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ABSTRACT

The purpose of this investigation was to fill several gaps in the literature on high-heating-rate properties of several commonly used aerospace, structural materials. High-heating-rate results were obtained for three low-alloy steels: 4340 (400°F temper), 4130 (800°F temper), and 4130 (1050°F temper) and two stainless steels: 17-7 PH (TH 1050) and 410 (700°F temper). Stress levels ranging from 10 to 125 ksi and heating rates varying from 40 to 2000°F/sec. were the testing parameters. A method is devised to compare yield temperature data of high-heating-rate tests to tensile yield data of steady-state elevated temperature tests.

Results indicate that high-heating-rate properties of all the materials are superior to steady-state elevated temperature properties for heating rates of 40 to 2000°F/sec. For the low alloy steels, the higher the tempering temperature, the better the high-heating-rate properties. Properties of 410 stainless steel are superior to those of all other materials investigated.

I. INTRODUCTION

The transient temperature conditions encountered by many missile structural components are such that it is necessary to have material design data for extreme cases. It has been shown (Ref. 1-9) that the yield and ultimate strengths of materials under high-heating-rate conditions are, in general, higher than those obtained from steady-state, high-temperature tensile tests. Thus, to obtain full capability of the structural components, it is necessary to know the strength of the materials used under the heating rates encountered.

A survey of the literature was made, and it was determined that there was a lack of information for commonly used structural materials at heating rates encountered in rocket motor cases or nozzles or in aerodynamic heating of ballistic missiles. The short-time elevated temperature properties were of little value, and the extremely high-heating-rate properties of the not commonly-used materials were also of little value. Therefore, the present coordinated program was undertaken.

II. MATERIALS AND SPECIMENS

For this investigation a 0.130-in.-thick sheet of 4340 steel and 0.063-in.-thick sheets of 4130 steel, 17-7 PH stainless steel, and 410 stainless steel were used. All high-heating-rate and tensile specimens (see Fig. 1) were machined from the same heat of each material. The chemical composition from the manufacturer's test report is shown for each material in Table 1. All heat treatments as shown in Table 2 are standard specifications except for the 4340 which had a low tempering temperature of 400°F. This, along with the two tempering temperatures for 4130, was expected to give a strength range of about 130 to 260 ksi over which high-heating-rate properties of low alloy steel could be evaluated.

III. EXPERIMENTAL TEST EQUIPMENT AND PROCEDURES

Tensile testing at steady-state elevated temperatures utilized a universal testing machine and a 2000°F furnace with related equipment as shown in Fig. 2. The furnace was calibrated to give temperature uniformity of ±5°F over the specimen gage length for temperatures from 600 to 1800°F. For a test run, the specimens were pulled at a strain rate of approximately 0.004 min^{-1} to slightly past the yield point and then at a crosshead speed of 0.1 in./min to fracture.

The equipment for the high-heating-rate tests was comprised of a 50-Kva transformer with ignitron pulser for self-resistance heating of the specimen, a temperature-control programmer to insure constant heating rates, a 20,000-lb modified creep tester, a clamp-on extensometer, and a direct read-out oscillograph for recording the temperature and deformation of the specimen. A complete layout of the equipment is shown in Fig. 3.

Heating-rates up to 500°F/sec were obtained with the programmer unit; rates higher than 500°F/sec were obtained manually. The linearity of the programmed heating rates were found to vary about ±7% over the entire temperature range. Somewhat larger variation was encountered for the manual runs at the beginning and end of the run. For the test parameters of this investigation, the maximum thermal gradient was less than 5% of the average temperature at any particular time during the test.

The clamp-on extensometer utilized a linear potentiometer with a 20:1 lever arm as shown in Fig. 4. Thermal transients were reduced by using sapphire gage points and an aluminum radiation shield. Calibration indicated the extensometer system had an accuracy of about ±2.0% of the measured strain at all temperatures.

Test procedures for the high-heating-rate tests consisted of dead-weight loading the specimen and then resistance-heating it using a programmed or manual temperature control. Outputs from a spot-welded 5-mil, chromel-alumel thermocouple and the clamp-on extensometer were recorded on the oscillograph. As there was a limited range on the extensometer, the specimen was tested to slightly past the yield point. A resulting temperature-time, strain-time record is shown in Fig. 5.

Details of calibration experiments, equipment, and procedures for both tensile and high-heating-rate tests are given in the Appendix.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. 17-7 PH (TH1050) Stainless Steel

Results of the steady-state high-temperature tensile tests are given in Table 3. The elongation and reduction of area values indicate there is an embrittling effect at 400 and 600°F. Typical stress-strain curves for this alloy are shown in Fig. 6 for various temperatures from 80 to 1200°F. A summary graph of ultimate, yield, and modulus data is given for all temperatures in Fig. 7. All three parameters decrease at about the same rate with increasing temperature. Also indicated in Fig. 7 is the fact that after the embrittling range of 600°F, both the tensile and 0.2% offset yield strengths fall off rapidly. High-heating-rate results are given in Table 4 for four heating rates at each of four stress levels. The 0.2% offset yield temperatures are obtained by experimentally determining the thermal expansion over the entire temperature range. To this was added an elastic strain which was obtained from the applied stress and the modulus at each particular temperature. Thus a strain curve is calculated from

$$\epsilon_{T_n} = (\text{T.E.})_{T_n} + \frac{\sigma}{E_{T_n}}, \qquad n = 70, \cdots, 1400°\text{F}$$

where ϵ is the total nonplastic strain, T.E. is the thermal expansion, σ is the applied stress, E is the modulus of elasticity, and T_n is a particular temperature. For an actual test, the strain deviates from the calculated line as it becomes plastic. The yield temperature is defined as the point at which a 0.2% offset line drawn parallel to the calculated line intersects with the experimental curve. This method of determining the yield temperatures is shown in Fig. 8 for all heating rates at the 20.7 ksi stress level. To compare with the high-heating-rate data, yield temperatures and pseudo-heating rates were calculated from the tensile data as follows: For a particular stress level, the temperature at which the yield strength occurs is found from Fig. 7. For this yield temperature, the strain at yielding is determined from Fig. 6. Knowing the strain rate to be 0.004 min^{-1} allows the time to the yield point to be calculated. Dividing the yield temperature by this time gives a pseudo-heating rate. Similar calculations for all materials and stress levels are given in Table 5.

A semi-log plot of yield temperature versus log heating-rate is shown in Fig. 9. For this material, the high-heating-rate data extrapolate very well to the yield temperatures determined from the elevated temperature tensile tests. For comparison purposes, data from Ref. 9 for the same material and heat treatment are also shown in Fig. 9. These data which ran from 1 to 100°F/sec bracketed the pseudo-heating rates calculated from their tensile data. Here again, the high-heating-rate yield temperatures were in close agreement with the tensile test yield temperatures. The reason their pseudo-heating rates were shifted to the left in Fig. 9 is that the strain rate of 0.002 min^{-1} reported in Ref. 9 was half that of this investigation. Considering the differences in material composition and test procedures, the observed differences are not large.

B. 4340 Steel

This material was the only one using 0.130-in. thick specimens as the others were all 0.063-in. thick. A summary of all tensile test data covering a temperature range of 75 to 1200°F is given in Table 6. Here, the elongation and reduction of area values indicate no embrittling effect at the test temperatures from 400 to 1200°F. Typical stress-strain curves and a summary graph of elastic modulus, ultimate strength, and yield strength are shown in Fig. 10 and 11. The data indicate that above the tempering temperature of 400°F the tensile strength drops very rapidly with increasing test temperature. The yield strength decreases at a less rapid rate at temperatures above room temperature. Table 7 gives all high-heating-rate results for four heating rates at each of four stress levels ranging from 10 to 60 ksi. These data are shown in a semi-log plot (Fig. 12) along with pseudo-heating rate data calculated in Table 5 from the tensile data. As before with the 17-7 PH, the yield temperatures of the high-heating-rate tests extrapolated quite well to the yield data of the tensile tests. The fastest heating rate of 1000°F/sec at the 60.5-ksi stress indicates only a slightly higher yield temperature (Fig. 12) than that determined from the tensile yield data that used a half-hour soak time. This suggests that any structural change at 950°F is practically complete in the 1-sec heating time to this yield temperature at the 60.5-ksi stress level

C. 4130 (800°F Temper) Steel

Results of the elevated-temperature tests are given in Table 8. Reduction of area data give no indication of any embrittling effects at the test temperatures between 500 and 1200°F. Typical stress-strain curves and modulus, yield strength, and ultimate strength data are shown in Fig. 13 and 14. There is an immediate fall-off in the tensile strength data above 500°F, but the yield strength data do not decrease as rapidly until 800°F is exceeded. Comparing the yield strength data of this material with that of 4340 indicates that below 900°F the 4340 is superior but above this temperature the 4130 with an 800°F temper is slightly better. All high-heating-rate data are given in Table 9 and replotted in Fig. 15 along with the pseudo-heating rate data calculated in Table 5. Here again the yield temperatures extrapolate fairly well to the tensile yield data although in this case a straight line extrapolation would be consistently higher. Comparing the high-heating-rate data of 4130 (800°F temper) to that of 4340 indicates that for all stress levels below 80 ksi, the yield temperatures of 4130 are superior to those of 4340 for any particular heating rate. Incidentally, these yield temperatures start at about 900°F which was the break-even temperature found from the tensile tests. These data suggest that the higher tempering temperature gives 4130 properties superior to 4340 above 900°F.

D. 4130 (1050°F Temper) Steel

Specimens were machined from the same heat of material that was used for the 800°F tempered 4130 steel. Tensile test results in Table 10 indicate no embrittling effects at the test temperatures between 400 and 1200°F. Typical stress-strain curves to just beyond the yield point are illustrated in Fig. 16. Yield and ultimate strength data in Fig. 17 do not drop off rapidly until 1000°F has been exceeded. Comparing the yield strength data of this material with the 800°F tempered 4130 reveals that the 1050°F tempered 4130 has superior strength above 900°F. High-heating-rate data for four stress levels at heating rates of 40 to 2000°F/sec are listed in Table 11. The yield temperature data versus heating rates are plotted in Fig. 18 along with the tensile yield data versus pseudo-heating rates. These data clearly demonstrate that this material has high-heating-rate properties markedly superior to the tensile yield properties. In this case, the high-heating-rate data do not extrapolate to the tensile yield data as before for the other three materials. From Fig. 15 and 18 it is seen that for all stress levels below 80 ksi, the 4130 with the higher tempering temperature has superior yield temperatures. These yield temperatures start at about 900°F which was the break-even temperature for the tensile yield strength data of these two heat treatments. This is very similar to the behavior observed when comparing the 4130 (800°F temper) to the 4340 alloy.

It can be seen from referring to Fig. 12, 15, and 18 that the 4340 high-heating-rate data extrapolate to the tensile yield data, the 4130 (800°F temper) data extrapolate to slightly above the tensile yield data, and the 4130 (1050°F temper) data extrapolate to considerably above the tensile yield data. This suggests the following for high-heating-rate tests of low-alloy steels: For low tempering temperatures, structural changes occurring above the tempering temperature at a particular yield temperature above 900°F are complete by the time this temperature is reached. These particular structural changes are not quite complete for tempering temperatures about equal to the yield temperatures. For high tempering temperatures, the original structure is sufficiently stable to give additional strengthening even at yield temperatures approaching 1300°F.

E. 410 Stainless Steel

A summary of all tensile test results is given in Table 12. Elongation and reduction of area data indicate an extreme embrittling effect at test temperatures from 600 to 1000°F. Several of the specimens at 1000°F were notch sensitive and broke at one of the gage points. Typical stress-strain curves and ultimate, yield, and modulus data are given in Fig. 19 and 20 for a temperature range of 75 to 1300°F. Several interesting results are seen in Fig. 20. First, the modulus of elasticity increases slightly between room temperature and 500°F. Similar behavior is observed for 410 stainless in Ref. 10. Secondly, both the yield and ultimate strengths increase in the temperature range of 500 to 750°F. It should be noted that the tempering temperature of this alloy was 700°F. The yield strength does not start to fall off rapidly until about 1000°F. This unusual tensile behavior is reflected in the high-heating-rate results given in Table 13. The data replotted in Fig. 21 along with the pseudo-heating rate data show that the high-heating-rate yield data extrapolate to a much higher temperature than the tensile yield data. Even though the room temperature yield strength is 133 ksi, all of the 126-ksi stress level high-heating-rate tests have yield temperature above 1100°F. Apparently some strengthening occurs when traversing the embrittling range of 600 to 1000°F. This is indicated by the strengthening that was observed in the tensile data. (See Fig. 20.) This mechanism is beneficial to the high-heating-rate results for stress levels greater than 20 ksi. For all heating-rates and stress levels investigated, the 410 stainless steel is superior to all other materials.

It should be cautioned here that such excellent properties of the 410 stainless might not be found at heating rates much less than the range covered. Also, the results presented here do not pertain to the type of heating cycle that heats rapidly to an elevated temperature, then holds at that temperature for a considerable length of time.

