TENSILE PROPERTIES OF SOME STRUCTURAL ALLOY STEELS AT HIGH TEMPERATURES

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ABSTRACT

The report gives results of determination of tensile strength, proportional limit, elongation, reduction of area, and strength at fracture throughout the range 20 to 550° C for four steels containing about 0.38 per cent carbon, as follows: (*a*) Plain carbon steel; (*b*) 3½ per cent nickel steel; (*c*) 3 per cent nickel, 1 per cent chromium steel; (*d*) 1 per cent chromium, 0.20 per cent vanadium steel.

Brief reference is made to the type of fractures obtained in testing steels at various temperatures, and particular attention is paid to comparison of the tensile properties of these alloys at 550° C.

CONTENTS

I. INTRODUCTION

In the attempted production of ammonia in the United States by the Haber process[1] gradual elongation and ultimate fracture of bolts in converter chamber heads have introduced serious operating difficulties. Under a mean temperature of 550° C to which heads, nuts, and bolts were subjected the elongation of the latter was such as to require tightening of the nuts almost daily. The use of some of the more commonly employed structural alloy steels did not remove this difficulty, and a search of the literature revealed little exact information on which a comparison of the high temperature tensile properties of various alloy steels could be based.

In view of the fact that an investigation of the resistance to corrosion by ammonia of various ferrous and nonferrous alloys

[1] R. S. Tour, "The direct synthetic ammonia process," Journ. Ind. and Eng. Chem., 12, No. 9, p. 844; September, 1920.

was in progress in connection with redesign of operating equipment by the Ordnance Department, the Bureau of Standards was requested to undertake determination of the tensile properties of a number of structural alloy steels throughout the temperature range 20 to 550° C (70 to 1020° F). From the combined results of investigation of resistance to corrosion of various metals and the tensile properties of steels at high temperatures it was hoped that selection of a suitable alloy for withstanding required stresses could be made, and if this proved unsatisfactory as regards resistance to attack by the gases encountered at least a more suitable metal lining for the converters could be installed.

The original plan of procedure included tests of a plain carbon steel and a number of structural alloy steels, most of which were of acknowledged industrial importance. However, because of the desire to keep variations in carbon content at a minimum, difficulty was encountered in obtaining some of the alloys, notably carbon-manganese and chromium-molybdenum steels, of the exact composition desired, so that this report comprises only tests of four steels.

It is further restricted to tests of these alloys in a normalized condition, as data so obtained form a basis of comparison with tests of samples first subjected to quenching and tempering. The high operating temperatures attained, which reach about 650° C (1200° F), limit the tempering subsequent to hardening to relatively high temperatures, while the large dimensions of the converter heads and some of the other parts of the equipment subjected to high temperatures, which would introduce difficulties in quenching, make the use of a forged or normalized steel highly desirable.

Shortly after completion of the tests about to be described tensile properties at high temperatures of a number of carbon and alloy steels subjected to varying thermal treatments were reported by MacPherran,[2] and in discussion of this paper by Spooner considerable additional data were presented. However, the work of MacPherran and Spooner was confined, in so far as the elastic properties are concerned, to determination of yield point; whereas the tests carried out by the present author include determinations of the limit of proportionality and strength at fracture, and the interpretation of these data is somewhat different from that given by either of the authors mentioned.

[2] R. S. MacPherran, "Comparative tests of steels at high temperatures," Proc. Amer. Soc. for Testing Materials; 1921.

II. PREVIOUS INVESTIGATIONS

As already indicated, there was until quite recently a scarcity of accurate data on the high temperature tensile properties of various structural alloy steels. This is still the case as regards the effect of temperature on the limit of proportionality, of importance in design of engineering equipment, and in addition there is some disagreement between results reported by different investigators for similar alloys. Bregowsky and Spring[3] determined yield point, tensile strength, elongation, and reduction of area from 20 to 550° C (70 to 1020° F) for rolled 30 per cent nickel steel.

In 1913 Schulz[4] reviewed available data relating to the high temperature properties of turbine materials, but the information presented for alloy steels was, in large part, for those containing varying proportions of nickel.

Guillet[5] reported, among several special alloys for use at high temperatures, a steel containing nickel, chromium, and tungsten which showed exceptionally high strength at 750 to 800° C (1380 to 1470° F).

A comprehensive analysis of the effects of high temperatures on hardness, tensile and impact properties, freedom from warpage, etc., of steels containing 3 per cent nickel and various proportions of chromium, high-speed steels and various chromium and chromium-cobalt steels was recently prepared by Gabriel.[6] As regards high tensile strength at elevated temperatures, these steels were considered of value in the following order: (1) High tungsten; (2) high chromium, high carbon; (3) high chromium, low carbon; (4) 3 per cent nickel and nickel-chromium.

In the selection of steels for valves the author recommended the different type alloys, as follows: (1) A tungsten steel, (2) a steel high in chromium, (3) a nickel steel.

MacPherran[7] recently reported tensile tests from 20 to about 650° C (70 to 1200° F) for a variety of alloy steels under different heat treatments, as shown in Table 1. In discussion of this paper A. P. Spooner presented a large number of tests at temperatures up to about 870° C (1600° F) for the different steels listed in

[3] I. M. Bregowsky and L. W. Spring, "The effect of high temperature on the physical properties of some alloys," Proc. Int. Assoc. for Testing Materials, VI Congress, VII1; 1912.

[4] Schulz, "Neuere versuche und erfahrungen mit turbinenschaufelmaterial für höhe temperaturen," Die Turbine, 9, p. 243; 1913.

[5] L. Guillet, "Alloys having remarkable properties at very high or very low temperatures," Rev. Met. 11, p. 969; 1914.

[6] G. Gabriel, "Comparative values of motor valve steels," Iron Age, 106, p. 1465; 1920.

[7] See note 2.

