress (psi) for rupture at 900°F		
Heat	50 hours	500 hours	2000 hours
166-6	59,000	56,000	56,000
168C	56,000	49,500	46,000
168D	114,000	81,000	66,000

This tabulation shows that the short time rupture strength of Heat 168D was the highest of the three heats. The strength of this heat, however, fell off very rapidly at the longer rupture times. This is very apparent in Figure 3, which shows the slope of the stress-rupture time curve to be steep. It is probable that the excellent short time strength of this heat, its poor rupture ductility (Table III) and its high degree of instability are related to the higher vanadium content of the alloy.

The alloy with the best long time properties was Heat 166-6. This heat had a very flat stress-rupture time curve (Fig. 3) and an apparent high degree of rupture ductility. Two rupture tests were discontinued after times of 1950 and 3430 hours because of the lack of any indication of impending failure.

Minimum creep rates were measured during the tests. These have been plotted as a function of stress in Figure 4. The minimum creep rates measured on the two discontinued specimens from Heat 166-6 were very low, approaching the limits of detectability. These low rates are probably the result of a structural change in the alloy. These rates are much lower than would be expected at such high stresses.

Complex Materials

Five Fe-Mo-B alloys were creep-rupture tested at 1200°F. Three specimens from each heat were tested with the results shown in Table IV. Stress versus rupture time graphs of the data are plotted in Figure 5.

Four of the five heats had rupture curves of approximately equal slope. The rupture curve exhibited by the fifth alloy Heat 166-2, had a much steeper slope, indicating an unstable composition. The minimum creep rate data, plotted as a function of stress in Figure 6, show the same trends as the rupture data. The slopes of the curves of Figure 6 are approximately equal for four of the alloys with the line through the data from Heat 166-2 having a much steeper slope.

The rupture data from these five materials have been evaluated in terms of stress for rupture in specific times at 1200°F. The time periods selected were 10, 100 and 1000 hours. The results are as follows:

	Stress (psi) for rupture at 1200°F		
Heat	10 hours	100 hours	1000 hours
170-3	24,700	17,600	12,800
170-4	31,000	22,000	15,500
170-5	30,500	22 000	16,000
170-6	23,000	15,300	10,200
166-2	19,000	6,900	2,500

This tabulation shows Heats 170-4 and 170-5 to have almost equivalent rupture strengths. Examination of Figure 6 shows their minimum creep rate behavior to also be very similar. The only aim compositional difference in the alloys was in boron level. This indicates that boron variations in the range from 150 to 480 ppm had only a minor effect on creep or rupture properties at 1200°F.

In the complex Fe-Mo-B alloys higher vanadium content (0.4%) was associated with reduced rupture strength just as was observed in the cobalt-free alloys. A reduction of cobalt level from 5.7 to 2.0 percent also resulted in reduced rupture strength in the complex alloys (compare results from Heat 170-4 with results from Heat 170-3). The alloy with the weakest properties at 1200°F also had the leanest composition (Heat 166-2). It is quite evident that the absence of cobalt resulted in reduced rupture strength and also reduced rupture ductility.

REFERENCES

1. Lena, A. J., Hawkes, M. F.: 475°C (885°F) Embrittlement in Stainless Steels, Transactions AIME, May 1954, p. 607.

2. Fisher, R. M., Dulis, E. J., and Carroll, K. G.: Identification of the Precipitate Accompanying 885°F Embrittlement in Chromium Steels, Transactions AIME, May 1953, p. 690.

3. Blackburn, M. J., Nutting, J.: Metallography of an Iron-21% Chromium Alloy Subjected to 475°C Embrittlement, Journal of the Iron and Steel Institute, July 1964, J 202 Part 7, p. 610.

