FLOW CHARACTERISTICS OF SPECIAL Fe–Ni–Cr ALLOYS AND SOME STEELS AT ELEVATED TEMPERATURES

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ABSTRACT

The results of "creep" tests at different temperatures are given for three groups of alloys. The 11 metals in the first group included commercial alloys of nickel, chromium, and iron, both with and without tungsten, and low chromium steels containing also tungsten, vanadium, or molybdenum. The second group comprised two carbon steels, a 3½ per cent nickel steel and two low nickel chromium steels which were tested only at 700° F.; the 12 alloys of the third group were melted in a high-frequency induction furnace, and their compositions were selected to show the general trends at 1,000° F. in the load-carrying ability of castings of the nickel-chromium-iron system. A metallographic study of the creep-test specimens revealed intercrystalline weakness in some of the wrought nickel-chromium-iron alloys especially at temperatures between 1,160° and 1,390° F. A study was also made of the effect of deformation in the creep tests at different temperatures on the hardness and impact resistance of a chromium vanadium steel at atmospheric temperatures.

CONTENTS

		Page
I.	Introduction	125
II.	Test methods	126
III.	Materials tested	130
IV.	Results and discussion	131
	1. General relations between stress, temperature, deformation, and time	131
	2. Commercial nickel-chromium-iron alloys	143
	3. Carbon and low alloy steels	174
	4. Effect of prolonged stress at different temperatures on hardness and impact resistance at atmospheric temperatures	175
	5. Trends at 1,000° F. in the system Ni–Cr–Fe	177
V.	Summary	181
VI.	Acknowledgments	183

I. INTRODUCTION

Considerable attention is now being given in both this country and Europe to "creep" tests (or flow tests) in which the time-deformation relationship is determined for metals subjected to constant loads for long periods at approximately constant temperatures. Previous tests at the Bureau of Standards have related jointly to the development of a testing technique and to the procurement of data intended to assist engineers in the selection of safe working stresses for equipment designed to operate at elevated temperatures. Correlations have also been made between the laborious flow tests and short-time tension tests with the object of finding, if possible, rapid methods of determining approximately the load-carrying ability of metals at different temperatures.

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So far, data have been published for only five steels, and the purpose of this report is to present the results of additional tests extending over several years so that comparisons can be made of a wider range of metals, based on data secured under comparable conditions in one laboratory. The work simply represents the extension to more materials of the methods of test already described in detail.[2 3 4]

Tests were made of three groups of metals; the first, comprising commercial nickel-chromium and nickel-chromium-iron alloys and low-chromium steels containing tungsten, vanadium, or molybdenum, were tested, with one exception, under the research associate plan [5] with a research associate from The Midvale Co., Philadelphia, Pa. The second group consisting of two carbon steels, a 3½ per cent nickel steel and two low nickel-chromium steels were tested at 700° F. to assist the Bethlehem Steel Co., Bethlehem, Pa., and the Combustion Engineering Corporation, New York, N. Y., in the selection of a composition suited for particular requirements of power-plant construction. The metals of the third group were used in a study of the flow characteristics at 1,000° F. of alloys of the nickel-chromium-iron system.

II. TEST METHODS

The test methods employed were substantially the same as those used previously, but subsequently to the last published descriptions a number of modifications were incorporated in the equipment and test procedure. Four of the ten horizontal loading machines were replaced by vertical units (fig. 1) in which the frictional losses of the mechanical lever system were materially reduced. The new units were, therefore, better adapted than the old horizontal units for tests at the highest temperatures where the applied loads were the smallest.

The temperature fluctuations within the test specimens were reduced by placing the control thermocouples at the furnace windings instead of in the test specimens. Resistors of improved form (fig. 2) were installed in the furnaces of the vertical test units to reduce the temperature gradients from top to bottom in the test specimens. In order to secure greater accuracy in the length measurements with the metals which oxidized most readily, the practice was followed of using platinum or silver wire (32 B. & S. gage) in small grooves as reference points for length measurements with an optical micrometer instead of the edge of the enlarged end section of the specimen.

Only a limited quantity of some of the metals was available. The desire to secure the maximum information under such conditions led to the adoption of a specimen having two different diameters within the customary 2-inch gage length as is shown in Figure 3. A given applied load produced different unit stresses in the two halves of the gage length of such a specimen, and this was equivalent to two of the customary specimens. However, the use of the modified test specimen is not advocated under ordinary conditions. It is disadvan-

[2] H. J. French and W. A. Tucker, Flow in a Low-Carbon Steel at Various Temperatures, B. S. Tech. Papers No. 296; 1925.

[3] H. J. French, Methods of Test in Relation to Flow in Steels at Various Temperatures, Proc. Am. Soc. Test. Matls., 26, p. 7; 1926.

[4] H. J. French, H. C. Cross, and A. A. Peterson, Creep in Five Steels at Different Temperatures, B. S. Tech. Papers, No. 362; 1928.