V. COMPARISON OF RESULTS

All of the materials of this investigation are compared as to the most severe and least severe conditions encountered during testing. As the lower heating rates gave lower yield temperatures, the most severe condition was the slowest heating rate and the highest stress level. Therefore, a 40°F/sec heating rate and an 82-ksi stress level were chosen. Actually, the most severe condition for several of the materials was 125 ksi. However, since the room temperature yield strength of 4130 (1050°F temper) steel was 125 ksi, the materials were not compared at this stress level. For the least severe condition, a 1000°F/sec heating rate and a 20.5-ksi stress level were selected. The resulting comparison of the yield temperatures for each of these conditions is shown in Fig. 22. For both the most severe and least severe conditions, the materials ranked in the same order starting with the best: 410 Stainless Steel (700°F temper), 4130 (1050°F temper) steel, 17-7 PH Stainless Steel, 4130 (800°F temper) steel, and 4340 (400°F temper) steel.

VI. CONCLUSIONS

The investigation described in this Report has yielded the following conclusions:

1. The temperature at which the 0.2% offset yield point occurs is greater than the corresponding temperature at which yielding occurs in a constant temperature tensile test. This is indicated by all of the materials investigated for heating rates of 40 to 2000°F/sec at all stress levels.

2. For the materials of this investigation which have a rapid decrease of tensile yield strength above 750°F, a semi-log plot of yield temperature versus heating rate extrapolates approximately to the tensile yield data.

3. For the materials of this investigation which do not have a rapid decrease of tensile yield strength until about 1000°F, a semi-log plot of yield temperature versus heating rate extrapolates to well above the tensile yield data.

4. The high-heating-rate yield data show greater improvement over constant temperature tensile yield data with increasing tempering temperatures for low alloy steels at heating rates above 40°F/sec and stress levels below 80 ksi.

5. For the parameters of this investigation, high-heating-rate yield temperatures of 410 stainless steel are superior to those of all other materials investigated.

Table 1. Composition of materials

Material	Composition, wt %											
	C	Mn	P	S	Si	Cr	Ni	Al	Mo	Co	Cu	N
17-7 PH	0.064	0.70	0.021	0.008	0.44	17.52	7.12	1.21				
4340	0.41	0.74	0.008	0.019	0.31	0.81	1.78	-	0.24			
4130	0.285	0.47	0.016	0.019	0.29	0.95	0.11	-	0.23	0.14		
410 S.S.	0.08	0.35	0.021	0.009	0.34	12.88	0.29	0.015	0.05	-	0.08	0.015

Table 2. Heat treatment of materials

Material Condition	Heat treatment procedure	Specification
17-7 PH TH(1050)	1400°F for 1½ hr; cool to 60°F. Within 1 hr, hold ½ hr; temper at 1050°F for 1½ hr, air cool.	Armco Steel Corp.
4340	Austenitize for 15 min at 1525°F; oil quench and temper at 400°F for 3 hr, air cool.	Jet Propulsion Laboratory
4130 800°F Temper	Austenitize for ½ hr at 1600°F; oil quench and temper at 800°F for 1 hr, air cool.	Mil. Spec. H-6875 B
4130 1050°F Temper	Austenitize for ½ hr at 1600°F; oil quench and temper at 1050°F for 1 hr, air cool.	Mil. Spec. H-6875 B
410 S.S.	1800°F for ½ hr; oil cool to room temp. and temper at 700°F for 1 hr, air cool.	Mil. Spec. H-6875 B

Table 3. Tensile test results for 0.063-in.-thick sheet of 17-7 PH (1050) stainless steel

Spec. No.	Temp, °F.	Modulus of elasticity, psi.	0.2% offset yield stress, ksi	Ultimate stress, ksi	Elongation in 2 in., %	Reduction of area, %
D-21	80	27.8×10^6	155	178	9.5	33.8
D-22	80	28.4	162	183	10.0	34.6
D-17	415	26.9	–	154	5.7	34.2
D-20	400	27.6	145	156	5.0	25.4
D-11	600	25.6	133	146	5.5	20.8
D-4	800	23.2	114	125	10.0	36.1
D-7	1000	21.2	63.6	81.3	35.3	65.0
D-8	1000	17.4	73.0	84.9	–*	58.2
D-1	1000	21.2	86.4	97.5	25.0	45.6
D-9	1200	14.5	21.8	35.8	57.0	81.0
D-19	1200	11.7	26.0	40.1	49.0	78.0

*Broke at gage point.

Table 4. High-heating-rate results for 0.063-in.-thick sheet of 17-7 PH(1050) stainless steel

Spec. No.	Area, In.^{2}	Load, lb.	Stress, ksi	Heating rate, °F/sec	0.2% yield Temp., °F
A-13	0.0244	500	20.5	41.5	1210
A-12	0.0238	500	21.0	137	1240
A-7	0.0239	500	20.9	439	1280
A-6	0.0243	500	20.6	1091	1315
A-8	0.0244	1000	41.0	47.0	1135
A-14	0.0243	1000	41.2	48.4	1120
A-9	0.0238	1000	42.0	121	1165
A-15	0.0239	1000	41.8	455	1180
A-11	0.0240	1000	41.7	967	1215
A-19	0.0237	2000	84.4	47.0	965
A-10	0.0238	2000	84.0	156	995
A-20	0.0237	2000	84.4	450	1000
A-16	0.0242	2000	82.6	1238	1050
A-4	0.0236	3000	127.0	44.1	700
A-5	0.0240	3000	125.0	138	715
A-1	0.0244	3000	123.0	409	735
A-3	0.0242	3000	124.0	1350	750

Table 5. Pseudo-heating-rate values calculated from tensile yield data for all materials

Material condition	Stress level, ksi	0.2% (1) yield temp., °F	Strain (2) at yield strength	Time to (3) yield strength, sec	Pseudo - (4) heating-rate, °F/sec
	21.0	1210	0.0035	52	23.3
17-7 PH	42.0	1110	0.0045	67	16.5
TH(1050)	84.0	960	0.0055	82	11.7
	125.0	685	0.0070	105	6.5
	10.1	1200	0.0026	39	30.8
4340	20.4	1140	0.0031	46	24.8
	41.0	1040	0.0040	60	17.3
	60.5	950	0.0050	75	12.7
	20.5	1155	0.0035	52	22.2
4130	41.0	1045	0.0041	61	17.1
800°F	82.0	875	0.0055	82	10.7
temper	123.5	650	0.0068	101	6.4
	20.1	1180	0.0035	52	22.6
4130	40.0	1100	0.0040	60	18.3
1050°F	61.0	1000	0.0048	71	14.1
temper	80.5	850	0.0052	78	10.9
	21.2	1220	0.0030	45	27.0
410	42.0	1125	0.0043	64	17.6
stainless	84.0	1000	0.0055	82	12.2
steel	126.0	750	0.0064	96	7.8

[1]Determined from yield stress vs temperature curves (Fig. 17, 21, 24, 27, and 30).
[2]Determined from Fig. 16, 20, 23, 26, and 29.
[3]Yield strain divided by strain rate of 0.000067 in./in./sec.
[4](1) divided by (3).

Table 6. Tensile test results for 0.130-in.-thick sheet of 4340 steel

Spec. No.	Temp, °F	Modulus of elasticity, psi	0.2% offset yield stress, ksi	Ultimate stress, ksi	Elongation in 2 in., %	Reduction of area, %
A-5	75	29.3×10^6	215	268	8.8	29.2
A-14	75	29.0	213	267	7.5	25.0
A-33	400	27.7	166	260	12.0	27.1
A-34	400	28.8	165	261	12.5	34.7
A-37	620	28.3	139	200	11.0	47.4
A-7	800	26.2	110	141	12.0	52.0
A-4	1000	21.2	43.4	81.3	23.0	75.2
A-20	1000	22.6	46.3	80.6	22.0	75.5
A-31	1000	23.3	50.3	80.3	27.0	73.4
A-8	1100	15.3	31.3	51.9	47.0	79.7
A-36	1120	16.8	29.1	44.6	36.0	77.2
A-10	1200	12.8	9.7	30.9	74.0	82.7
A-30	1200	12.4	10.0	26.8	70.0	81.2

Table 7. High-heating-rate results for 0.130-in.-thick sheet of 4340 steel

Spec. No.	Area, in.^{2}	Load, lb	Stress, ksi	Heating rate, °F/sec	0.2% yield temp, °F
10	0.0486	500	10.3	60.8	1230
11	0.0487	500	10.3	172	1260
12	0.0505	500	9.9	414	1290
15	0.0498	500	10.0	835	1320
7	0.0502	1000	19.9	60.6	1160
8	0.0490	1000	20.4	182	1190
9	0.0485	1000	20.6	428	1210
16	0.0485	1000	20.6	965	1270
4	0.0482	2000	41.5	62.4	1070
5	0.0496	2000	40.3	185	1110
6	0.0483	2000	41.4	450	1130
20	0.0491	2000	40.7	560	1125
18	0.0488	2000	41.0	1030	1160
1	0.0506	3000	59.4	65.6	950
2	0.0493	3000	60.8	177	970
3	0.0491	3000	61.1	454	975
19	0.0496	3000	60.5	1030	1000

Table 8. Tensile test results for 0.063-in.-thick sheet of 4130 (800°F temper) steel

Spec. No.	Temp, °F	Modulus of elasticity, psi	0.2% offset yield stress, ksi	Ultimate stress, ksi	Elongation in 2 in., %	Reduction of area, %
B-30	75	28.0×10^6	173	182	6.0	36.7
B-31	75	28.3	169	178	6.0	33.2
B-19	85	30.2	170	178	5.5	31.2
B-14	500	28.6	136	172	11.0	33.2
B-12	500	26.6	142	172	14.0	36.1
B-5	630	25.4	129	152	9.0	44.0
B-9	800	24.7	95.9	119	8.0	42.1
B-11	800	22.2	102	121	9.0	44.6
B-4	1000	18.7	48.1	67.6	19.0	58.8
B-2	1000	21.2	50.1	70.3	19.0	58.4
B-17	1000	21.1	53.2	73.1	23.0	65.4
B-7	1200	14.9	12.9	24.5	44.0	76.1
B-20	1200	13.1	14.1	26.6	63.0	79.9
B-3	1200	–	12.1	27.4	53.0	84.2

Table 9. High-heating-rate results for 0.063-in.-thick sheet of 4139 (800°F temper) steel

Spec. No.	Area, in.^{2}	Load, lb	Stress, ksi	Heating rate, °F/sec	0.2% yield temp, °F
B-9	0.0242	500	20.6	47.1	1190
B-10	0.0244	500	20.5	145	1235
B-6	0.0242	500	20.6	473	1260
B-11	0.0244	500	20.5	1660	1290
B-14	0.0244	1000	41.0	54.0	1070
B-13	0.0244	1000	41.0	145	1080
B-7	0.0243	1000	41.1	404	1100
B-8	0.0244	1000	41.0	1670	1140
B-16	0.0242	2000	82.6	47.9	925
B-18	0.0244	2000	82.0	142	935
B-19	0.0246	2000	81.3	519	950
B-15	0.0245	2000	81.6	1450	980
B-2	0.0243	3000	123.5	48.6	690
B-3	0.0243	3000	123.5	155	705
B-21	0.0243	3000	123.5	493	715
B-20	0.0243	3000	123.5	1320	710
B-12	0.0241	3000	124.5	2350	725

Table 10. Tensile test results for 0.063-in.-thick sheet of 4130 (1050°F temper) steel

Spec. No.	Temp, °F	Modulus of elasticity, psi	0.2% offset yield stress, ksi	Ultimate stress, ksi	Elongation in 2 in., %	Reduction of area, %
E-3	75	28.6×10^6	129	136	10.0	49.7
E-7	75	28.5	125	132	10.0	54.1
E-1	400	25.4	108	131	8.5	46.9
E-4	400	28.8	104	129	8.5	49.3
E-2	600	25.1	98.5	122	16.0	47.6
E-5	800	24.6	85.6	98.7	9.0	56.3
E-6	1000	21.0	60.8	72.5	15.0	61.6
E-20	1000	21.4	60.7	72.4	25.5	64.4
E-10	1200	14.8	14.2	31.0	50.0	83.3
E-11	1200	12.4	15.7	31.7	44.5	74.8

Table 11. High-heating-rate results for 0.063-in.-thick sheet of 4130 (1050°F temper) steel

Spec. No.	Area. In.^{2}	Load lb.	Stress ksi	Heating rate °F/sec	0.2% yield temp., °F
C-13	0.0249	500	20.0	44.6	1290
C-11	0.0246	500	20.3	139	1315
C-2	0.0248	500	20.2	380	1330
C-1	0.0250	500	20.0	1760	1360
C-3	0.0250	1000	40.0	41.9	1170
C-7	0.0251	1000	39.8	135	1200
C-6	0.0251	1000	39.8	395	1230
C-14	0.0248	1000	40.3	1785	1265
C-18	0.0245	1500	61.2	45.7	1100
C-16	0.0247	1500	60.8	145	1120
C-5	0.0248	1500	60.5	361	1140
C-15	0.0244	1500	61.4	1850	1180
C-19	0.0248	2000	80.6	51.9	1015
C-10	0.0254	2000	78.7	158	1040
C-17	0.0246	2000	81.3	566	1080
C-9	0.0246	2000	81.3	1920	1105

Table 12. Tensile test results for 0.063-in.-thick sheet of 410 stainless steel

Spec. No.	Temp, °F	Modulus of elasticity, psi.	0.2% offset yield stress, ksi	Ultimate stress, ksi	Elongation in 2 in., %	Reduction of area, %
F-3	75	30.1×10^6	133	171	7.0	34.3
F-8	75	29.4	134	168	8.0	36.1
F-2	400	29.9	118	171	6.0	28.6
F-10	430	31.2	118	172	7.5	32.5
F-18	600	28.4	127	182	6.0	26.4
F-12	800	27.3	119	166	5.5	12.4
F-20	1000	24.4	87.8	112	5.0	28.3
F-17	1000	25.0	83.1	103	–[1]	37.1
F-9	1000	25.7	80.4	109	–[1]	27.9
F-13	1000	20.0	90.2	114	6.0	34.6
F-15	1200	18.8	23.5	35.1	16.0	74.6
F-14	1200	18.3	23.7	35.5	24.5	71.9
F-16	1300	–	10.5	19.9	22.5	94.8

[1]Broke at gage point.