Table 2 and, in general, confirmed the work of MacPherran where direct comparisons were possible.

TABLE 1.—Alloy Steels Tested at High Temperatures [a]

Type composition (per cent)					Condition in which steel was tested
C	Mn	Ni	Cr	V	
0.21	....	3.25	....	....	Annealed at 802° C (1475° F)
.25	....	33.9	....	....	Do.
.34	....	2.38	0.38	....	816° C (1500° F) water, 705° C (1300° F)
.53	....	20.78	7.42	....	As rolled
.30	....	....	.83	0.17	857° C (1575° F) water, 732° C (1350° F)
.69	....	....	3.36	....	843° C (1550° F) water, 705° C (1300° F)
.72	0.92	....	....	....	Annealed at 802° C (1475° F)
.82	....	....	.91	.18	816° C (1500° F) water, 705° C (1500° F)

[a] MacPherran, Amer. Soc. for Testing Materials; 1921.

TABLE 2.—Alloy Steels Tested at High Temperatures [a]

Type composition (per cent)						Condition in which steel was tested
C	Ni	Cr	V	Mo	W	
0.10	....	....	....	....	....	Normalized 870° C (1600° F)
.45	....	....	....	....	....	Do.
.33	3.5	....	....	....	....	Do.
.38	2.0	1.0	....	....	....	Do.
.37	....	1.0	0.20	....	....	Do.
.47	....	1.0	....	0.35	....	Do.
1.10	....	.50	.20	....	....	Annealed 740° C (1360° F)
.48	....	1.3	.20	....	....	Annealed 730° C (1350° F)
.25	....	14.0	....	....	....	Annealed 790° C (1450° F)
.66	....	3.2	.70	....	15.9	Annealed 905° C (1660° F)
.20	....	31.0	....	....	....	Annealed 760° C (1400° F)

[a] A. P. Spooner, Proc. Amer. Soc. for Testing Materials; 1921.

These data, while the most recently presented, are together the most comprehensive compilation of tests so far recorded for the modern types of structural alloy steels, but consist of determinations of tensile strength, elongation, reduction of area, and, in part of the temperature ranges given, values for yield point.

III. MATERIALS AND METHODS USED

The four steels tested were made by the electric furnace process at the plant of the Halcomb Steel Co., Syracuse, N. Y., and supplied through the Nitrate Division, Ordnance Department, in the form of 1 by ½ inch hot-rolled bars of the compositions shown in Table 3. After cutting into desired lengths for test specimens the bars were normalized by heating to 800 or 850° C (Table 3) and cooled in still air. They were then machined to the form and dimensions shown in Fig. 1. All tests were made with the special apparatus devised by the author and in the manner previously described[8] in detail.

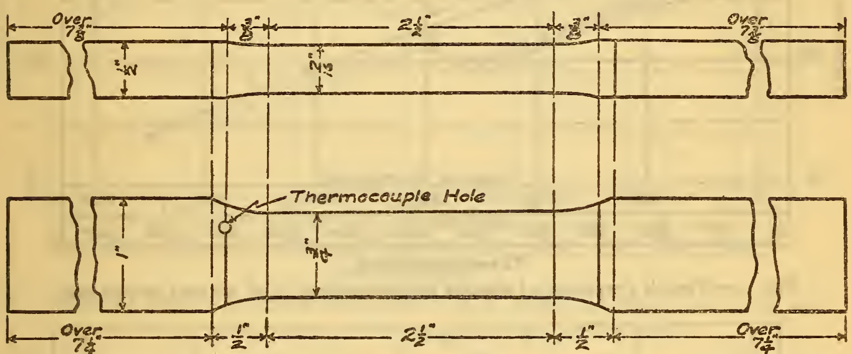

FIG. 1.—*Form and dimensions of test specimen used*

TABLE 3.—Composition and Heat Treatment of Steels Tested

Steel	Composition (per cent)								Heat treatment: Heated for 30 minutes at temperature designated and cooled in still air
	C	Mn	P	S	Si	Ni	Cr	V	
A	0.38	0.56	0.014	0.013	0.14				850° C
B	.37	.67	.021	.010	.20	3.43			800° C
C	.39	.59	.019	.009	.23	3.05	0.93		850° C
D	.37	.74	.020	.023	.21		1.04	0.17	850° C

IV. EXPERIMENTAL RESULTS

1. TENSILE TESTS

(*a*) TENSILE STRENGTH.—The results of tensile tests at various temperatures throughout the range 20 to 550° C (70 to 1020° F) are given in Tables 4, 5, 6, and 7, and represented graphically in Figs. 2 to 5, inclusive.

[8] Forthcoming Bureau Tech. Paper: Effect of Temperature Deformation and Rate of Loading on the Tensile Properties of Low Carbon Steel Below the Thermal Critical Range. Also H. J. French, "Tensile properties of boiler plate at elevated temperatures," Min. and Met., 158, sec. 15; 1920.