[5] Described in Circular No. 296 of the Bureau of Standards

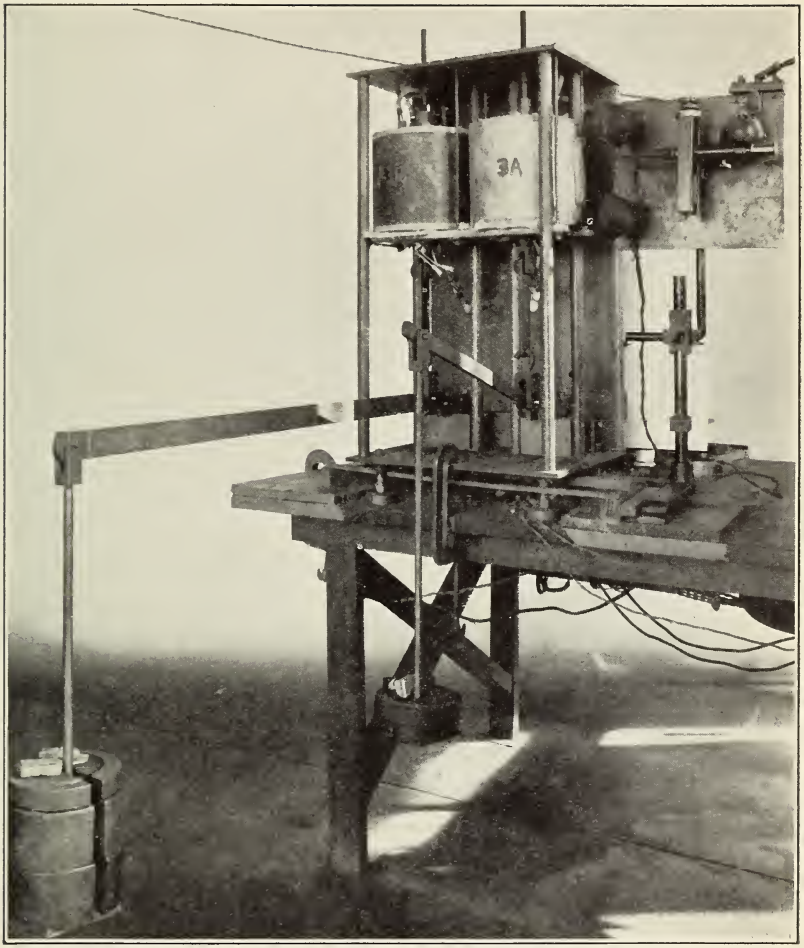

FIGURE 1.—*Two of the vertical test units for flow tests at different temperatures*

Four vertical and six horizontal test units constituted the testing equipment for the flow tests. The optical micrometer used in making length measurements is shown on the stand at the right.

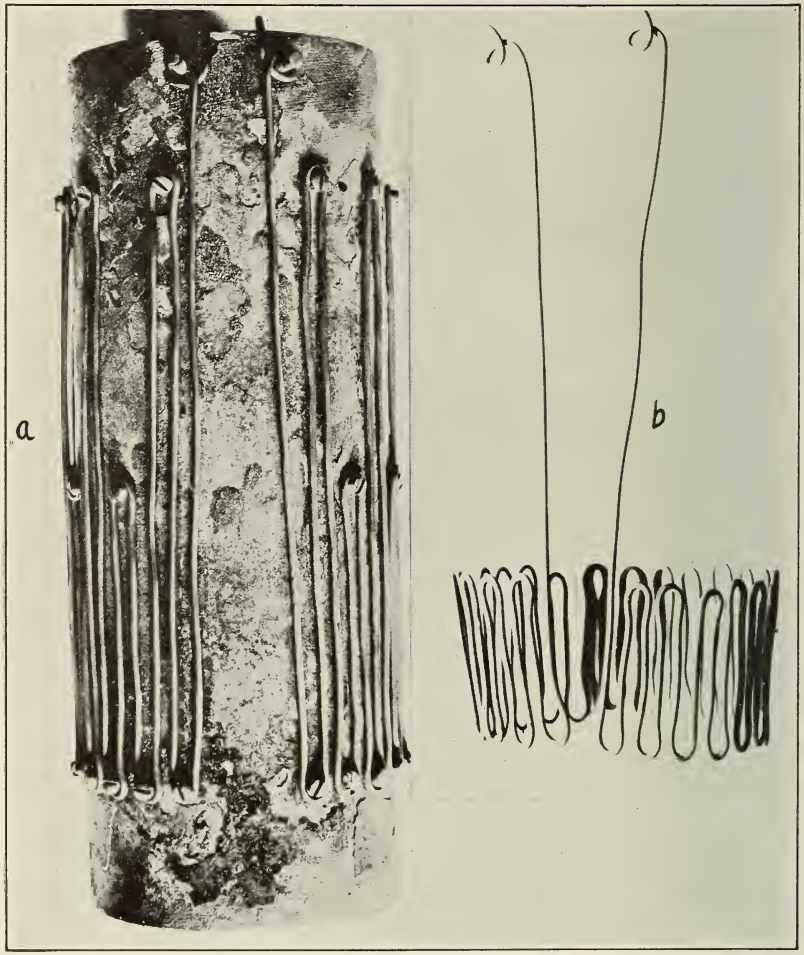

FIGURE 2.—*Improved resistors of the heating units*

a, The main resistor on the forming fixture; *b*, auxiliary resistor placed outside and at the lower end of the main resistor.