Table 13. High-heating-rate results for 0.063-in.-thick sheet of 410 stainless steel

Spec. No.	Area, In.^{2}	Load, lb.	Stress, ksi	Heating rate, °F/sec	0.2% yield temp, °F
10	0.0236	500	21.2	43.6	1270
8	0.0237	500	21.1	132	1340
7	0.0236	500	21.2	379	1370
5	0.0238	1000	42.0	40.0	1210
2	0.0241	1000	41.5	132	1250
11	0.0234	1000	42.6	380	1325
12	0.0237	1000	42.1	895	1370
13	0.0237	2000	84.3	41.5	1145
16	0.0237	2000	84.3	133	1190
1	0.0243	2000	82.2	401	1245
15	0.0237	2000	84.3	1000	1285
17	0.0238	3000	126.0	43.9	1110
18	0.0238	3000	126.0	143	1155
20	0.0239	3000	125.6	472	1190
19	0.0237	3000	126.5	1305	1210

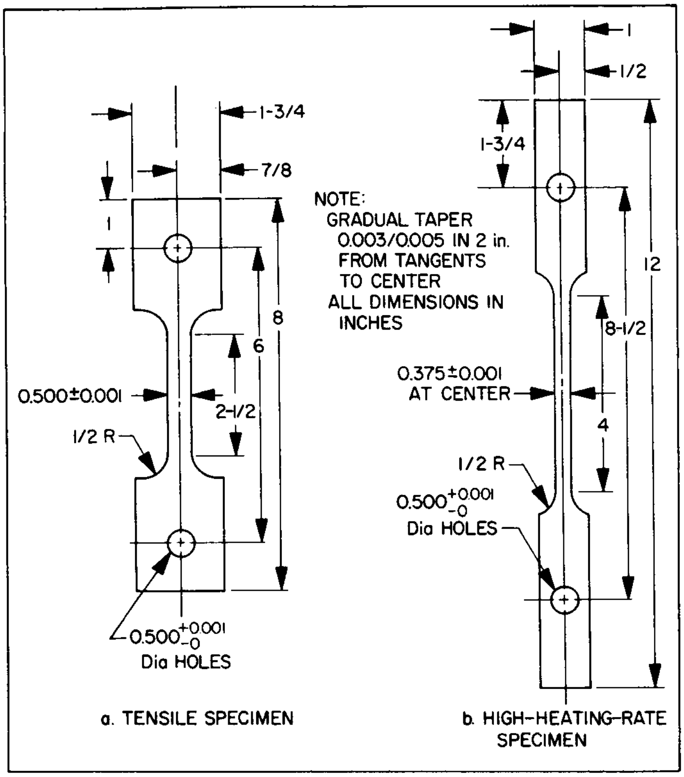


Fig. 1. Tensile and high-heating-rate test specimens

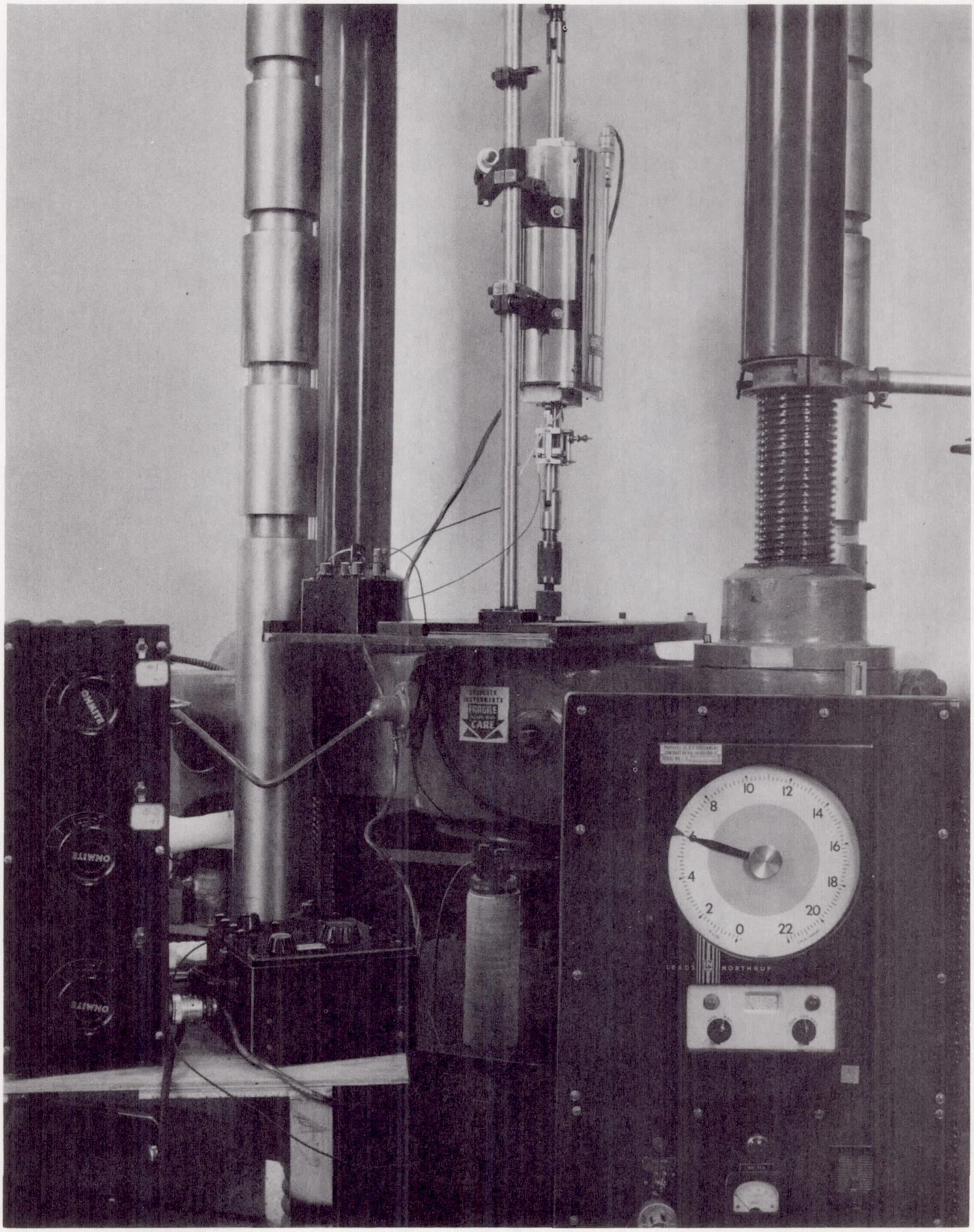


Fig. 2. Equipment for steady-state high-temperature tensile tests

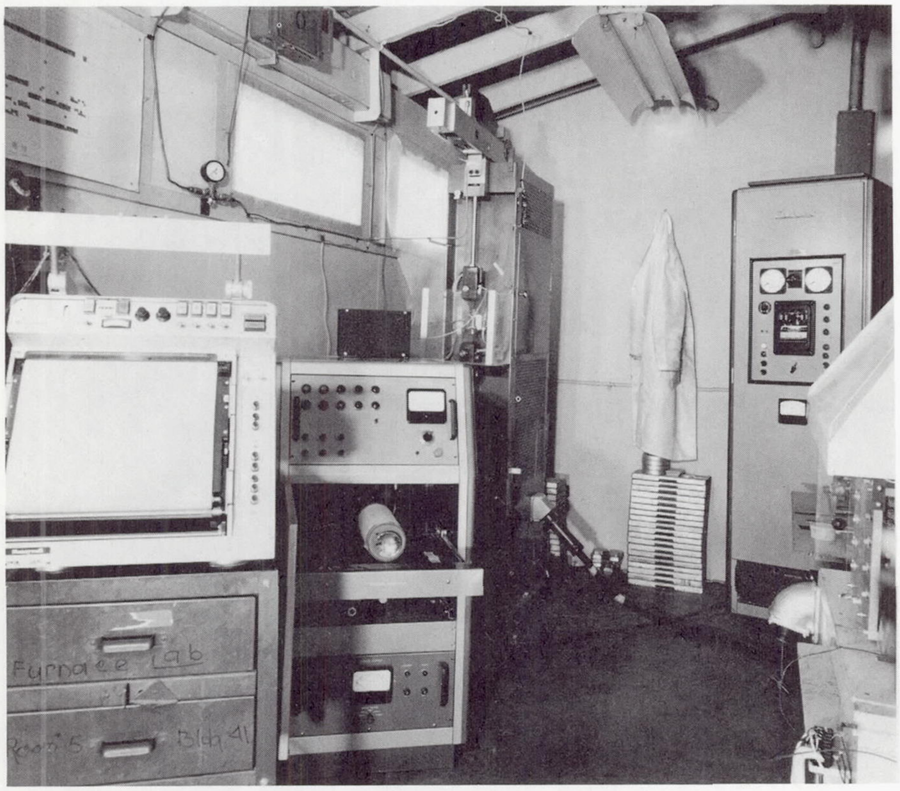


Fig. 3. Equipment for high-heating-rate tests

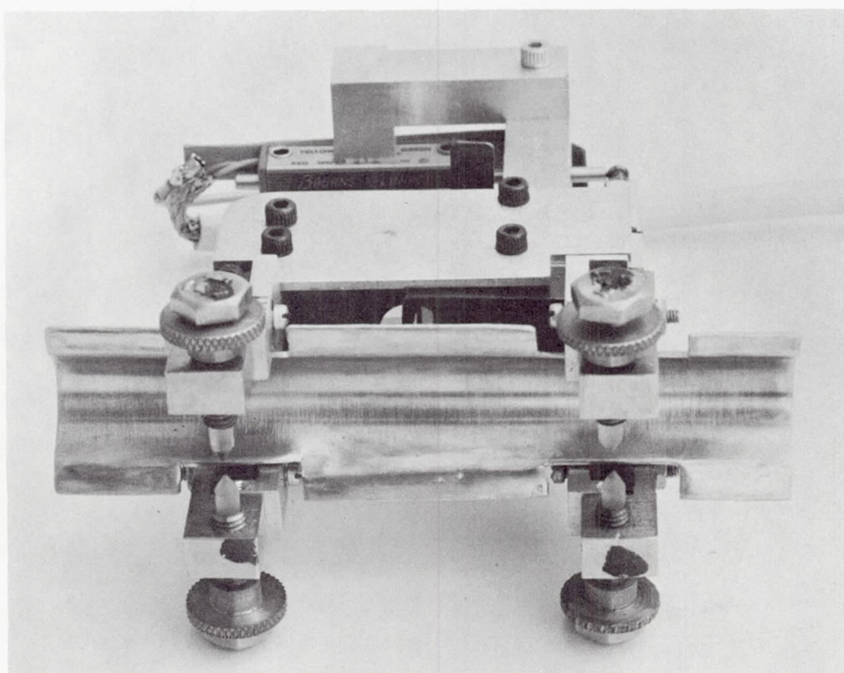