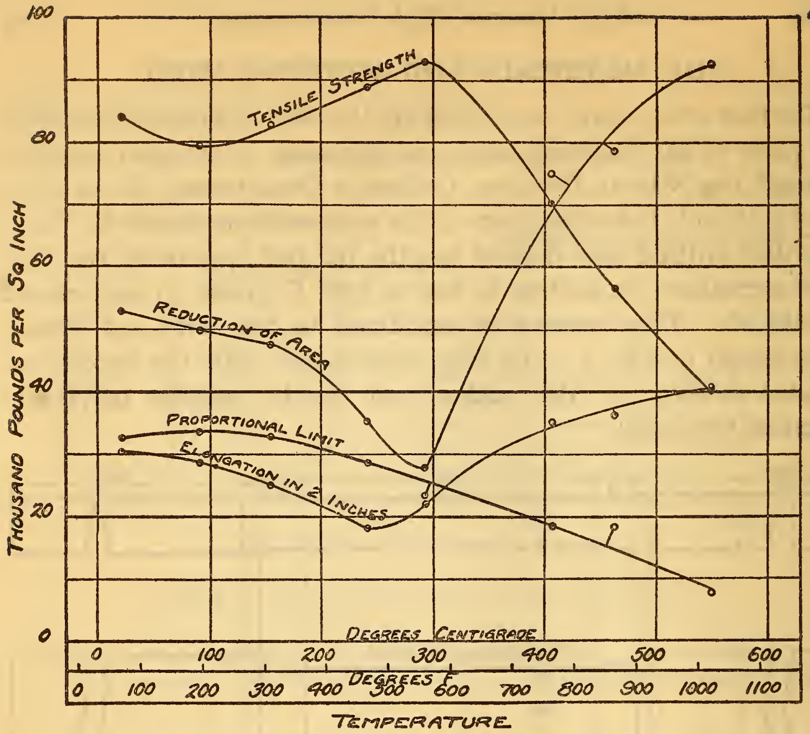

Fig. 2.—*Tensile properties at elevated temperatures of 0.38 per cent carbon steel*

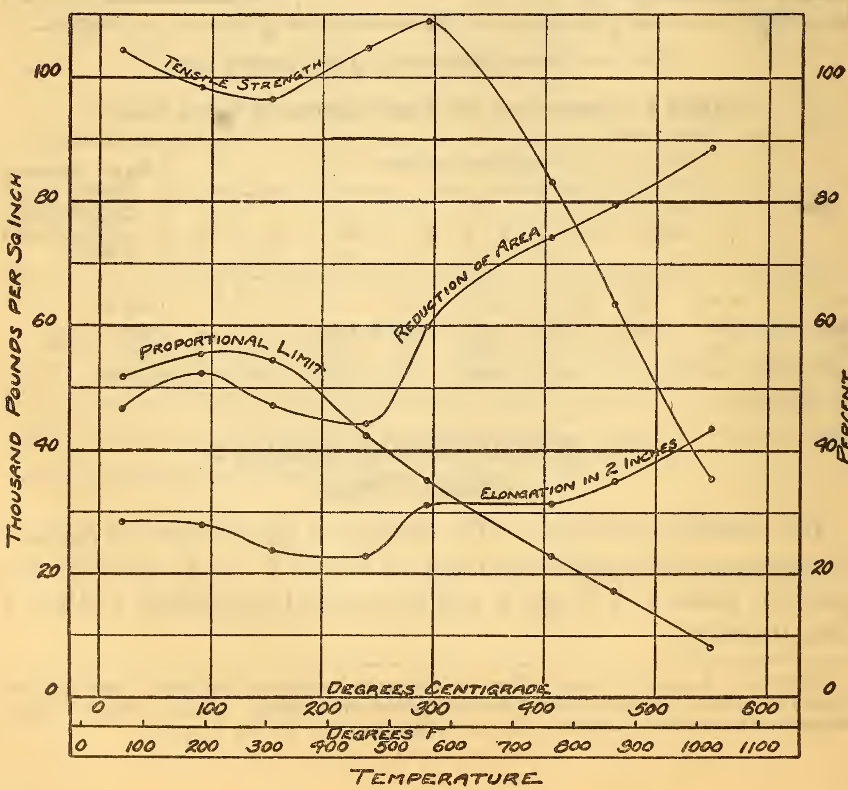

Fig. 3.—*Tensile properties at elevated temperatures of 3½ per cent nickel steel containing 0.37 per cent carbon*

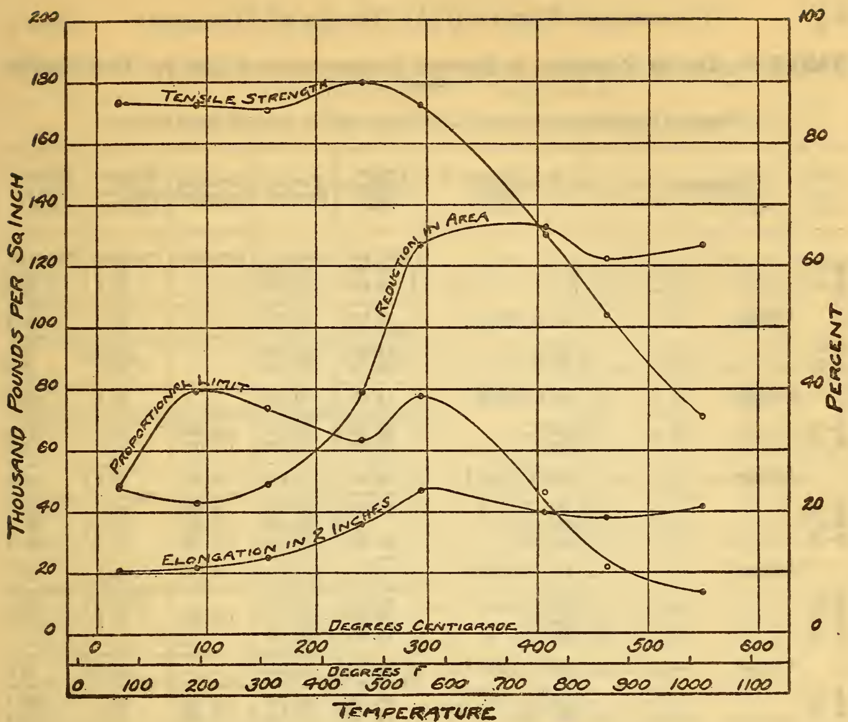

FIG. 4.—*Tensile properties at elevated temperatures of nickel-chromium steel o the type 3 per cent nickel, 1 per cent chromium, and 0.4 per cent carbon*