4. Elevated Temperature Properties of Chromium Steels, ASTM Special Technical Publication No. 228, p. 95.

TABLE I

RUPTURE TEST RESULTS FROM TYPE 434 FERRITIC STAINLESS STEEL

Specimen Code	Temp. °F	Stress psi	Rupture Time, Hours	Elong. %	R. A. %
Initial Heat					
434-2	900	35,000	>2594.5[a]	3.0	4.0
434-3	900	38,000	>1898.6[a]	7.0	8.0
434-10	900	41,000	>2690.2[a]	11.0	12.0
434-11	900	42,500	10.2	28.0	55.0
434-5	1050	19,000	59.7	58.0	70.5
434-4	1050	15,000	369.3	59.0	74.5
434-6	1050	13,500	114.9	42.0	73.5
434-9	1200	9,000	16.3±4.5	76.0	83.0
434-7	1200	7,000	102.2	71.0	82.0
434-8	1200	5,000	1001.7	68.0	81.5
Heat 32708					
2	900	52,500	0.08	25.0	58.5
3	900	48,000	1.1	32.0	61.5
4	900	40,000	> 578.3[a]	1.0	0.8
5	900	45,000	4.5	36.0	53.5

a - Test discontinued

TABLE II

EXPOSURE HISTORY OF SPECIMEN 434-1 AT 900°F

Stress (psi)	Time at Stress (hours)	Comment
30,000	2038.5	Cooled under load
35,000	165	Test restarted, after 165 hours stress raised
38,000	387	Stress then raised
41,000	553	Stress then raised
41,500	233	Stress then raised
42,000	342	Stress then raised
43,000	403	Test discontinued, cooled under load

Specimen tensile tested at 900°F

Ultimate Tensile Strength	90,500 psi
0.2 percent Offset Yield Strength	73,500 psi
Elongation	20%
Reduction of Area	35.5%

TABLE III

CREEP-RUPTURE RESULTS AT 900°F FROM COBALT-FREE Fe-Mo-B ALLOYS

Specimen Code	Stress psi	Rupture Time, hours	Elong. %	R. A. %	Min. Creep Rate (%/hr.)
168A	53,000	5.4	20.0	83.8	-
168B	59,000	0.4	21.0	79.5	-
166-4	57,000	25.5	21.0	73.0	-
168C	56,000	54.7	20.0	82.0	-
168C-1	50,000	400.2	16.0	76.0	0.0013
168C-2	45,500	2372.9	12.0	44.0	0.000224
168D	90,000	> 223	(Failed in threaded section)		
168D-2	100,000	123.4	2.5	6.5	0.0022
168D-3	95,000	158.3	1.0	2.0	0.00197
168D-4	75,000	1083.7	1.0	3.5	0.00029
168D-5	70,000	1077.2	2.0	1.0	0.00018
166-6B	59,000	76.9	25.0	74.0	0.0606
166-6C	55,000	>3434.2	(Discontinued)		0.00001
166-6D	57 000	94.4	18.0	73.0	0.0359
166-6E	56,000	>1950.3	(Discontinued)		0.000012

TABLE IV

CREEP-RUPTURE RESULTS AT 1200°F FROM COMPLEX Fe-Mo-B ALLOYS

Specimen Code	Stress psi	Rupture Time, hours	Elong. %	R. A. %	Min. Creep Rate (%/hr.)
170-3A	21,000	32.2	56	86	0.47
170-3B	17,000	112.3	43	89	0.0882
170-3C	12,000	1661.7	39	90	0.00286
170-4A	26,000	34.5	37	82	0.31
170-4B	22,000	26.6	48	88.5	0.49
170-4C	15,000	1242.6	55	85	0.0027
170-5A	26,000	24.4	61	84	0.57
170-5B	22,000	106.0	55	89	0.074
170-5C	17,000	692.8	38	85.5	0.00547
170-6A	29,000	2.8	53	81	5.775
170-6B	22,000	13.0	57	84	1.42
170-6C	11,000	677.5	83	86	0.017
166-2A	16,000	14.3	10	10.3	0.23
166-2B	12,000	26.4	8.5	6.5	0.059
166-2C	9,000	53.4	6	6.2	0.020