Fig. 4. Clamp-on extensometer for high-heating-rate tests

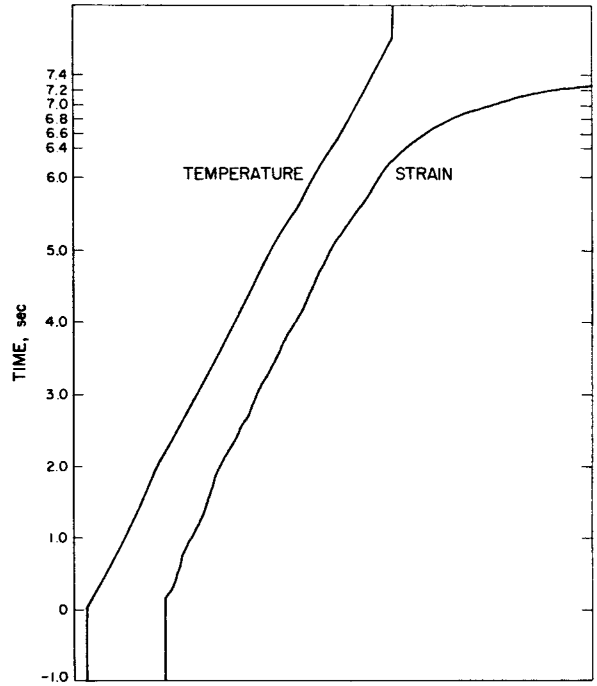


Fig. 5. Oscillograph recording of temperature and strain vs time

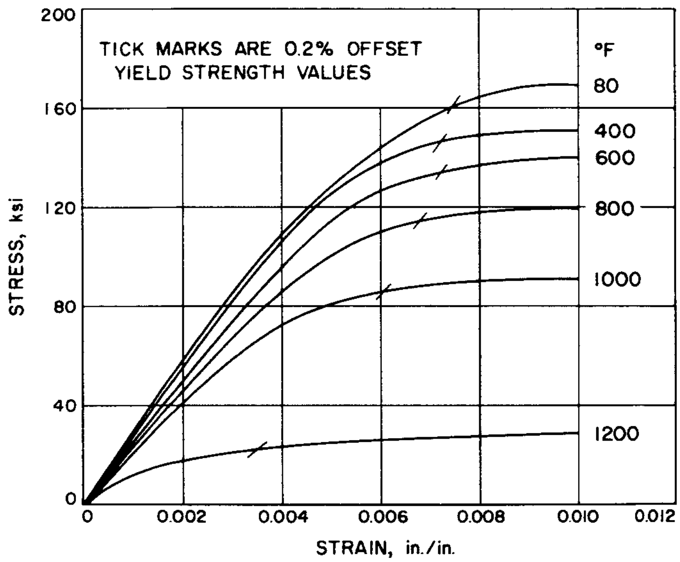


Fig. 6. Typical stress-strain curves for 17-7 PH (1050) stainless steel

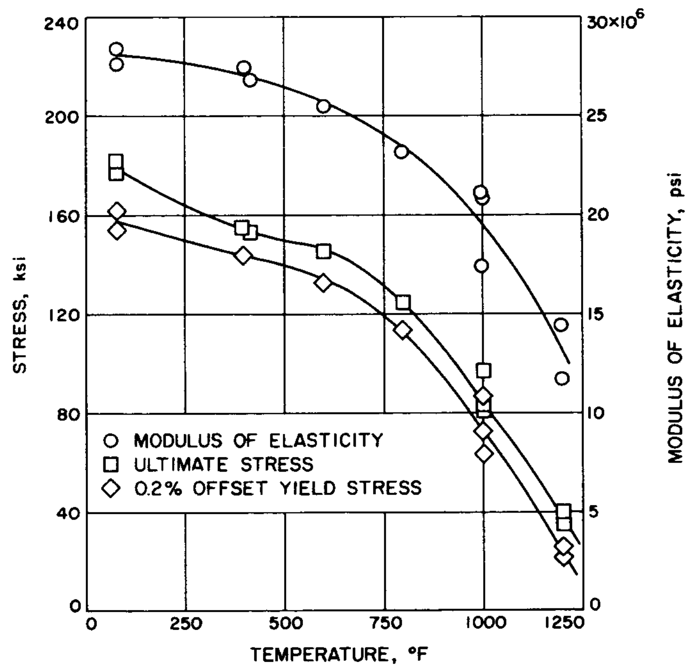


Fig. 7. Ultimate, yield, and modulus data for 17-7 (1050) stainless steel at temperatures from 75 to 1200°F

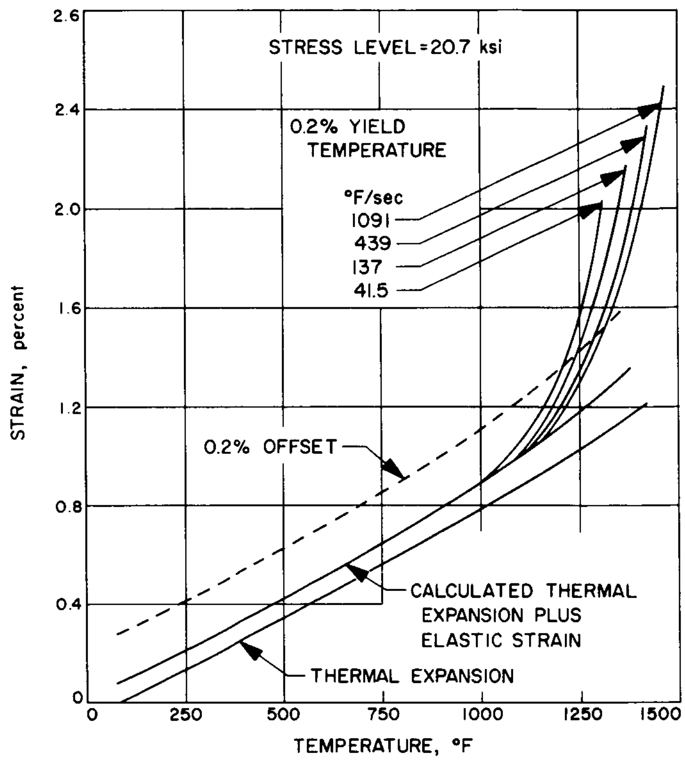


Fig. 8. Determination of 0.2% yield temperatures for 17-7 PH stainless steel at the 20.7-ksi stress level

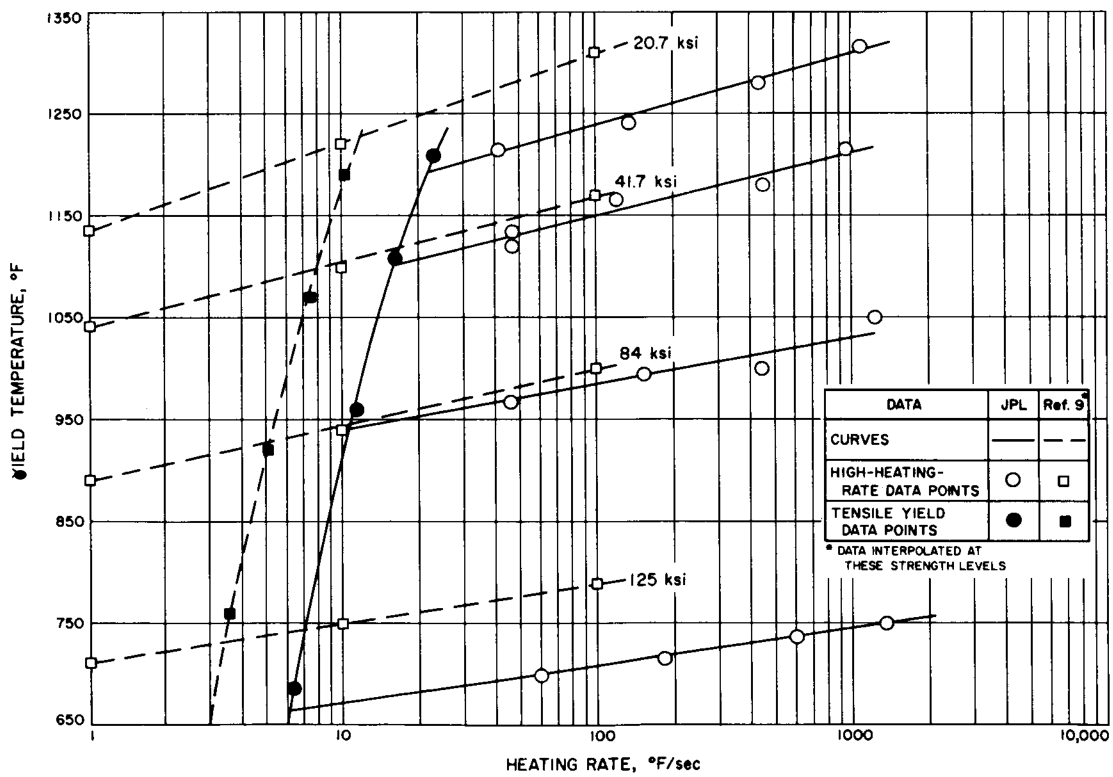


Fig. 9. High-heating-rate data for 17-7 PH (1050) stainless steel

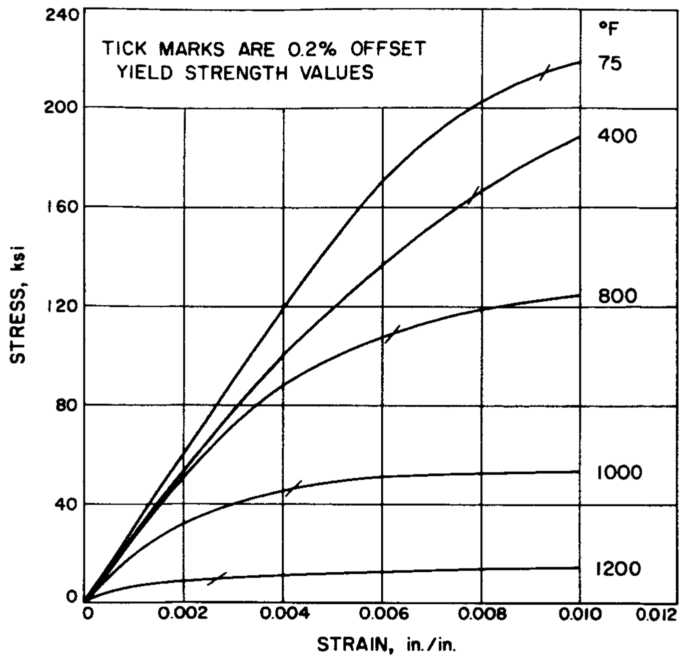


Fig. 10. Typical stress-strain curves for 4340 steel

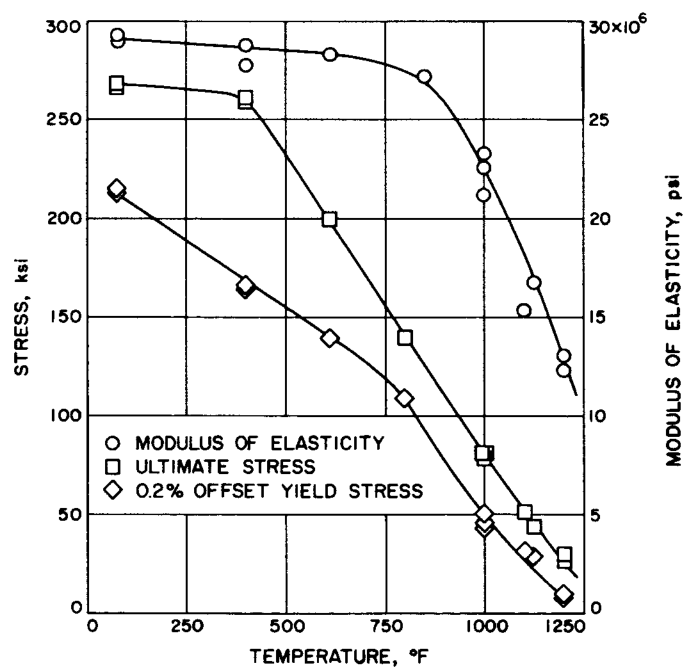


Fig. 11. Ultimate, yield and modulus data for 4340 steel at temperatures from 75 to 1200°F