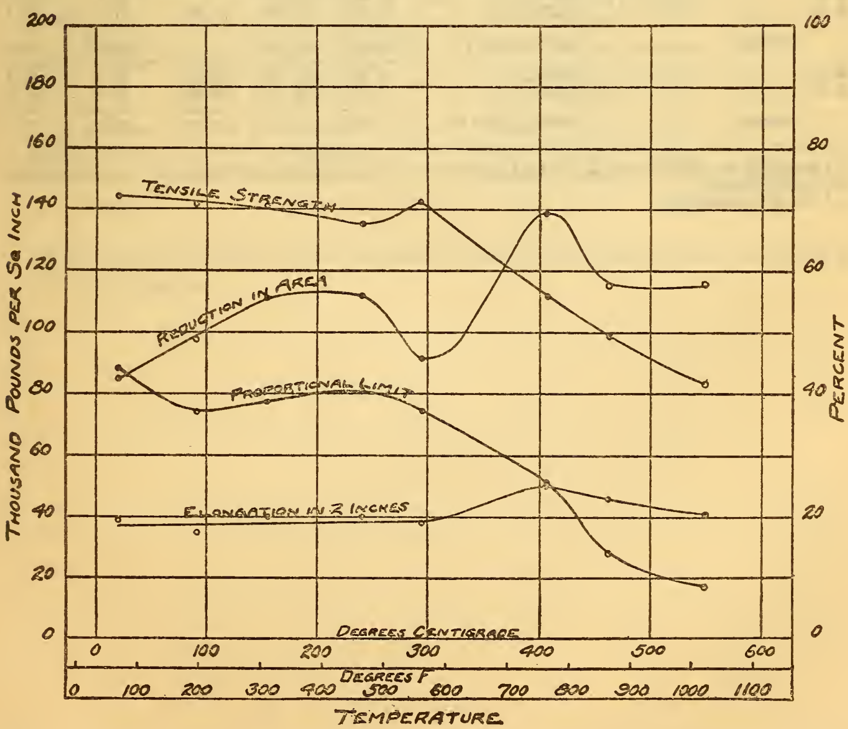

FIG. 5.—*Tensile properties at elevated temperatures of chromium-vanadium steel of the type 1 per cent chromium, 0.2 per cent vanadium, and 0.37 per cent carbon*

TABLE 4.—Tensile Properties at Elevated Temperatures of 0.38 Per Cent Carbon Steel

[Chemical composition (per cent): C, 0.38; Mn, 0.55; P, 0.014; S, 0.013; Si, 0.14]

Number	Temperature of test	Proportional limit	Tensile strength	Breaking strength[a]	Elongation in 2 inches	Reduction of area
		Lbs./in.²	Lbs./in.²	Lbs./in.²	Per cent	Per cent
A-1	(b)	34 900	85 200		27.5	52.3
A-2		30 500	83 200		33.5	53.3
Average	21° C (70° F)	32 700	84 200		30.5	52.8
A-6	92° C	34 000	79 400		28.0	47.6
A-9	92° C	33 700	79 500		29.5	52.2
Average	92° C (198° F)	33 850	79 450		28.8	49.9
A-10	155° C	33 250	85 500	140 000	24.5	47.2
A-13	155° C	32 750	80 200	137 000	26.0	48.3
Average	155° C (311° F)	33 000	82 850	138 500	25.2	47.8
A-12	241° C	27 500	87 500	129 000	19.0	37.0
A-17	241° C		90 400	127 400	18.0	32.7
A-18	241° C	30 000	88 900	129 700	17.5	36.9
Average	241° C (466° F)	28 750	88 950	128 700	18.2	35.5
A-8	292° C	26 000	91 500		24.0	28.6
A-11	294° C	24 500	93 500	116 700	20.0	27.5
A-19	294° C	20 000	94 000			
Average	293° C (559° F)	23 500	93 000		22.0	28.0
A-7	407° C	18 500	68 000	137 700	36.5	76.2
A-15	407° C	18 500	72 500	145 800	34.0	73.8
Average	407° C (765° F)	18 500	70 250	141 750	35.2	75.0
A-3	463° C	21 400	57 300		35.5	78.1
A-16	463° C	15 300	56 000	123 700	37.0	79.2
Average	463° C (865° F)	18 350	56 650		36.2	78.6
A-21	550° C	9 500	41 700	133 200	38.0	93.0
A-22	550° C	6 000	38 150	100 300	43.0	92.5
Average	550° C (1022° F)	7 750	39 950	116 750	40.5	92.7

[a] Breaking strength is taken as the load observed at fracture (in pounds) divided by the reduced area (in square inches).

[b] Room temperature.

TABLE 5.—Tensile Properties at Elevated Temperatures of 3½ Per Cent Nickel Steel Containing 0.37 Per Cent Carbon

[Chemical composition (per cent): C, 0.37; Mn, 0.67; P, 0.021; S, 0.010; Si, 0.20; Ni, 3.43]