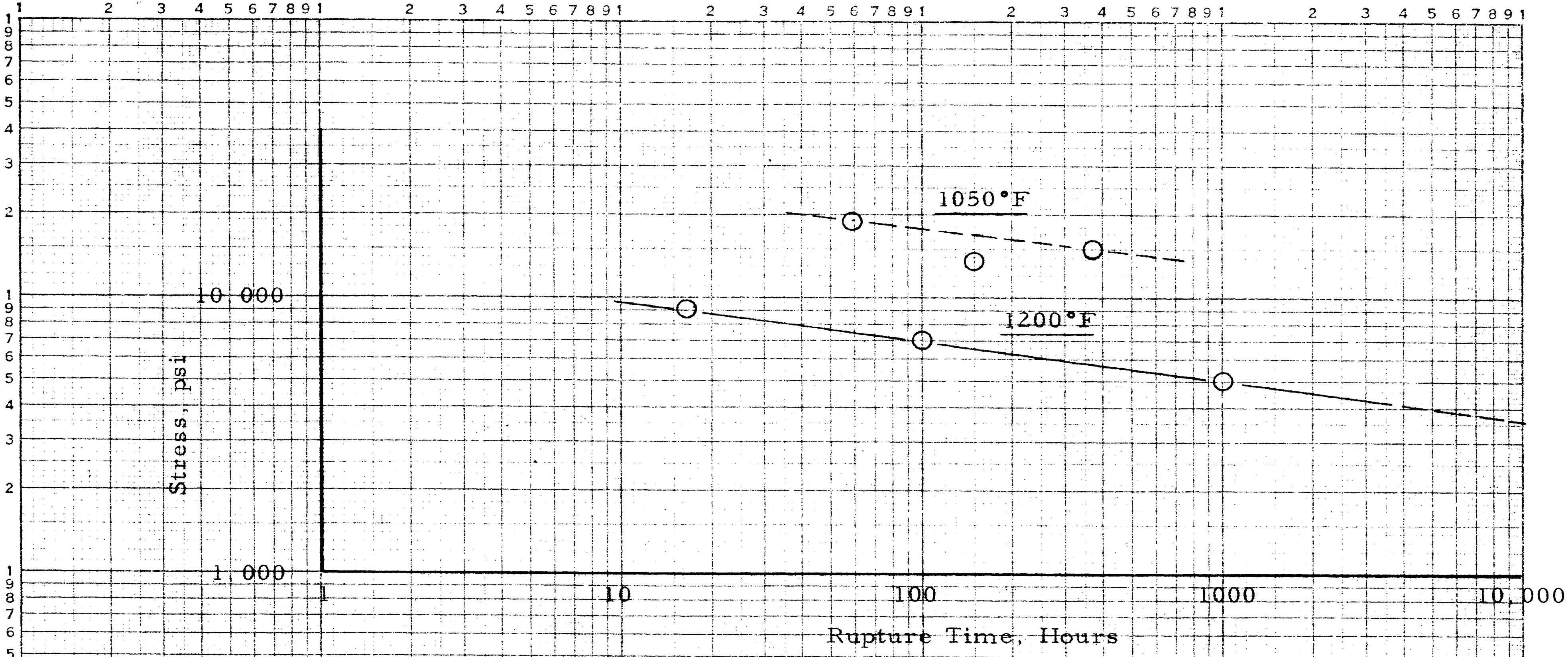

Figure 1. Stress-rupture time behavior at 1050° and 1200°F of Type 434 ferritic stainless steel.