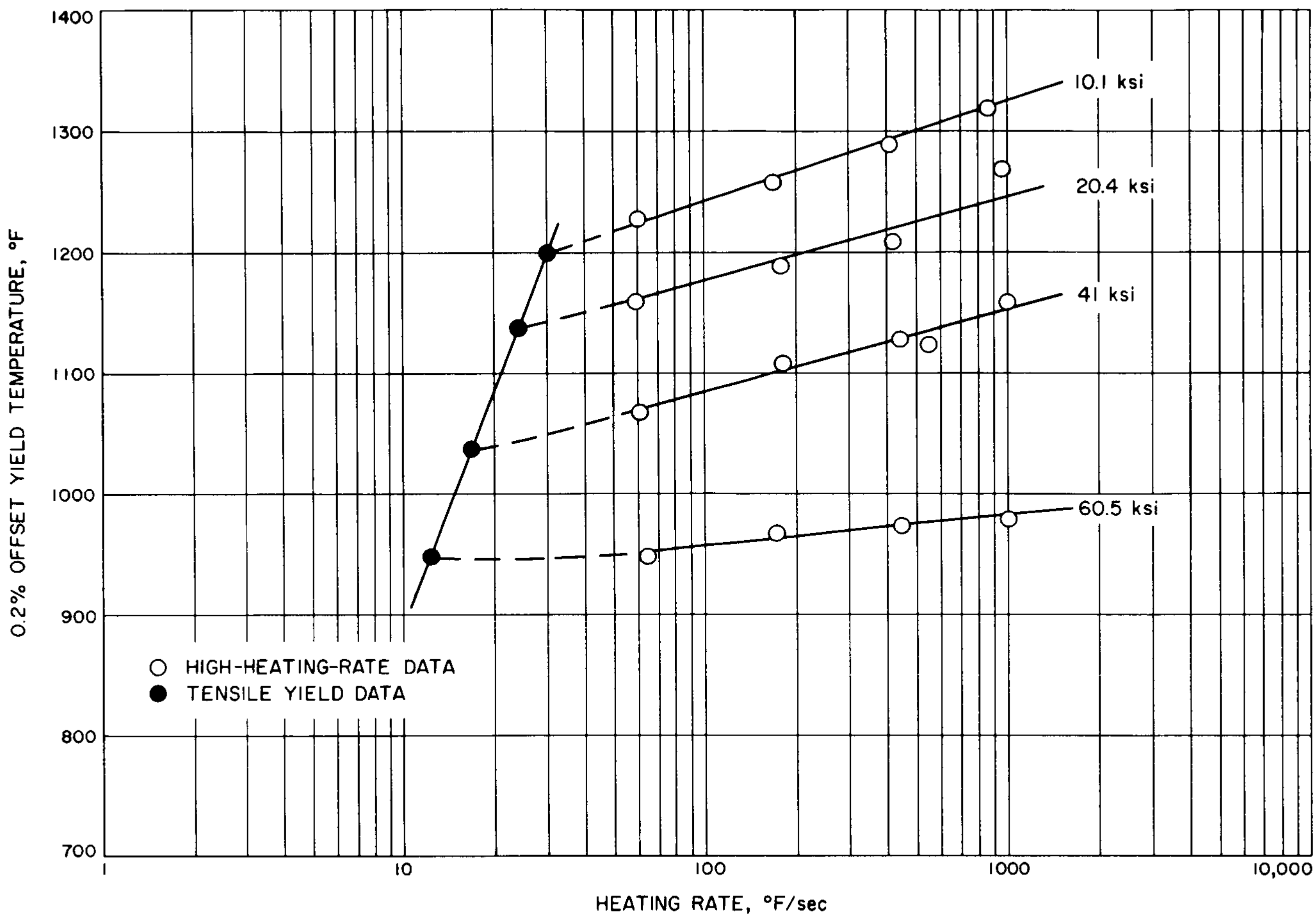
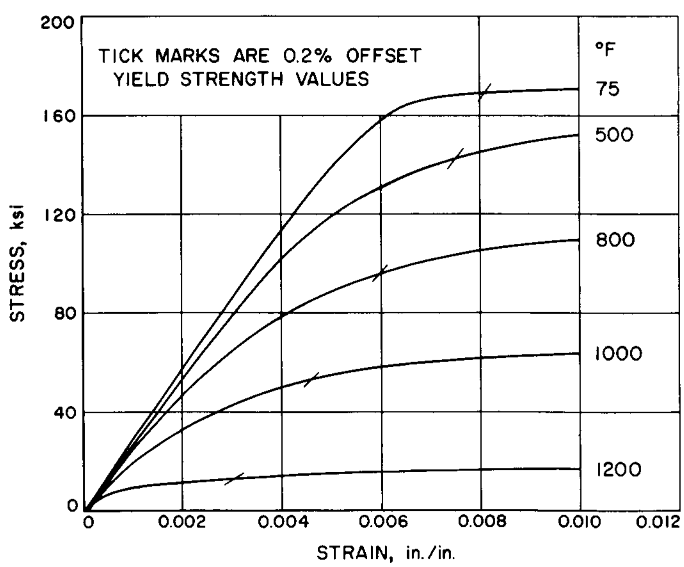


Fig. 12. High-heating-rate data for 4340 steel

Fig. 13. Typical stress-strain curves for 4130 (800°F temper) steel



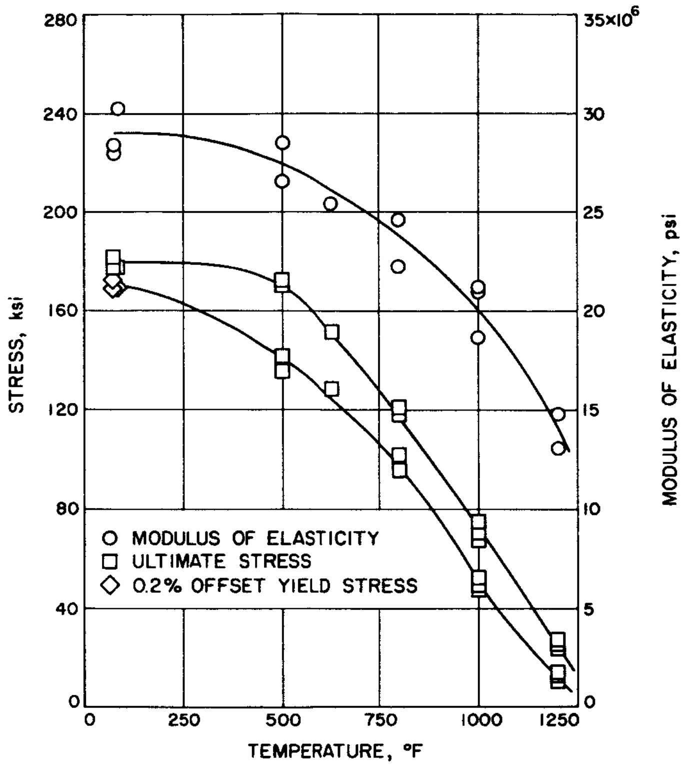


Fig. 14. Ultimate, yield, and modulus data for 4130 (800°F temper) steel at temperatures from 75 to 1200°F

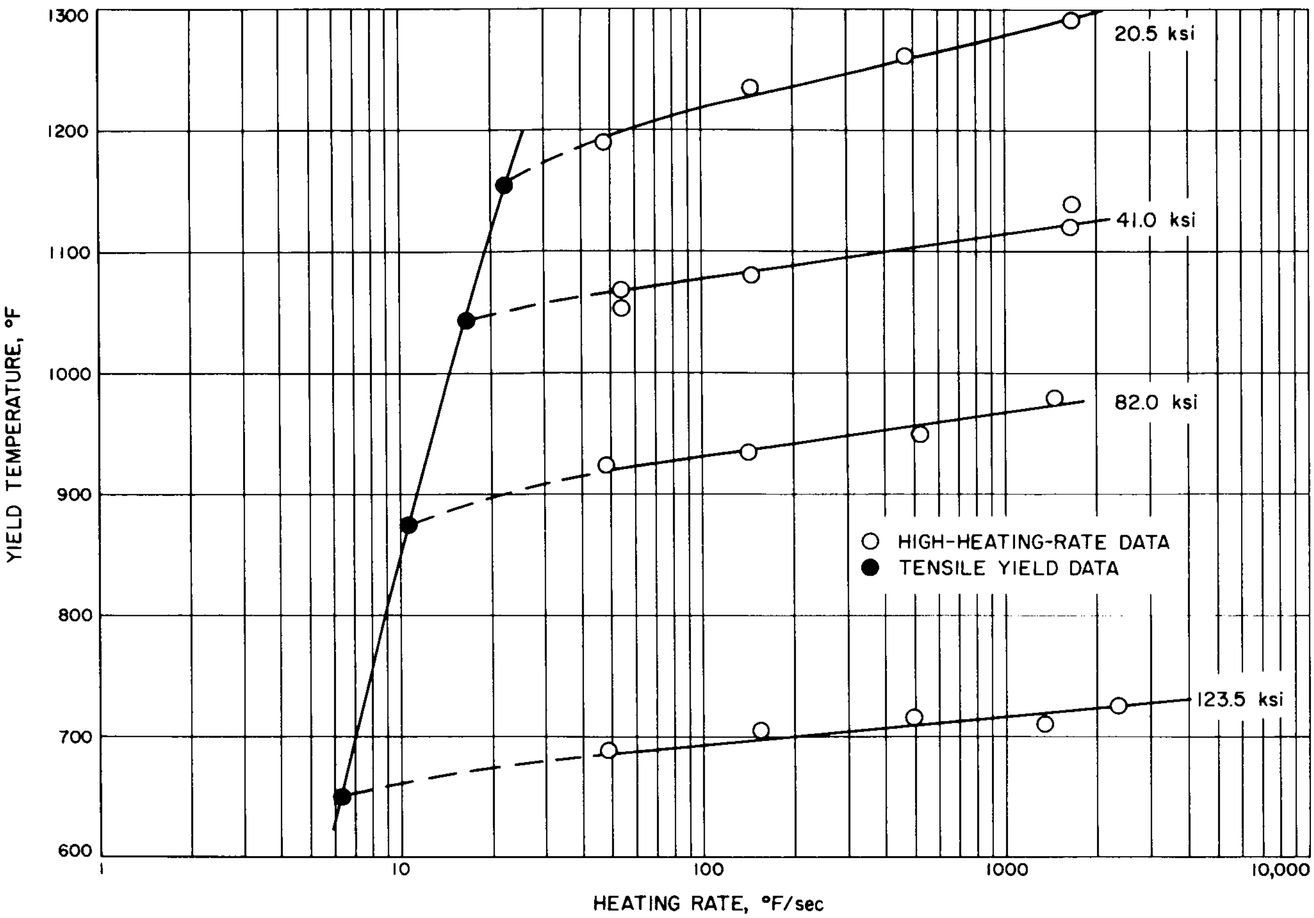


Fig. 15. High-heating-rate data for 4130 (800°F temper) steel

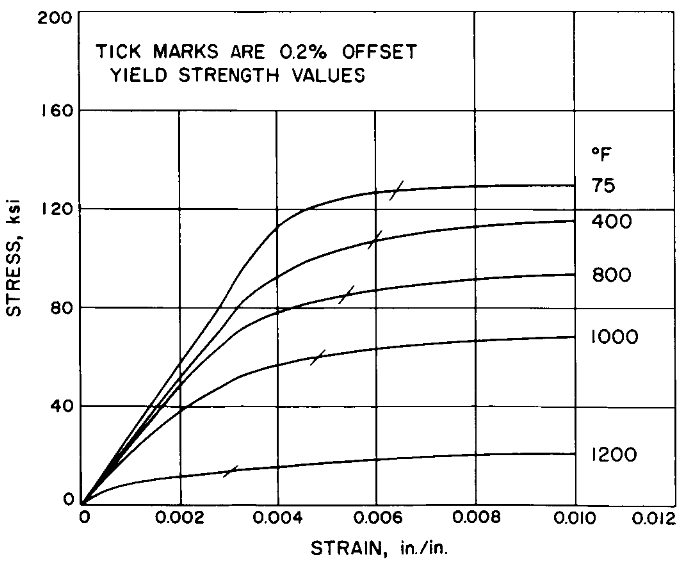


Fig. 16. Typical stress-strain curves for 4130 (1050°F temper) steel

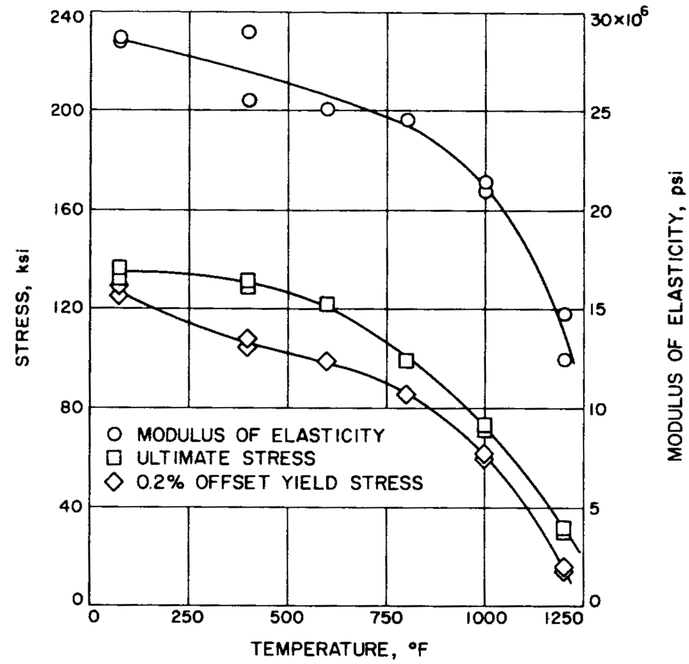


Fig. 17. Ultimate, yield, and modulus data for 4130 (1050°F temper) steel at temperatures from 75 to 1200°F