tageous to reduce the measured length from 2 inches to 1 inch and the abrupt change in section at the center of the 2-inch gage length may introduce stress concentrations and also tend to increase the temperature variations in the test sections. As a result, the flow

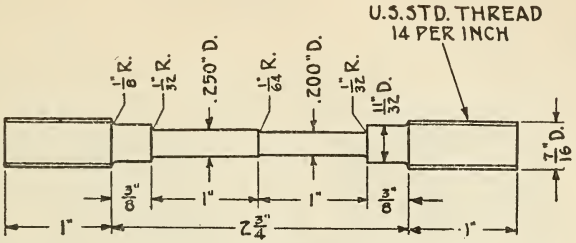

FIGURE 3.—*Modified flow test specimen used in some of the tests*

The flow under two different stresses can be followed on the one test specimen. See text for discussion.

produced by a given stress in the large half was not always as close as could reasonably have been expected to that produced by the same stress in the small half of the gage length. In cases of doubt many of the tests were repeated on test bars having a gage length of uniform diameter.

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TABLE 1.—*Chemical composition*

Group I.—TESTED AT DIFFERENT TEMPERATURES

Designation	Chemical composition											
	C	Mn	P	S	Si	Ni	Cr	W	Mo	V	Fe	Cu
	Per cent [1]	*Per cent* [1]	*Per cent* [1]	*Per cent* [1]	*Per cent* [1]	*Per cent* [1]	*Per cent* [1]	*Per cent* [1]	*Per cent* [1]	*Per cent* [1]	*Per cent* [1]	*Per cent* [1]
K4	0.31	2.79	------	------	0.27	76.0	18.8	------	------	------	0.80	0.66
E1894	.25	1.40	0.028	0.020	.06	60.8	10.75	2.8	------	------	------	------
FS-1, lot A	.19	1.62	.028	.027	.10	57.6	10.28	3.19	------	------	------	------
FS-1, lot B	.20	1.66	.026	.029	.08	57.4	10.34	3.30	------	------	------	------
FS-2, lot A	.32	1.52	.028	.038	.03	34.9	12.93	tr.	------	------	------	------
FS-2, lot B	.28	1.45	.032	.027	.03	35.9	11.12	.34	------	------	------	------
E1567	.28	1.50	.024	.018	.07	38.6	10.64	1.77	------	------	------	------
EE1114	.29	.50	------	------	1.18	8.0	19.86	4.5	------	------	------	------
E1912	.15	.35	.020	.021	.22	8.46	17.32	------	------	------	------	------
10-518, lot A	.40	.57	------	------	.25	------	2.26	------	------	0.20	------	------
10-518, lot B	.40	.57	------	------	.25	------	2.26	------	------	.20	------	------
EE1139	.46	.37	------	------	.19	------	2.2	1.65	------	.25	------	------
E1549	.53	.95	.037	.015	.23	------	1.07	------	0.44	------	------	------
E1490	.75	.52	.028	.016	.31	.15	1.45	------	.54	.27	------	------
Group II.—TESTED AT 700° F. (370° C.)												
4H451	0.23	0.48	0.015	0.024	0.18	0.05	------	------	------	------	------	------
2H384	.45	.55	.016	.027	.15	.24	------	------	------	------	------	------
4H247	.37	.68	.018	.023	.21	3.46	------	------	------	------	------	------
1H391	.36	.63	.014	.022	.19	1.25	0.62	------	------	------	------	------
1H396	.35	.49	.017	.017	.19	1.66	0.99	------	------	------	------	------
Group III.—TESTED AT 1,000° F. (540° C.)												
1000A	0.19	0.75	------	------	0.69	------	------	------	------	------	Bal.[5]	------
1001D	.25	.80	------	------	.89	Bal.	------	------	------	------	------	------
1002A	.24	.88	------	------	.52	68.5	------	------	------	------	Bal.[5]	------
1003A	.18	.75	------	------	.57	30.6	------	------	------	------	Bal.[5]	------
1004A	.37	.67	------	------	.53	------	14.5	------	------	------	Bal.[5]	------
1004B	.24	.59	------	------	.39	------	14.6	------	------	------	Bal.[5]	------
1005B	.38	.73	------	------	.82	------	30.2	------	------	------	Bal.[5]	------
1006B	.49	.68	------	------	1.01	------	55.3	------	------	------	Bal.[5]	------
1007B	.51	.74	------	------	.75	78.2	18.3	------	------	------	------	------
1008B	.24	.88	------	------	1.14	49.7	46.3	------	------	------	------	------
1009A	.41	.53	------	------	.78	58.7	14.8	------	------	------	------	------
1010A	.11	.54	------	------	.77	25.5	16.4	------	------	------	------	------
1011A	.11	.59	------	------	.87	35.4	27.2	------	------	------	Bal.[5]	------
Group IV.—STEELS PREVIOUSLY TESTED (INCLUDED FOR CONVENIENCE OF GENERAL COMPARISONS)												
	0.24	0.37	0.021	0.028	0.01	------	------	------	------	------	------	------
K3	.39	.51	.015	.029	.19	------	0.87	------	0.21	------	------	------
A336	.77	.24	.031	.035	.42	0.14	3.9	13.6	------	1.9	------	------
A340	.28	.38	.026	.013	.17	------	20.5	------	------	------	------	0.98
A347	.24	.53	.009	.005	2.96	23.3	18.05	------	------	------	------	------

[1] As reported by the maker for Groups I and II; by the Bureau of Standards, H. A. Bright, for Groups III and IV.