Number	Temperature of test	Proportional limit	Tensile strength	Breaking strength[a]	Elongation in 2 inches	Reduction of area
		Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent
B-16	([b])	47 000	105 150	172 500	30.5	50.6
B-17	([b])	56 000	104 900	164 000	27.5	46.7
B-2	([b])	....	103 600	152 000	27.5	39.9
B-4	([b])	52 500	103 400	170 800	28.0	49.7
Average	21° C (70° F)	51 850	104 250	164 800	28.4	46.7
B-21	92° C	53 000	97 600	169 200	28.5	54.1
B-22	92° C	58 000	97 800	170 300	29.0	52.3
B-1	92° C	....	99 600	169 500	26.0	51.3
B-3	92° C	....	99 300	172 300	28.0	52.4
Average	92° C (198° F)	55 500	98 600	170 300	27.9	52.5
B-6	155° C	52 500	97 100	170 800	22.0	43.2
B-12	155° C	56 000	96 200	159 700	24.5	47.3
B-19	155° C	55 000	98 300	169 300	25.0	49.4
B-5	155° C	....	95 000	161 300	23.5	48.5
Average	155° C (311° F)	54 500	96 650	165 300	23.8	47.1
B-18	241° C	42 500	104 600	181 200	25.0	51.5
B-7	241° C	....	106 200	163 600	22.0	40.6
B-8	241° C	42 500	103 500	154 300	21.5	40.9
Average	241° C (466° F)	42 500	104 750	166 350	22.8	44.3
B-10	294° C	34 000	109 500	194 400	31.0	60.2
B-9	294° C	36 500	108 900	194 800	32.0	59.7
Average	294° C (561° F)	35 250	109 200	194 600	31.5	60.0
B-15	407° C	21 500	83 000	152 600	31.5	74.4
B-13	407° C	24 000	83 250	169 700	31.5	74.5
Average	407° C (765° F)	22 750	83 150	161 150	31.5	74.5
B-14	463° C	16 000	63 900	126 400	35.0	79.6
B-11	463° C	18 500	63 500	127 900	35.0	79.7
Average	463° C (865° F)	17 250	63 700	127 150	35.0	79.7
B-24	550° C	7 500	37 400	79 000	42.5	88.3
B-25	550° C	9 000	33 300	76 300	44.5	89.5
Average	550° C (1022° F)	8 250	35 350	77 650	43.5	88.9

[a] Breaking strength is taken as the load observed at fracture (in pounds) divided by the reduced area (in square inches).
[b] Room temperature.

TABLE 6.—Tensile Properties at Elevated Temperatures of Nickel-Chromium Steel of the Type 3 Per Cent Nickel, 1 Per Cent Chromium, 0.4 Per Cent Carbon

[Chemical composition (per cent): C, 0.39; Mn, 0.59; P, 0.019; S, 0.009; Si, 0.23; Ni, 3.05; Cr, 0.93]

Number	Temperature of test	Proportional limit	Tensile strength	Breaking strength[a]	Elongation in 2 inches	Reduction of area
		Lbs./in.²	Lbs./in.²	Lbs./in.²	Per cent	Per cent
C-14	(b)	58 500	175 000	213 700	10.0	22.9
C-15	(b)	58 500	171 800	207 000	11.0	25.2
Average	21° C (70° F)	58 500	173 400	210 350	10.5	24.0
C-2	92° C	84 700	175 000		11.0	20.3
C-3	92° C	74 000	170 000		11.0	23.1
Average	92° C (198° F)	79 350	172 500		11.0	21.7
C-6	155° C	75 000	175 200		12.5	23.2
C-7	155° C	72 500	166 000		12.5	26.2
Average	155° C (311° F)	73 750	170 600		12.5	24.7
C-4	241° C	63 500	181 300		18.0	39.6
C-5	241° C	62 500	178 000			
Average	241° C (466° F)	63 000	179 650			
C-8	294° C	75 000	174 000		23.5	62.4
C-9	294° C	80 000	171 000		23.5	63.8
Average	294° C (561° F)	77 500	172 500		23.5	63.1
C-10	407° C	43 000	127 600	181 200	20.0	66.5
C-11	407° C	49 000	132 200	209 000	20.0	65.4
Average	407° C (765° F)	46 000	129 900	195 100	20.0	66.0
C-12	463° C	22 000	105 000	137 700	19.0	59.9
C-13	463° C	21 500	102 500	150 300	19.0	62.0
Average	463° C (865° F)	21 750	103 750	144 000	19.0	61.0
C-16	550° C	12 000	72 100	90 000	19.0	59.0
C-17	550° C	15 000	69 500	95 750	22.5	67.3
Average	550° C (1022° F)	13 500	70 800	92 850	20.8	63.2

[a] Breaking strength is taken as the load observed at fracture (in pounds) divided by the reduced area (in square inches).
[b] Room temperature.

TABLE 7.—Tensile Properties at Elevated Temperatures of Chromium-Vanadium Steel of the Type 1 Per Cent Chromium, 0.2 Per Cent Vanadium, 0.37 Per Cent Carbon

[Chemical composition (per cent): C, 0.37; Mn, 0.74; P, 0.020; S, 0.023; Si, 0.21; Cr, 1.04; V, 0.17]

Number	Temperature of test	Proportional limit	Tensile strength	Breaking strength[a]	Elongation in 2 inches	Reduction of area
		Lbs./in.²	Lbs./in.²	Lbs./in.²	Per cent	Per cent
D1	(b)	88 000	141 600	236 000	20.0	55.5
D-16	(b)	88 000	147 000	224 500	19.0	49.4
Average	21° C (70° F)	88 000	144 300	230 250	19.5	42.5
D-3	92° C	81 000	150 800	229 400	17.5	48.4
D-4	92° C	70 000	135 100	224 300	18.0	51.7
D-15	92° C	73 000	139 500	224 100	17.5	46.2
Average	92° C (198° F)	74 650	141 800	225 950	17.7	48.8
D-7	155° C	76 000	136 200.	240 000	20.0	55.7
D-8	155° C	79 000	146 500	203 000	....	....
Average	155° C (311° F)	77 500	141 350	221 500	....	....
D-5	241° C	81 000	133 600	252 300	21.0	58.6
D-6	241° C	80 000	137 200	238 700	19.0	53.3
Average	241° C (466° F)	80 500	135 400	245 500	20.0	56.0
D-9	294° C	76 000	145 500	223 400	19.0	45.8
D-10	294° C	73 000	139 000	261 300	....	....
Average	294° C (561° F)	74 500	142 250	242 350	....	....
D-11	407° C	50 000	108 000	182 300	25.0	67.7
D-12	407° C	51 500	115 200	213 000	25.0	71.2
Average	407° C (765° F)	50 750	111 600	197 500	25.0	69.5
D-13	463° C	27 000	97 500	122 500	23.5	52.9
D-14	463° C	29 000	101 000	147 300	22.5	62.4
Average	463° C (865° F)	28 000	99 250	134 900	23.0	57.7
D-18	550° C	16 500	82 600	118 800	22.0	61.7
D-19	550° C	17 500	84 000	111 000	19.0	54.4
Average	550° C (1022° F)	17 000	83 300	114 900	20.5	58.0

[a] Breaking strength is taken as the load observed at fracture (in pounds) divided by the reduced area (in square inches).
[b] Room temperature.