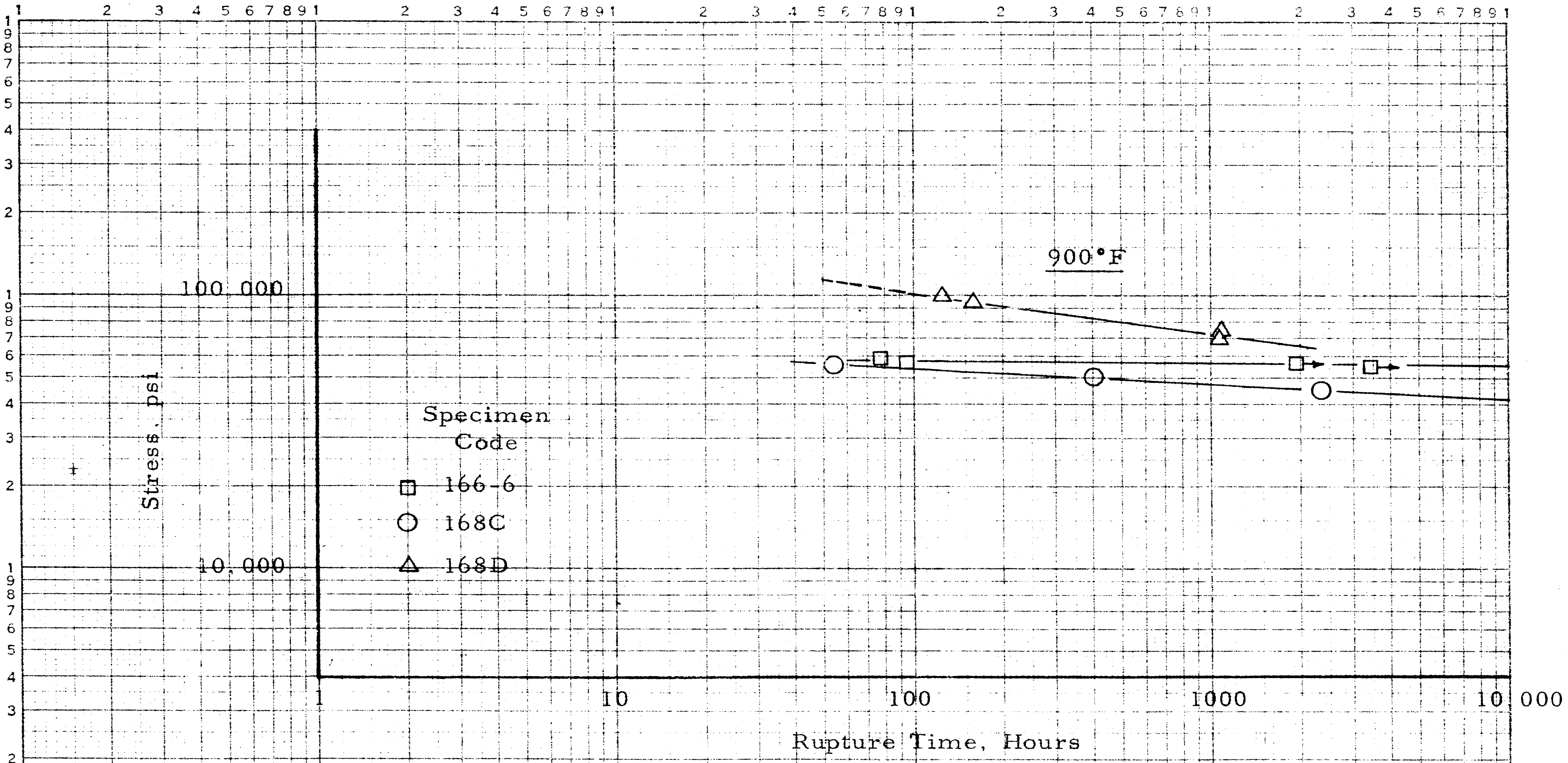

Figure 3. Stress-rupture time behavior at 900°F of simple Fe-Mo-B Alloys.