[2] Specimens cut at 90° to the direction of rolling, half way between center and surface of blooms at some distance from the ends.

and other details of the metals

Group I.—TESTED AT DIFFERENT TEMPERATURES

Specimens taken from—	Treatment before test	Properties at room temperature				
		Yield point	Tensile strength	Elongation in 2 inches	Reduction of area	Brinell No.
		1,000 lbs./in.²	*1,000 lbs./in.²*	*Per cent*	*Per cent*	
Rolled ¾-inch bars	1,900° F., 3 hours air cooled	39.5	116.5	37.5	50.3	--------
Riser from casting	Annealed 1,470° F	23.0	75.2	10.0	11.5	--------
Rolled bars	As rolled	63.0	112.5	30.0	36.9	207
do	Annealed 1,650° F	57.5	110.0	31.0	51.6	200
do	As rolled	68.0	100.0	33.0	54.1	181
do	Annealed 1,650° F	54.0	99.5	33.0	47.7	172
As rolled		69.0	120.5	24.0	44.9	--------
Experimental melt, forged.		--------	--------	--------	--------	--------
Rolled bars	Lot A	40.0	95.0	45.0	60.0	--------
	Lot B, 1,850° F., water	64.8	112.2	[3] 54.5	[3] 63.5	--------
do	1,575° F., 1 hour slow cool; 1,375° F., 1 hour furnace.	54.2	87.2	28.3	69.2	--------
do	1,575° F., 1 hour air; 1,300° F., 1 hour furnace.	86.0	105.6	23.7	68.2	--------
Experimental melt, rolled.	1,400° F., 2 hour slow cool; 1,740° F., 1 hour oil; 1,000° F., 1 hour air cool.	207.0	231.5	7.8	22.8	444
Forged bars	1,550° F., 1 hour oil; 1,200° F., 4 hours slow cool.	124.0	143.0	[4] 18.7	[4] 56.0	--------
do	1,550° F., 1 hour oil; 1,100° F., 4 hours slow cool.	--------	174.0	[4] 7.5	[4] 16.7	--------

Group II.—TESTED AT 700° F. (370° C.)

6 by 6 inch rolled blooms.[2]	1,650° F., 4 hours furnace; 1,600° F., 4 hours air; 1,330° F., 4 hours furnace.	39.0	60.0	17.5	29.2	--------
5 by 5 inch rolled blooms.[2]	1,650° F., 4 hours furnace; 1,500° F., 4 hours air; 1,330° F., 4 hours furnace.	42.5	80.0	17.0	27.5	--------
6 by 5 inch rolled blooms.[2]	1,650° F., 4 hours furnace; 1,500° F., 4 hours air; 1,360° F., 4 hours furnace.	57.0	97.0	16.0	25.1	--------
6 by 6 inch rolled blooms.[2]	1,650° F., 4 hours furnace; 1,500° F., 4 hours air; 1,280° F., 4 hours furnace.	55.0	94.0	15.0	17.0	--------
5 by 4 inch rolled blooms.[2]	1,650° F., 4 hours furnace; 1,500° F., 4 hours air; 1,320° F., 4 hours furnace.	52.0	93.0	24.0	47.7	--------

Group III.—TESTED AT 1,000° F. (540° C.)

1½ inch octagonal ingots weighing about 3 pounds.	1,650° F., ½ hour air cool	--------	--------	--------	--------	150
	1,500° F., ½ hour air cool	--------	--------	--------	--------	114
	1,650° F., ½ hour air cool	--------	--------	--------	--------	131
	1,450° F., 1 hour furnace cool	--------	--------	--------	--------	147
	1,650° F., 2 hours furnace cool	--------	--------	--------	--------	298–319
	do	--------	--------	--------	--------	219–222
	1,800° F., 2 hours air cool	--------	--------	--------	--------	217
	1,900° F., 3 hours air cool	--------	--------	--------	--------	363–388
	do	--------	--------	--------	--------	183
	do	--------	--------	--------	--------	285
	do	--------	--------	--------	--------	138
	2,000° F., 1 hour air cool	--------	--------	--------	--------	113
	1,900° F., 3 hours air cool	--------	--------	--------	--------	144

Group IV.—STEELS PREVIOUSLY TESTED (INCLUDED FOR CONVENIENCE OF GENERAL COMPARISONS)