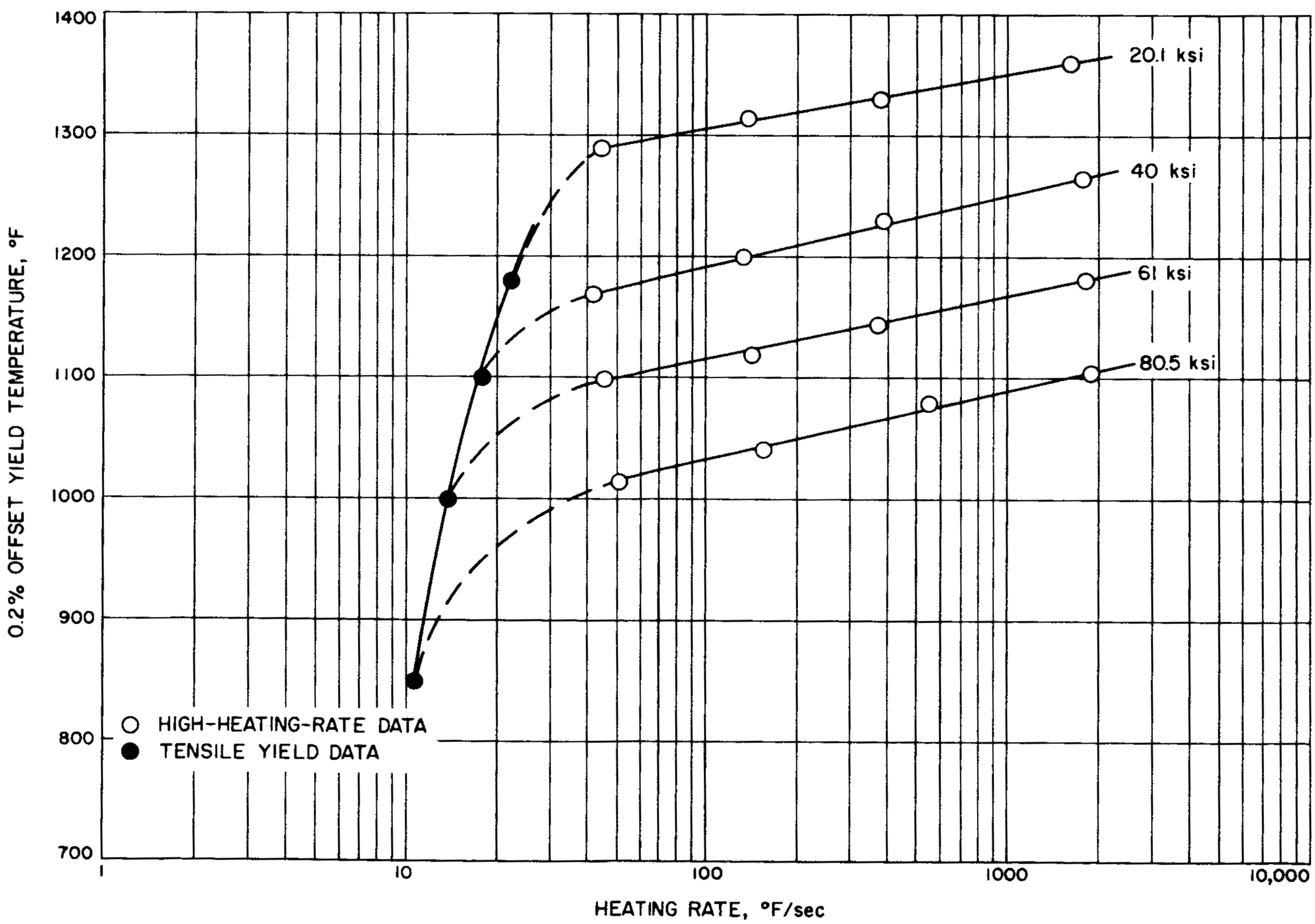


Fig. 18. High-heating-rate data for 4130 (1050°F temper) steel

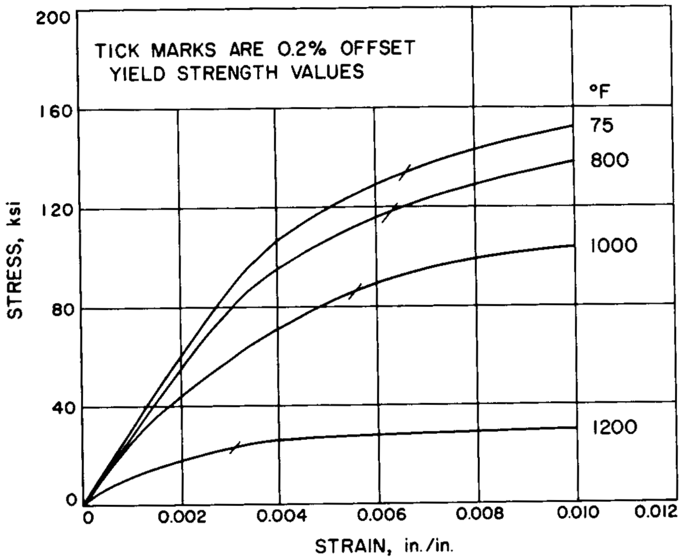


Fig. 19. Typical stress-strain curves for 410 stainless steel

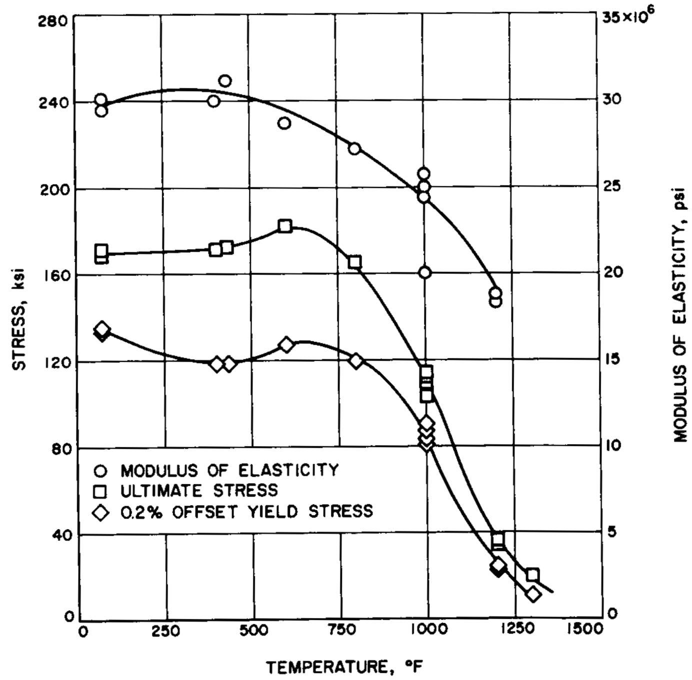


Fig. 20. Ultimate, yield, and modulus data for 410 stainless steel at temperatures from 75 to 1300°F

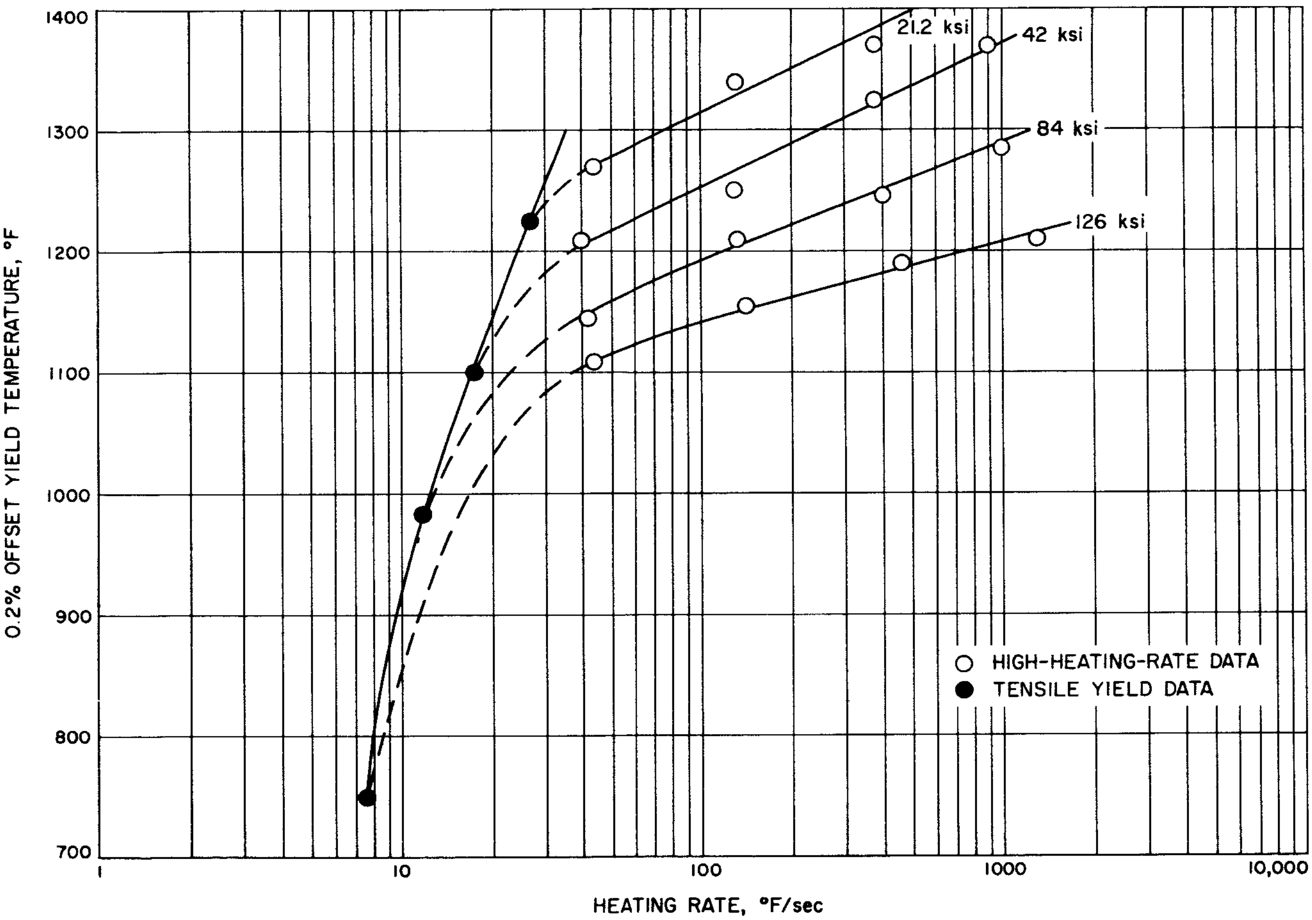


Fig. 21. High-heating-rate data for 410 stainless steel

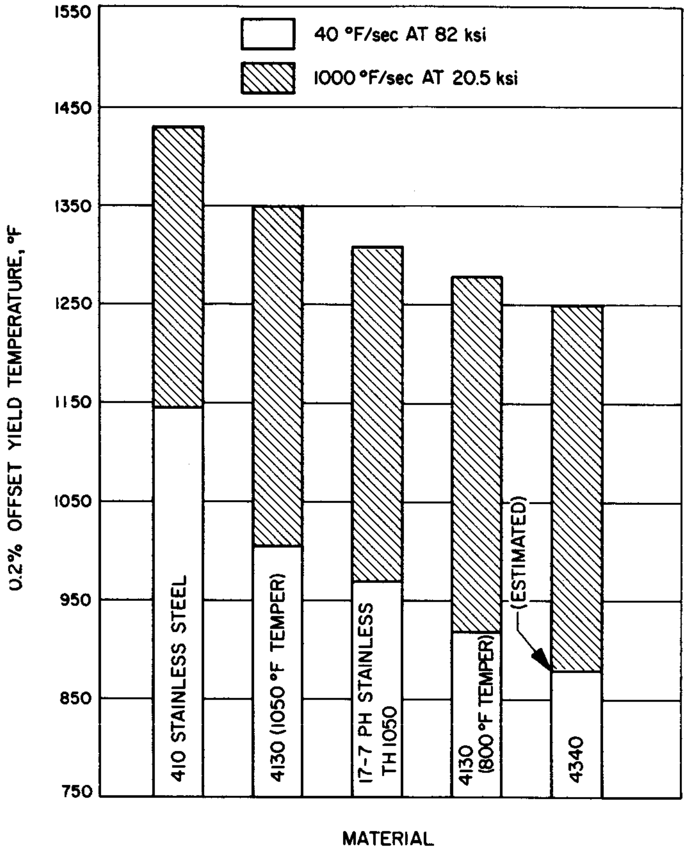


Fig. 22. Comparison of yield temperatures obtained under most and least severe conditions for all materials

APPENDIX. TEST EQUIPMENT AND PROCEDURES

I. EXPERIMENTAL TEST EQUIPMENT

For the steady-state tensile tests, the equipment consisted of a 2000°F furnace, an automatic temperature controller, a 300,000-lb universal testing machine, and a high-temperature extensometer as pictured in Fig. 2. Prior to testing, calibrations of shunting resistors for the furnace were made at all temperatures to insure a temperature uniformity of ±5°F over the gage length of the specimen. In Fig. A-1, the thermal gradients over the gage section after a half-hour soak time are shown for temperatures ranging from 600 to 1800°F. High-temperature extensometer arms and tensile pull rods made of Inconnel and Inconnel X are shown in Fig. A-2. Calibration of the extensometer was facilitated with a micrometer-screw jig for the three magnifications of the recording unit. Results in Fig. A-3 indicate the maximum error of the strain-measuring system to be 1.2%.