Maximum strength of the carbon, 3½ per cent nickel and nickel-chromium steels, occurs between about 240 and 300° C (465 and 565° F), whereas the strength of the chromium-vanadium steel does not exceed its room temperature value within the temperature range under consideration. However, a rapid decrease in this factor is observed in all steels above 300° C (565° F).

At 550° C (1020° F) the strength of the chromium-vanadium steel is very much greater than that of the other alloys and more than twice that of the carbon steel. It has likewise decreased the least in strength from its room temperature value, as shown in Table 8. However, at all temperatures below about 475° C (885° F) the strength of the nickel-chromium steel is greater than that of the chromium-vanadium.

TABLE 8.—Comparison of Tensile Strengths of Carbon and Alloy Steels at Room Temperature and 550° C

Steel	Tensile strength at room temperature	At 550° C (1022° F)		
		Actual tensile strength	Decrease from room temperature value	Ratio of tensile strengths with carbon steel as unity
	Lbs./in.²	Lbs./in.²	Per cent	
Carbon	84 200	39 950	52.5	1.0
Nickel	104 250	35 350	66.0	.9
Nickel-chromium	173 400	70 800	59.1	1.8
Chromium-vanadium	144 300	83 300	42.4	2.1

(*b*) PROPORTIONAL LIMIT.—The proportional limits of the carbon, 3½ per cent nickel and nickel-chromium steels, increase with first rise in temperature and reach maximum values in the neighborhood of 150° C (300° F), whereas that of the chromium-vanadium steel is greatest at room temperature and, following a marked decrease, again increases perceptibly between about 150 to 250° C (300 to 480° F) before final decrease occurs. While the maximum value of the limit of proportionality of the nickel-chromium steel occurs at about 150° C (300° F) and is followed by a material decrease, a second rise in value is observed at about 300° C (570° F), so that this factor is maintained above its room temperature value until temperatures above about 370° C (700° F) are reached.

The limit of proportionality of the chromium-vanadium steel at 550° C (1020° F) has decreased proportionally more than either the carbon or nickel-chromium steels, as shown in Table 9, but its value at the high temperature indicated is greater than either of the latter and more than twice that of the carbon steel.

TABLE 9.—Comparison of Proportional Limits of Carbon and Alloy Steels at Room Temperature and 550° C

Steel	Proportional limit at room temperature	At 550° C (1022° F)		
		Actual proportional limit	Decrease from room temperature value	Ratio of proportional limits with carbon steel as unity
	Lbs./in.²	Lbs./in.²	Per cent	
Carbon	32 700	7750	76.3	1.0
Nickel	51 850	8250	84.2	1.1
Nickel-chromium	58 500	13 500	77.6	1.7
Chromium-vanadium	88 000	17 000	80.7	2.2

(c) Elongation and Reduction of Area.—The effect of temperature is greater upon the values of reduction of area than elongation. In general, the inflections in the temperature elongation and temperature reduction of area curves shown in Figs. 2, 3, 4, and 5 are so varied that no attempt will be made to describe them. However, several generalizations may be made. The carbon and 3½ per cent nickel steels behave similarly, in that rise in temperature is accompanied by a general decrease in ductility, which is followed above the range 200 to 300° C (390 to 565° F) by an increase until at 550° C (1020° F) values of elongation and reduction of area are greater than those observed at room temperature.

The elongation of the chromium-vanadium steel is about the same at 550° C (1020° F) as at room temperature and does not show any very great changes throughout this temperature range, whereas elongation of the nickel-chromium steel increases to a maximum at about 295° C (565° F) (blue heat).

While the carbon and nickel steels are much more ductile at 550° C (1020° F) than either the chromium-vanadium or nickel-chromium steels, as shown in Tables 10 and 11, yet the last two alloys have high ductility, and the latter shows by far the greatest increase over its room temperature value.

TABLE 10.—Comparison of Elongations of Carbon and Alloy Steels at Room Temperature and 550° C

Steel	Elongation in 2 inches at room temperature	At 550° C (1022° F)		
		Actual elongation in 2 inches	Increase from room temperature value	Ratio of elongations with carbon steel as unity
	Per cent	Per cent	Per cent	
Carbon	30.5	40.5	32.8	1.0
Nickel	28.4	43.5	51.4	1.1
Nickel-chromium	10.5	20.8	98.0	.5
Chromium-vanadium	19.5	20.5	5.1	.5

TABLE 11. Comparison of Reductions of Area of Carbon and Alloy Steels at Room Temperature and 550° C

Steel	Reduction of area at room temperature	At 550° C (1022° F)		
		Actual reduction of area	Increase from room temperature value	Ratio of reductions of area with carbon steel as unity
	Per cent	Per cent	Per cent	
Carbon	52.8	92.7	75.5	1.0
Nickel	46.7	88.9	90.3	1.0
Nickel-chromium	24.0	63.2	163.3	.7
Chromium-vanadium	42.5	58.0	36.5	.6

(*d*) Breaking Strength.—The strength at fracture of the different steels tested, obtained by dividing the load observed at the moment of breaking by the reduced area, is shown in Fig. 6. While the data are incomplete and in some cases the variations in duplicate determinations are wide, the results are interesting when taken in conjunction with the changes previously described, for at 550° C (1020° F) the highest breaking strength is shown