1-inch hot-rolled plate		33.0	66.7	30.0	59.2	--------
1⅛-inch diameter rolled bars.	1,625° F., 2 hours air; 1,550° F., 1½ oil; 1,300° F., 2 hours oil.	--------	98.5	22.0	70.9	--------
1-inch diameter rolled bars.	Tested "as received," probably annealed.	95.7	110.1	[3] 17.0	[3] 36.5	--------
½-inch diameter rolled bars.	1,830° F., water; 1,200° F., air	67.3	89.8	[3] 21.5	[3] 55.6	--------
1⅛-inch diameter rolled bars.	1,450° F., 2 hours furnace cool	49.0	110.0	33.0	47.5	--------

[3] Determined on tensile-test specimens with a diameter of about 0.25 inch and a gage length of 2 inches.
[4] Determined on tensile-test specimens with a section ⅝ by 0.1565 inch.
[5] Containing impurities, such as small amounts of phosphorus and sulphur.

III. MATERIALS TESTED

The composition and other details of the metals tested are summarized in Table 1. The 11 metals of the first group may be divided into three classes; the first comprised the one alloy, K–4, which was prepared for the Joint Research Committee on Effect of Temperature on the Properties of Metals [6] to represent the alloy 80 nickel, 20 chromium, widely used as resistance wire. Its composition is actually not representative of the bulk of the metal used in such wires, but it should serve to indicate in a general way the flow characteristics of this class of material. The second class in the first group comprised nickel-chromium-iron alloys both with and without appreciable proportions of tungsten, while the third class consisted of low-alloy steels having not more than 4 per cent of alloying elements.

The six nickel-chromium-iron alloys in the first group represent compositions which have been used industrially in the construction of chemical or engineering equipment operating at high temperatures. Alloys E1894 and E1567 were made in this country and the test bars from heat E1894 were taken from the riser of a casting and do not represent the best properties obtainable at either room or elevated temperatures (Table 1.) The similar alloys, marked FS–1 and FS–2 were made abroad.

Alloy E1912 is an austenitic steel of the type of Krupp's V2A and the English corrosion resistant steel called Stabrite. Since austenitic steels are often said to retain a high proportion of their room temperature strength at elevated temperatures, this nickel-chromium steel was included for comparison with the high-chromium "stainless" steels previously tested. Alloy EE1114 is similar to alloy E1912 with the exception that it has somewhat higher carbon and silicon and 4.5 per cent of tungsten.

The materials designated as E1894, FS–1, FS–2 and E1567 have been used extensively abroad and to a lesser degree in this country, the first two chiefly in the form of castings, the latter pair largely as forgings. Alloy EE1114 which has been used both in castings and in forgings, is claimed to be resistant to softening at elevated temperatures and to resist scaling, even in oxidizing and sulphurous atmospheres at temperatures as high as 2,000° F.

The chromium-vanadium steel, No. 10–518, Table 1, has been used widely for autoclaves, and, especially with a somewhat lower carbon content, for vessels for ammonia synthesis. The treatments to which this steel was subjected before test were intended to produce conditions comparable to those existing in the walls of forgings too large to quench and too thick to harden effectively in the air.

Steels EE1139, E1549, and E1490 are compositions used in cylinders for the extrusion of metals. Such cylinders, or the liners for such cylinders, are subjected to severe service. The material must flow only very slowly under fairly high pressures at temperatures as high as 1,200° or 1,300° F. and at the same time exhibit sufficient toughness to resist cracking.

The two carbon steels and the three low-alloy steels comprising the second group of metals in Table 1 were made in 75-ton basic open-hearth furnaces and cast into large-end-up, hot-top ingots.

[6] A committee sponsored by the American Society for Testing Materials and the American Society of Mechanical Engineers.