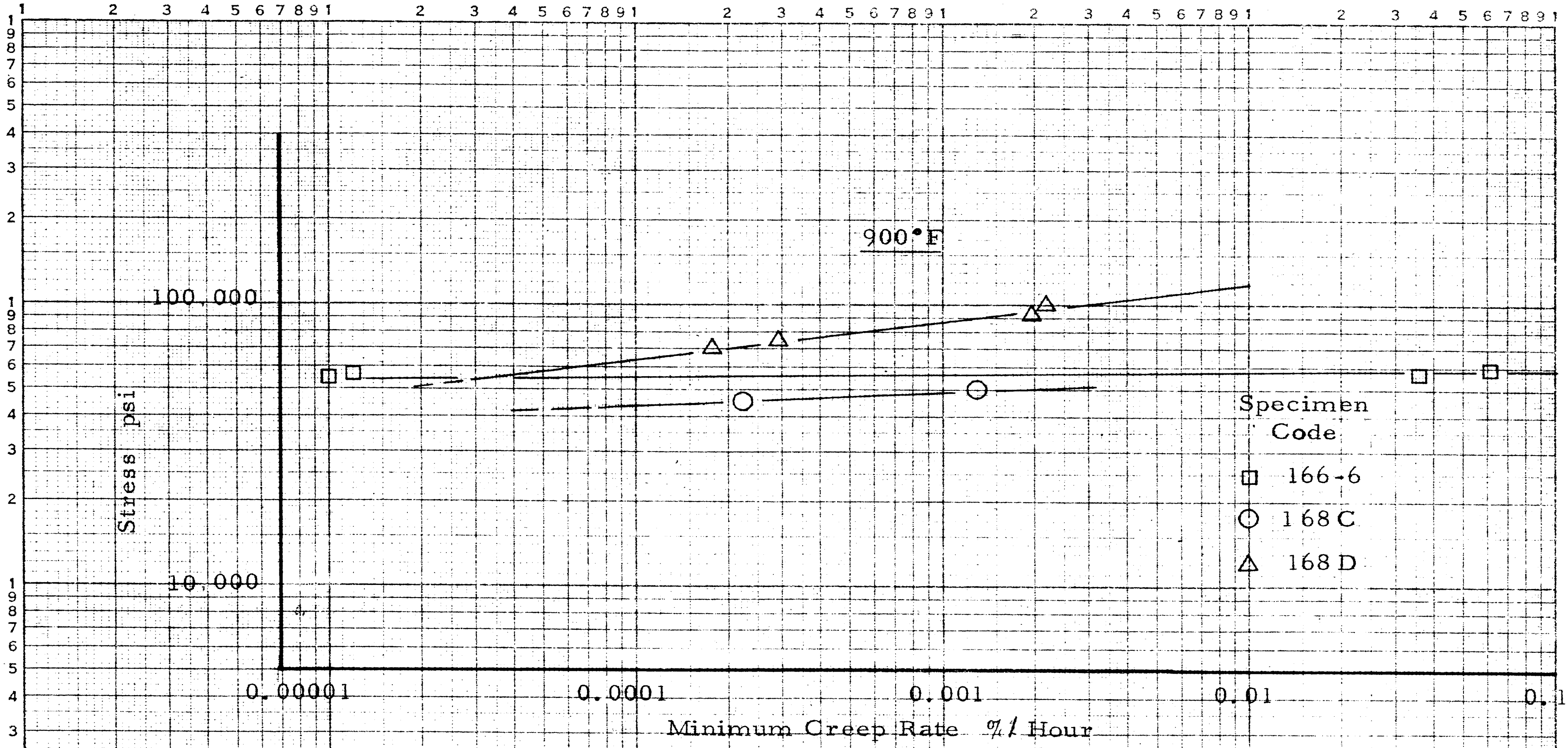

Figure 4. Stress-Minimum Creep Rate behavior at 900°F of simple Fe-Mo-B Alloys.