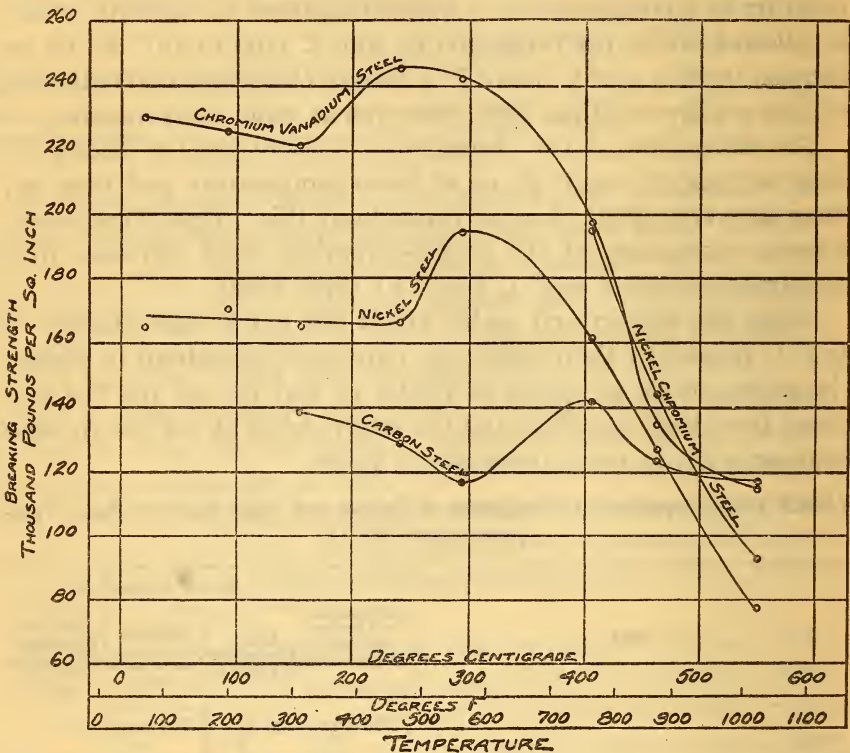

Fig. 6.—*Breaking strength at elevated temperatures of carbon, nickel, nickel-chromium, and chromium-vanadium steels. (For compositions refer to Table 3)*

by the chromium-vanadium and carbon steels and the lowest value is observed in the alloy containing 3½ per cent nickel.

2. MICROSCOPIC EXAMINATION OF FRACTURES

The fracture of steels subjected to tensile stress at room temperature is transcrystalline, while at high temperatures it takes place at the grain boundaries. The change from transcrystalline to intercrystalline fractures will occur beginning at temperatures somewhat above that of equal cohesion of the amorphous and crystalline phases, but the temperatures at which these fractures

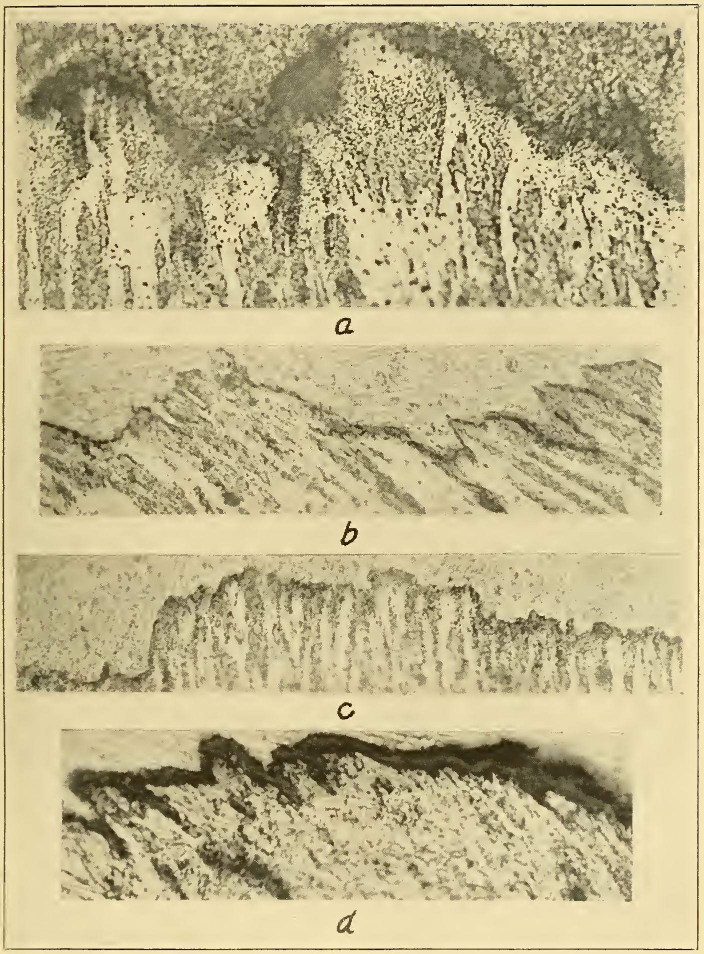

FIG. 7.—*Microphotographs of fractures of carbon and 3 1/2 per cent nickel steels broken in tension at high temperatures*

(*a*) Specimen A 16. Broken at 463° C. ×500
(*b*) Specimen A 22. Broken at 550° C. ×500
(*c*) Specimen B 11. Broken at 463° C. ×500
(*d*) Specimen B 24. Broken at 550° C. ×1000
All specimens etched with 5 per cent picric acid in alcohol