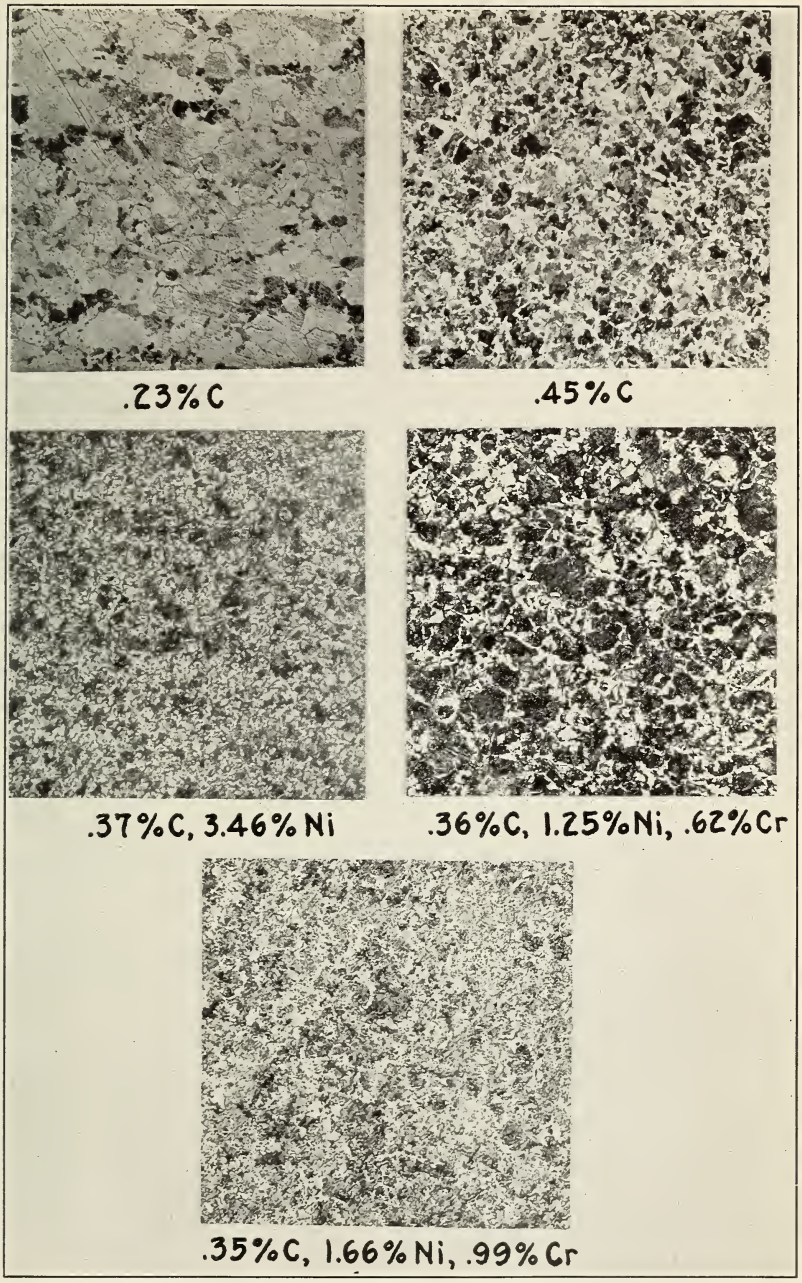


FIGURE 4.—*Micrographs of the steels of Group II, Table 1, in the conditions tested, ×100*

These photographs supplied by the maker. Etched with 3 per cent HNO_3 in alcohol.

The ingots were charged hot into the soaking pits, and after being brought to the proper rolling temperatures, rolled to the bloom sizes shown in Table 1. After heat treatment, as indicated, flow test specimens were cut from the blooms, the long axis being at 90° to the direction of rolling, at points halfway between the center and surface, but at an appreciable distance from the ends. The heat treatment and the method of taking the flow test specimens were selected to represent the metal in large forgings for high-temperature, high-pressure, power-plant equipment, and the tests at 700° F., were made to assist in the selection of a steel to meet special design requirements. The specified heat treatments did not reduce the strengths of the steels at atmospheric temperatures to the desired values in all cases, and it was necessary to repeat the treatments for some of the steels in order to obtain the desired properties.

In view of the fact that some of these steels were heat treated more than once, the structural condition of the material as tested is shown in the micrographs of Figure 4.

The metals of the third group, Table 1, were melted in a high-frequency induction furnace, the charges being based on a carbon content of about 0.25 per cent, manganese of 0.5 per cent, and silicon of about 0.5 per cent. As far as was practicable, the nickel and chromium contents of the different alloys were selected to conform to those found in typical commercial alloys, but the primary basis of selection was a widespread scattering over the nickel-chromium-iron ternary diagram, so that the general trend of effects of composition on the flow characteristics at 1,000° F. could be determined. The alloys were all tested in the cast condition after being heat-treated as shown in Table 1.

The results of tensile tests at atmospheric temperatures or Brinell hardness tests are given in Table 1 for many of the materials in order to define better the conditions in which the different metals of the several groups were tested. Since the properties of the metals in Groups I and II are compared with those of five steels previously reported upon the chemical compositions and preliminary treatments of the latter have been included for convenience in Table 1.

IV. RESULTS AND DISCUSSION

1. GENERAL RELATIONS BETWEEN STRESS, TEMPERATURE, DEFORMATION, AND TIME

The flow of the metals of Groups I and II, Table 1, when loaded at different temperatures, is shown graphically in Figures 5 to 17, inclusive. The relations between stress, temperature, deformation, and time are similar to those observed in the steels previously tested and the time-elongation curves fall into three classes which depend upon the metal and the temperature.

At atmospheric and slightly elevated temperatures, initial changes in dimensions (initial flow) are not necessarily followed by continuous flow but, due to strain hardening, the rates of flow may decrease with time. In many cases the flow rates subsequent to the initial period (second stage of flow), may be considered to be zero for all practical purposes and determination of allowable working stresses is therefore a function of the permissible initial deformation.