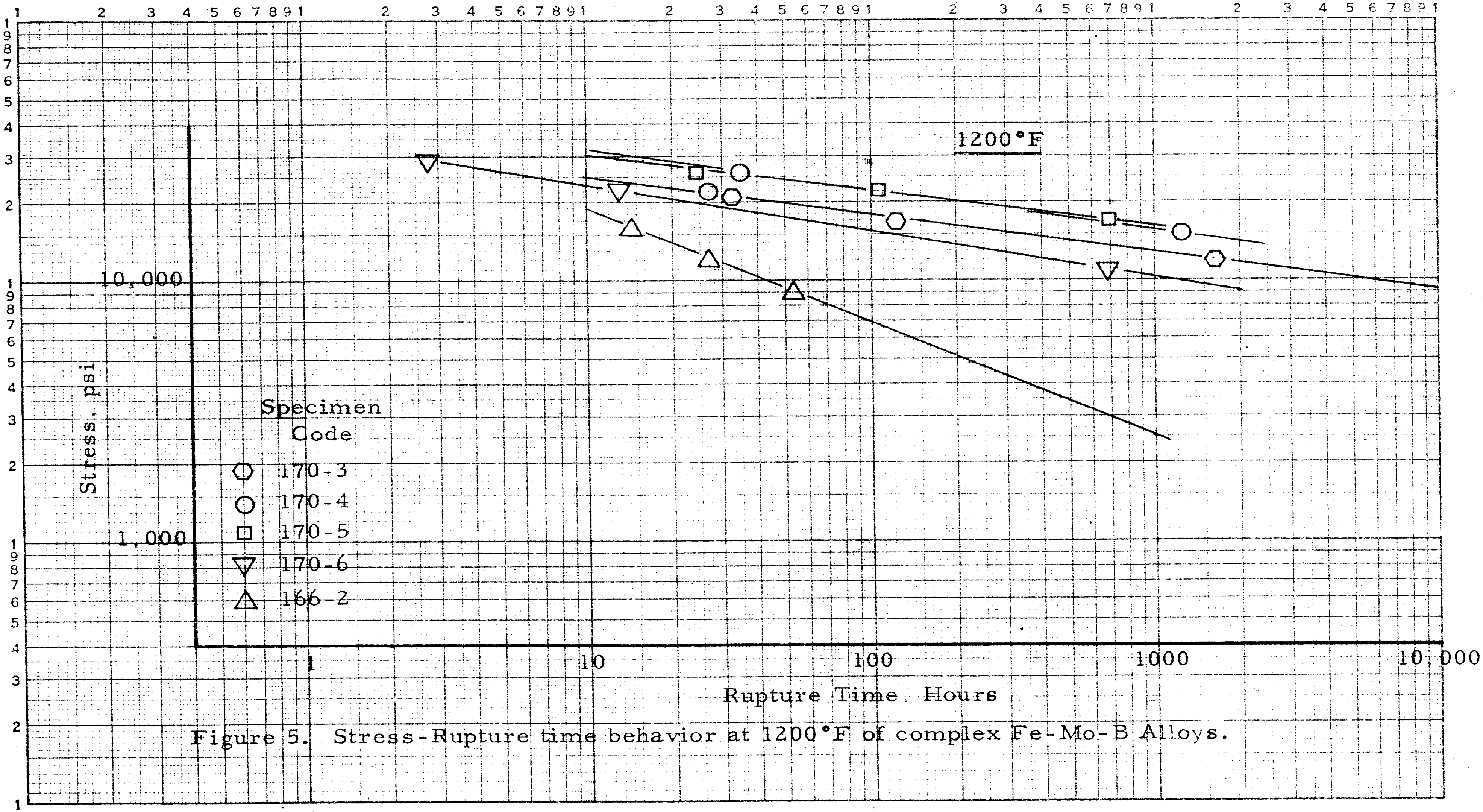

Figure 5. Stress-Rupture time behavior at 1200°F of complex Fe-Mo-B Alloys.