The equipment for the high-heating-rate tests was comprised of a 50-Kva transformer with ignitron pulser for self-resistance heating of the specimen; a temperature-control programmer to insure constant heating rates; a 20,000-lb modified creep tester; an extensometer and a direct read-out oscillograph for recording the temperature and deformation of the specimen. A complete layout of the equipment is shown in Fig. 3.

As heating rates up to 2000°F/sec were desired, the 50-Kva transformer with an amperage range of 0 to 7500 amps was sufficient for all materials. However, the voltage range of 0 to 10 v limited the length of reduced section in the specimens to 4 in. Specimens with reduced sections shorter than 4 in. gave higher heating rates but the resulting thermal gradients were intolerable.

Any number of heating rates up to 500°F/sec may be obtained with a single master chart for the programmer by varying the time and temperature range of the function generator. A probe follows a line of conducting ink drawn on the chart and excites a millivolt signal representing the desired temperature. A schematic of the programmer and power units is shown in Fig. A-4. The specimen temperature, T_s, is measured with a 5-mil chromel-alumel thermocouple spot-welded to the center of the specimen. This millivolt signal is transmitted to the range card unit. At the same time the function generator imports a millivolt signal to the unit as called out by the desired temperature, T_d, from the programmer chart. A difference between the two, $T_d - T_s$, causes a net dc error signal which eventually causes the ignitron pulser unit to fire the thyratron tubes varying the power input to the specimen. This variable power input allows a constant heating rate to be achieved. This method gave heating rates which varied about ±7% over the entire temperature range.

Besides the thermocouple for the programmer, a thermocouple was used for recording the temperature. Here a problem of superimposed voltages from the power supply was encountered. As there was a voltage gradient of about 6 v alternating across the 12-in.-long specimen, a 0.01-in. gap between thermocouple leads would cause a 5 millivolt oscillation of the galvonometer spot. Thus, it was necessary to have the thermocouple leads spot-welded on top of each other. Even then there was some superimposed voltage which was eliminated using a three-wire thermocouple as shown in Fig. A-5. The resistance, R_1, varies the galvanometer sensitivity and the resistance, R_2, nullifies the superimposed voltage.

To record relatively fast temperature and strain-transients, a direct read-out oscillograph with a 12-in. wide chart was used. This was equipped with galvanometers that yielded a 10-in. deflection for 45 millivolts. These galvanometers have a frequency response of 120 cps. A close-up view of the programmer and the oscillograph with resistance box to handle five recording channels is shown in Fig. A-6. These five channels were used to determine the thermal gradient of the specimen gage length for heating rates of about 10 to 1000°F/sec. Five 3-wire thermocouple were spot-welded at ½-in. intervals over the 2-in. gage length. Thermal gradient results for 410 stainless steel specimens heated at several heating rates are shown for two temperatures in Fig. A-7 and A-8. The maximum gradient resulting was less than 5% of the average temperature. These and other tests indicated that a specimen with a 4-in. reduced section was adequate for heating rates greater than 40°F/sec.

The strain measuring device consisted of a clamp-on extensometer with a 20:1 lever arm actuating a linear potentiometer. (See Fig. 4.) The potentiometer used a continuous carbon resistor so that no stepping was encountered. A constant voltage source of mercury cells in series with a variable carbon resistor provided the desired signal for the potentiometer. Two calibration curves in Fig. A-9 obtained with a micrometer-screw jig indicate the maximum error of the system to be ±2.0%. To reduce any thermal effects on the potentiometer, sapphire gage points to cut down conduction and an aluminum shield to cut down radiation were used as shown in Fig. 4. Two tests were run to determine the temperature rise at the potentiometer. For one, a specimen was held at 1000°F for six minutes resulting in a 1°F rise in temperature; for the other, the specimen was held at 2000°F for one minute resulting in a 25°F rise in temperature. The latter test represented more severe conditions than were encountered during any of the test runs. The extensometer, when calibrated at 25°F above room temperature, had the same calibration as the room temperature runs.

II. EXPERIMENTAL TEST PROCEDURES

During a tensile test run, the temperature was monitored by two chromel-alumel thermocouples spot-welded to the center of the gage section. One thermocouple was connected to the controller, and the other to a hand-balanced potentiometer. Both thermocouples were connected through a switching box so that either could be used for the potentiometer or the controller. In this way, both thermocouples could be checked against each other during the half hour soak time. Just preceding and during the test run, temperature was recorded every three minutes. The average of these temperatures is reported as test temperature. The specimens were pulled at a strain rate of approximately 0.004 min^{-1} to slightly past the yield point and then at a crosshead speed of approximately 0.1 in./min to fracture. A load-deformation curve was recorded to a deformation of about .020 in.

In general, the test procedures for the high-heating-rate tests were to dead-weight load the specimen and resistance-heat the specimen using a programmed or manual temperature control. For the programmed runs, two 5-mil, chromel-alumel thermocouples were used: one to the oscillograph recorder and one for feedback to the programmer. The two thermocouples were spot-welded to the center of the gage section as shown in Fig. A-10. A predetermined time scale was set on the function generator of the programmer for the desired heating rate. After the extensometer was attached and the specimen was loaded, the programmer was energized. A resulting temperature-time, strain-time record made to slightly past the yield point is shown in Fig. 5. As the extensometer had a limited range, a mechanical stop under the loading platform prevented the specimen from deforming much past the yield point. These runs were limited to 500°F/sec by the programmer response. For higher heating rates, a manually operated voltage regulator was used. With 12 different settings, heating rates from 500 to 2000°F/sec were obtained depending upon the specimen material.

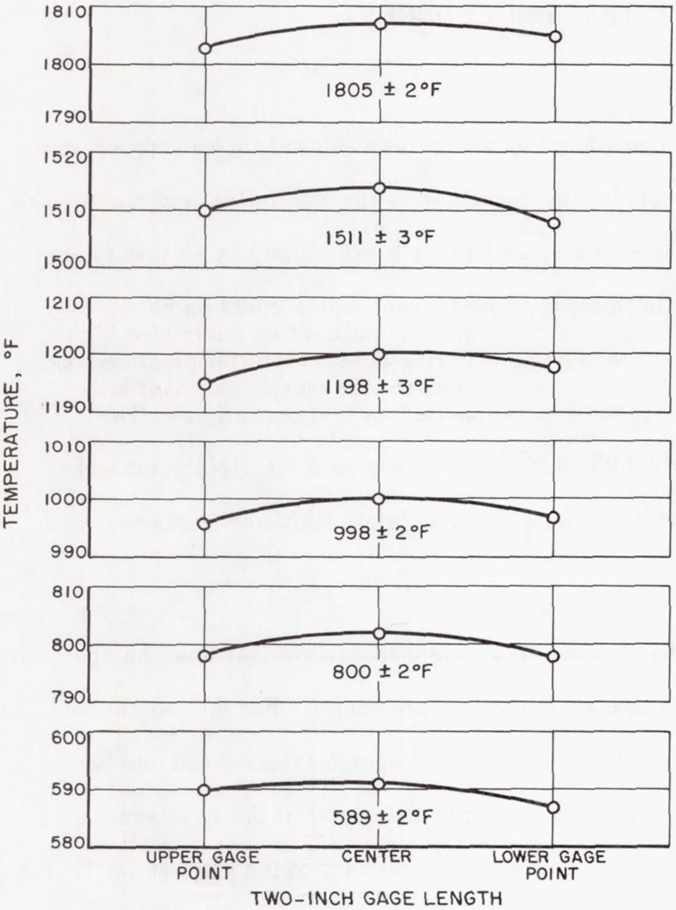


Fig. A-1. Thermal gradient calibration of 2000°F furnace for tensile tests

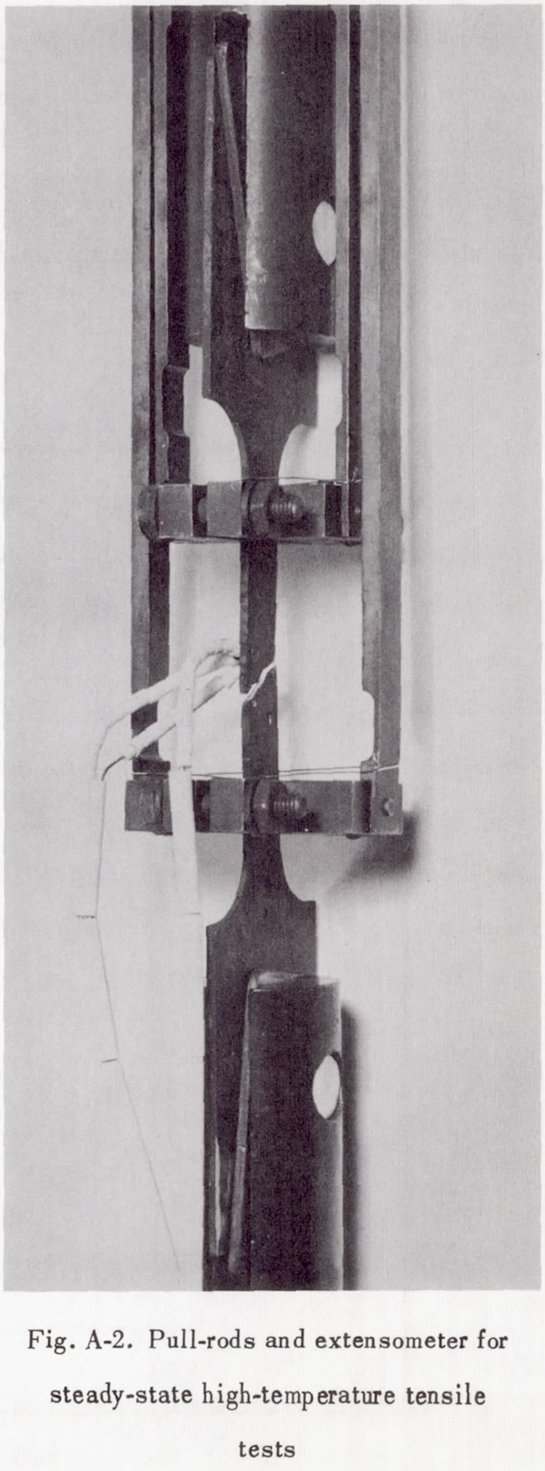


Fig. A-2. Pull-rods and extensometer for steady-state high-temperature tensile tests