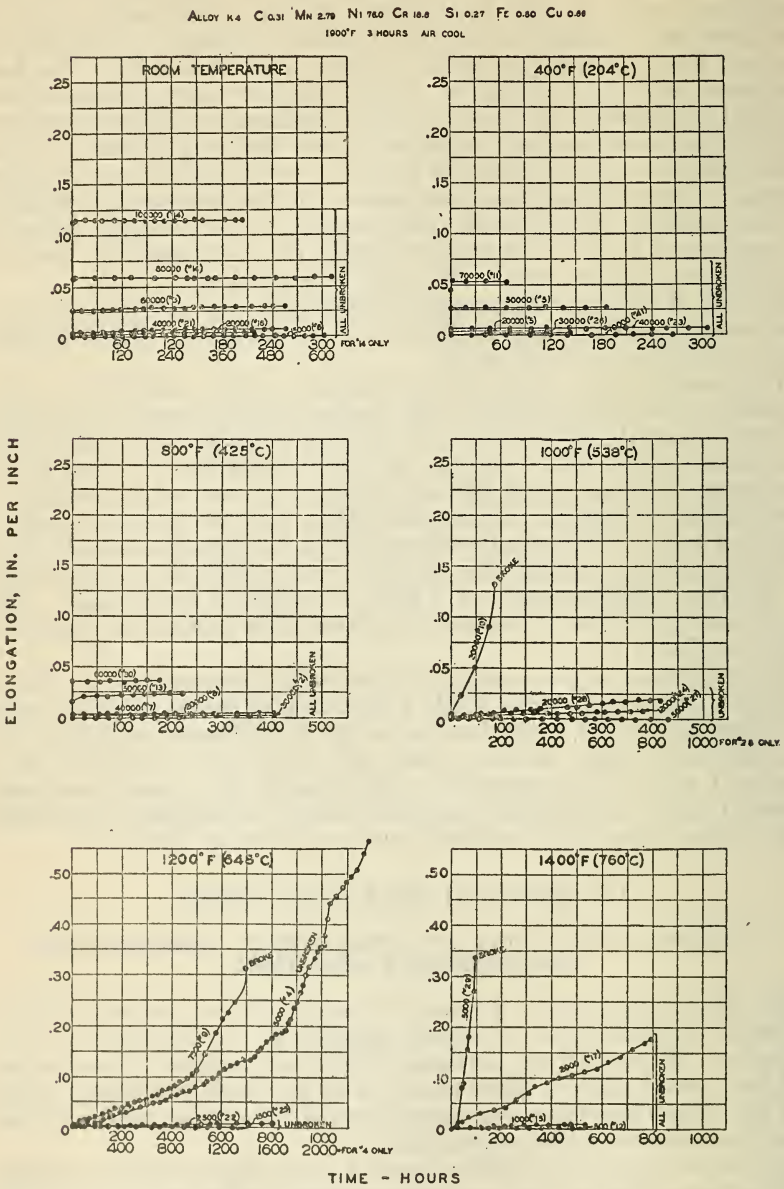


FIGURE 5.—*Time-elongation curves for the alloy K–4*

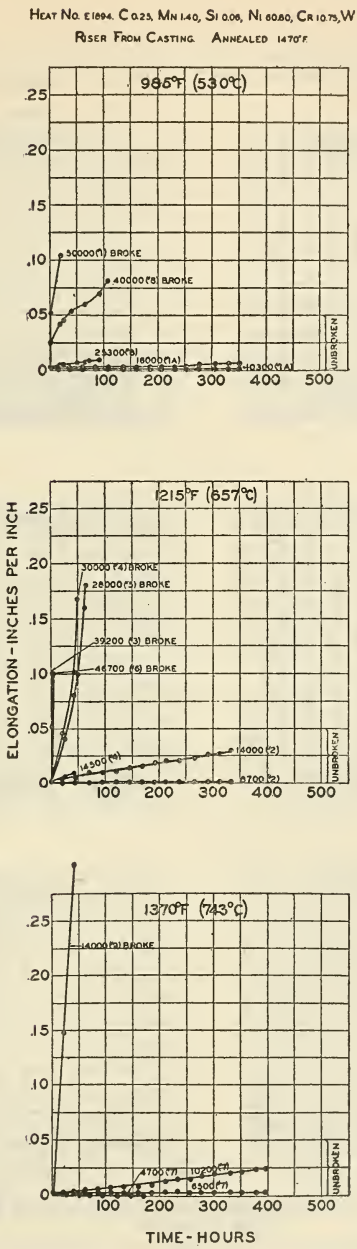


FIGURE 6.—*Time-elongation curves for the Ni-Cr-Fe alloy E1894*