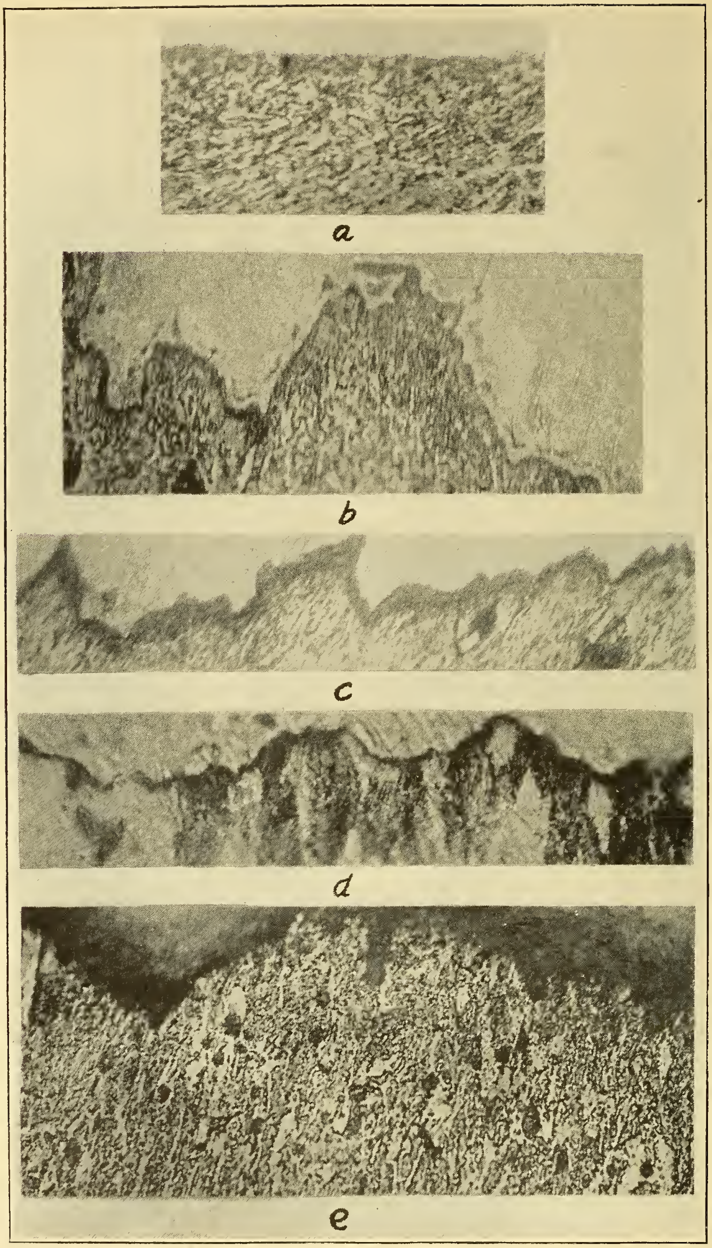

FIG. 8.—*Microphotographs of fractures of nickel-chromium and chromium-vanadium steels broken in tension at high temperatures*

(*a*) Specimen C 8. Broken at 294° C. ×1000
(*b*) Specimen C 13. Broken at 463° C. ×500
(*c*) Specimen C 16. Broken at 550° C. ×500
(*d*) Specimen D 14. Broken at 463° C. ×1000
(*e*) Specimen D 18. Broken at 550° C. ×500

a, *d*, and *e* etched with 5 per cent picric acid in alcohol; *b* and *c* with 2 per cent nitric acid in alcohol first appear in a given alloy depend upon the rate of loading.[9] The faster the load is applied the higher is the temperature required to produce intercrystalline breaks.

Jeffries states that in most metals the equicohesive temperature occurs at about 0.35 to 0.45 of the melting point on the absolute temperature scale, so that for steels the change from fractures across the grains to those along the crystal boundaries should on slow loading first appear in the neighborhood of 550° C (1020° F). This temperature is approximately the highest at which tensile tests were made, and, as these were likewise considered of particular interest from the standpoint of operation in the Haber process, specimens of the several steels tested were examined under the microscope to determine the character of the fractures.

Typical microphotographs are reproduced in Figs. 7 and 8, and while no general statements can be made with certainty they show the tendency of the fracture in the carbon and 3½ per cent nickel steels to follow the grain boundaries when broken at about 550° C (1020° F).

The outstanding feature of the nickel-chromium steel is the fineness of the structure, making it difficult to determine the character of the break, while in the case of the chromium-vanadium steel the fractures appear more nearly intracrystalline (8*e*) even at the highest temperatures under investigation.

V. SUMMARY

The following points appear to deserve emphasis in connection with the tests previously described:

1. Of the four steels tested in normalized condition it appears that the two alloys containing chromium show greater resistance to weakening by increase in temperature to about 550° C (1020° F) than either the plain carbon or 3½ per cent nickel steels, and at this highest temperature the chromium-vanadium steel is to be preferred from the standpoint of high tensile strength and limit of proportionality.

2. The carbon and 3½ per cent nickel steels behave alike with rise in temperature, and at about 550° C (1020° F) the addition of the nickel appears to have a very small effect on the tensile properties of the carbon steel.

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[9] Zay Jeffries, "Effect of temperature, deformation, and grain size on the mechanical properties of metals," Trans. A. I. M. E., **60**, p. 474; 1919.

3. At 550° C (1020° F) the strength and limit of proportionality of the chromium-vanadium steel are more than twice that of the carbon steel, while the ductility of the former, as measured by elongation and reduction of area, is about half that of the latter, though still quite high. However, at all temperatures below about 475° C (885° F) the strength of the nickel-chromium steel is greater than that of the chromium-vanadium and both show higher strength values throughout the range 20 to 550° C (70 to 1020° F) than the carbon or 3½ per cent nickel steels.

4. While no general statements regarding types of fractures can be made with certainty, the tendency of carbon and 3½ per cent nickel steels at about 550° C (1020° F) is to follow the grain boundaries, while at the same temperature the fractures of the chromium-vanadium steel appear largely transcrystalline.

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