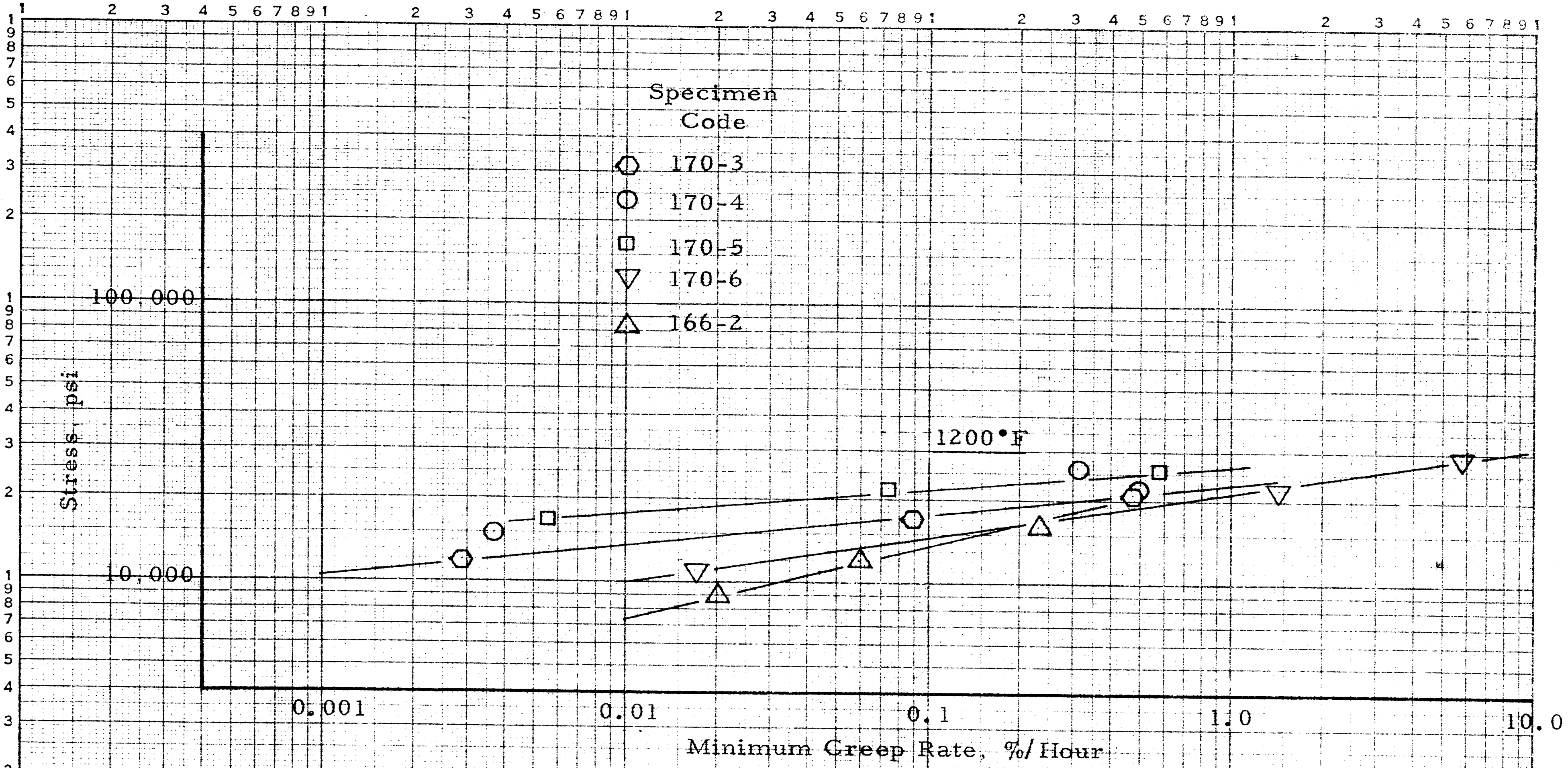

Figure 6. Stress-Minimum Creep Rate behavior at 1200°F of complex Fe-Mo-B Alloys.