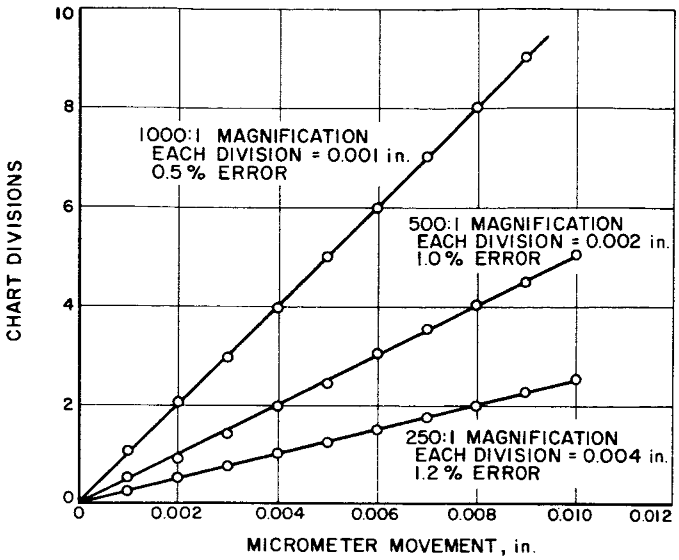


Fig. A-3. Calibration curves for high-temperature tensile extensometer

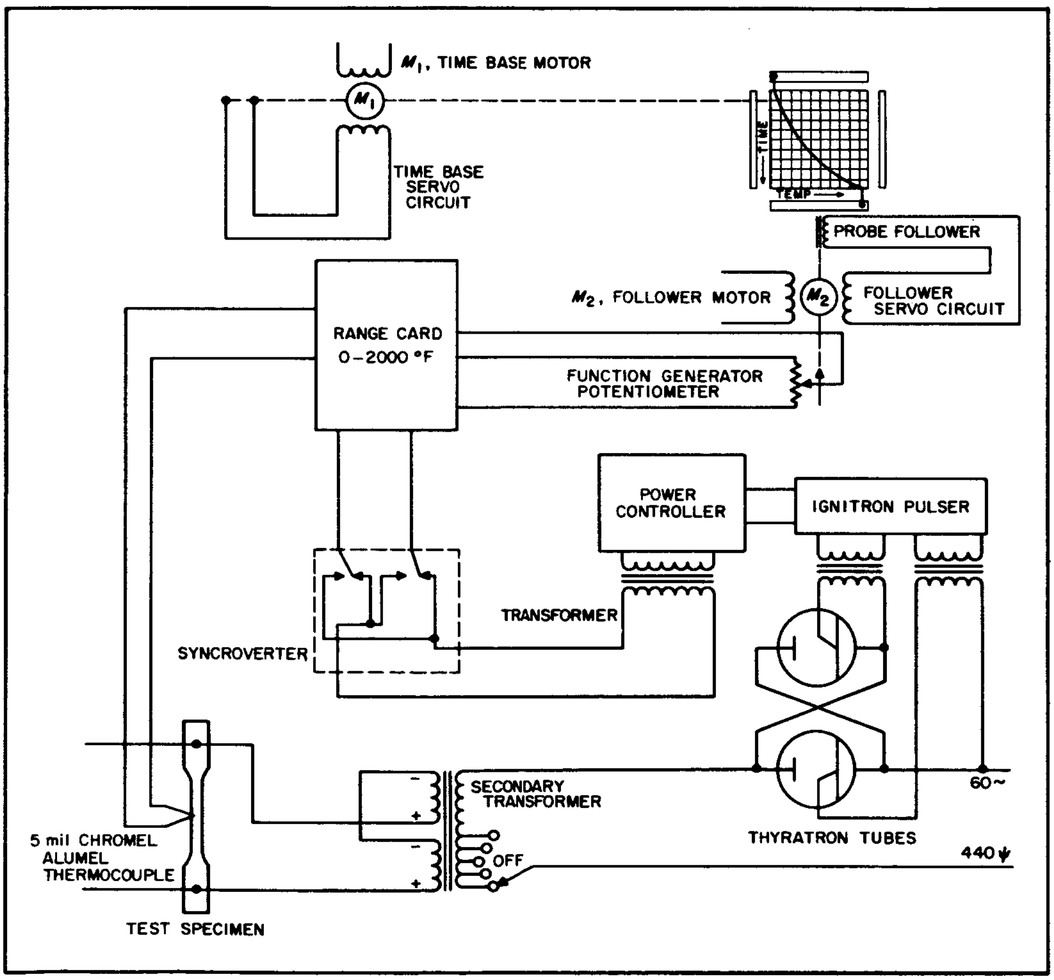


Fig. A-4. Schematic of programmer and power units

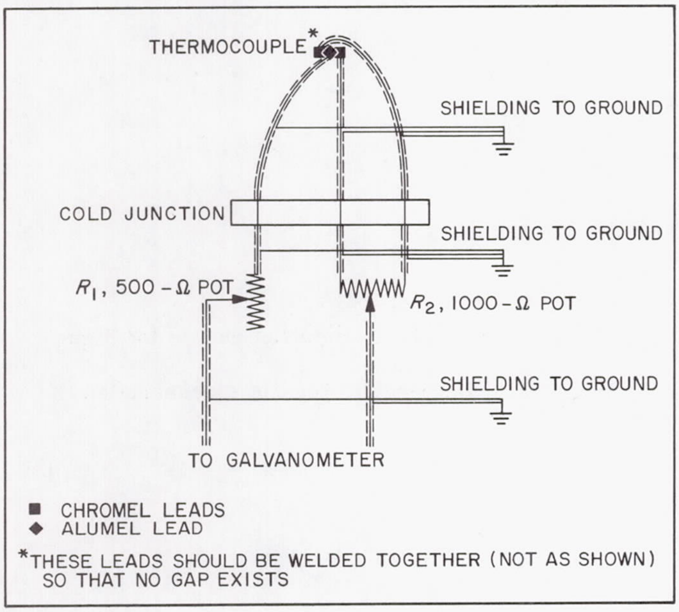


Fig. A-5. Thermocouple circuit to eliminate super-imposed voltages

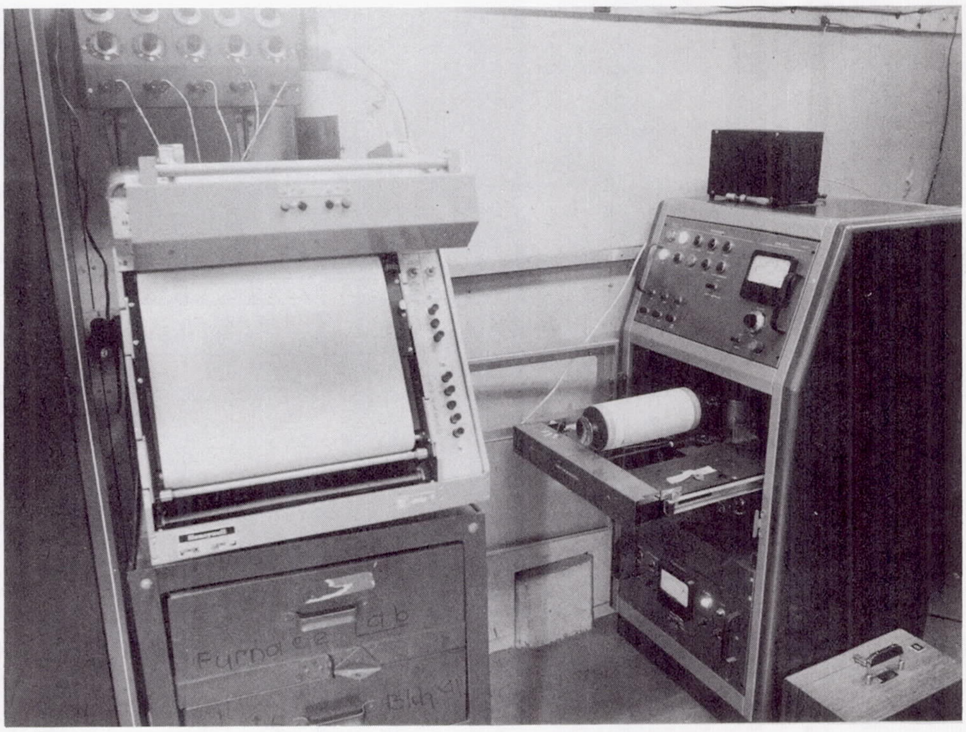


Fig. A-6. Oscillograph and programmer units

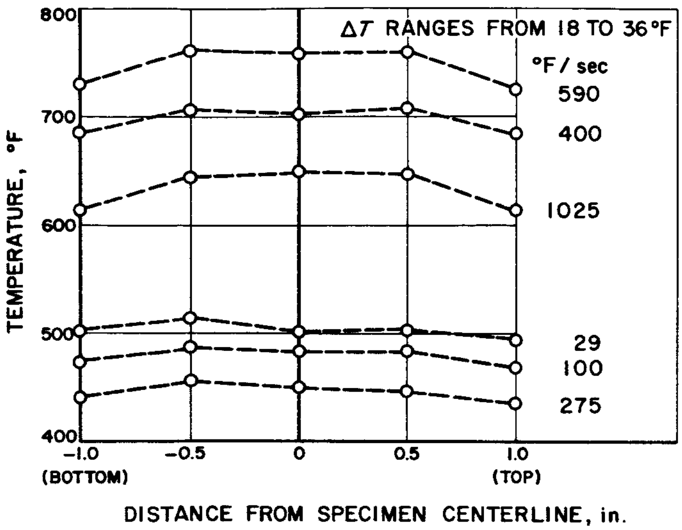


Fig. A-7. Thermal gradient calibration of high-heating-rate equipment at about 600°F

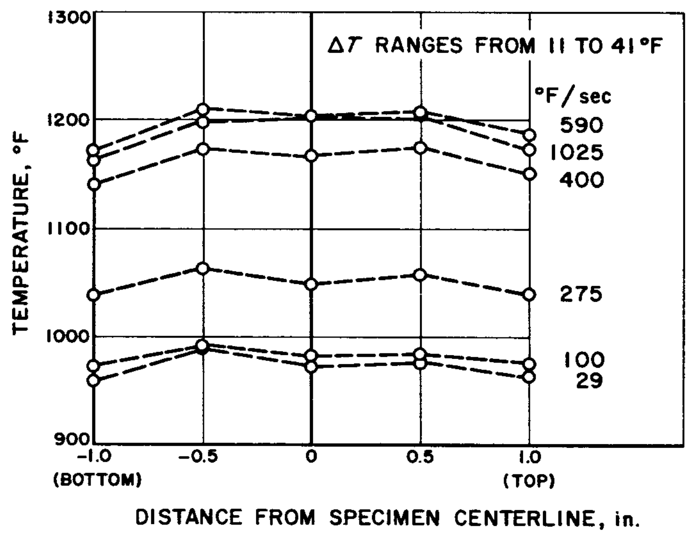


Fig. A-8. Thermal gradient calibration of high-heating-rate equipment at about 1100°F

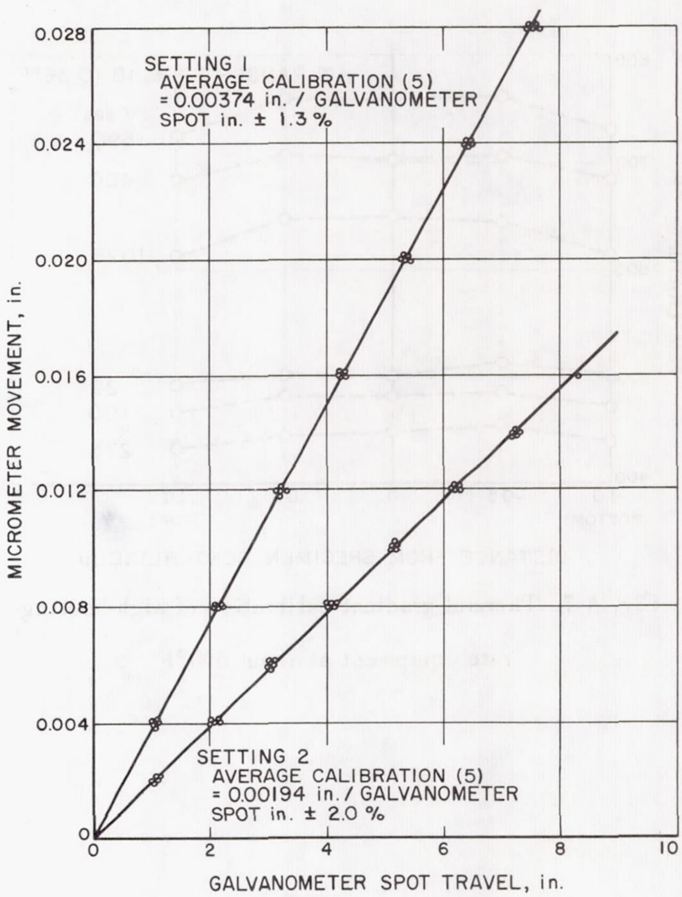


Fig. A-9. Calibration curves for high-heating-rate extensometer

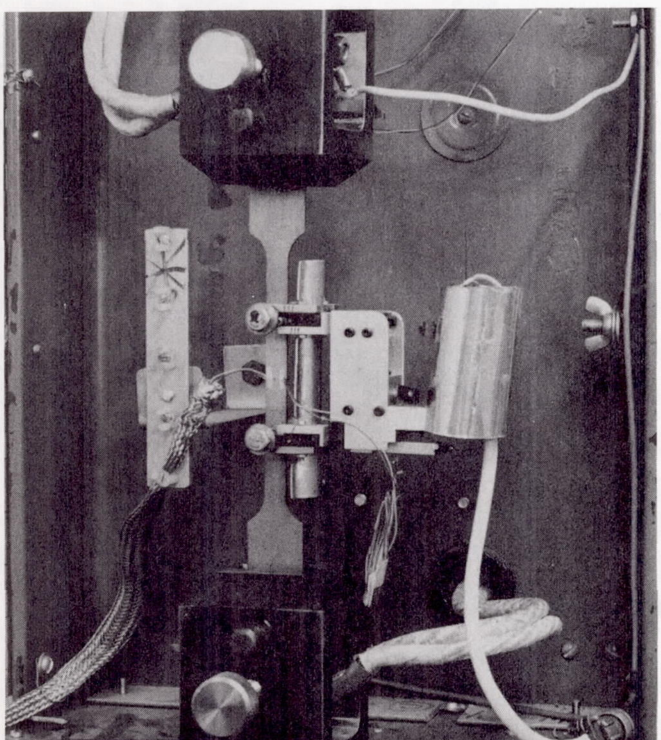


Fig. A-10. Assembly of thermocouples and extensometer on high-heating-rate specimen

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