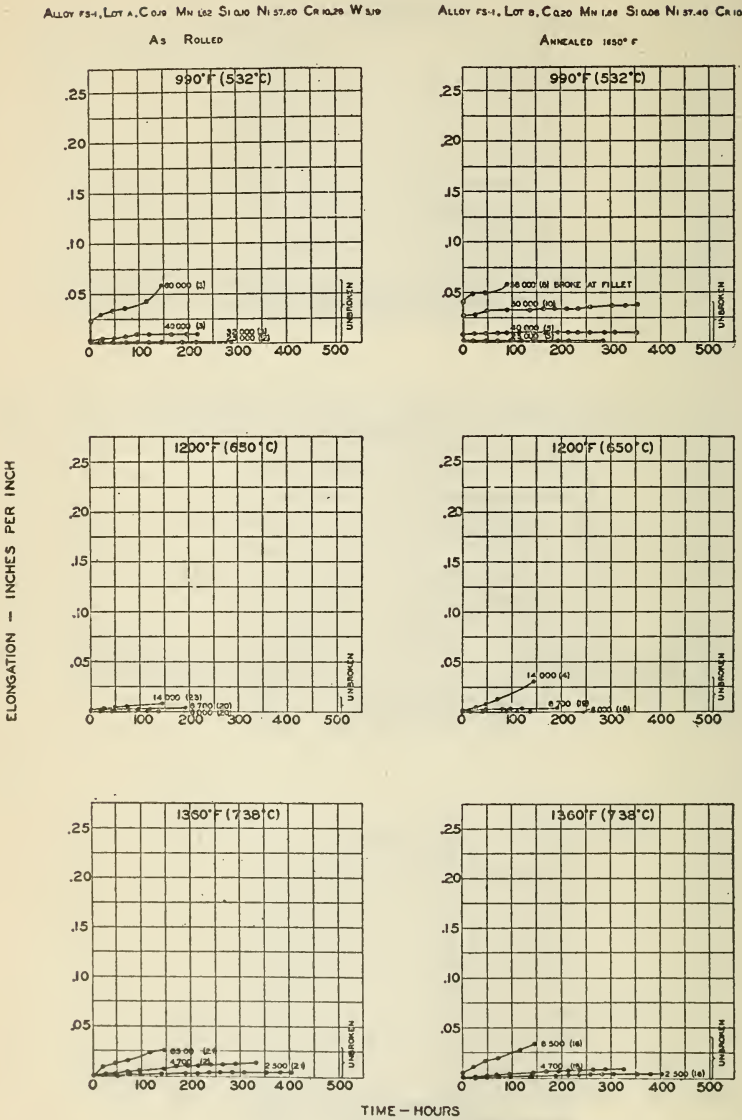


FIGURE 7.—*Time-elongation curves for the Ni-Cr-Fe-W alloy FS–1, lots A and B*

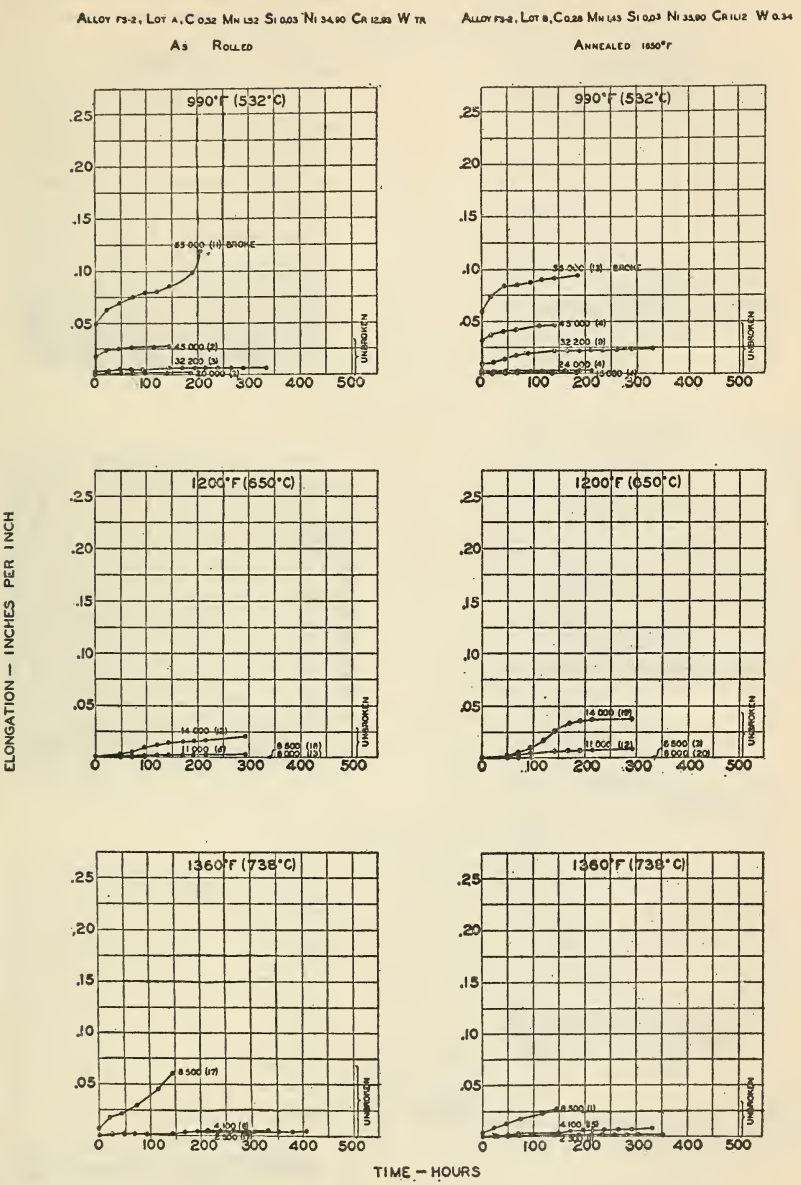


FIGURE 8.—*Time-elongation curves for the Ni-Cr-Fe alloy FS-2, lots A and B*

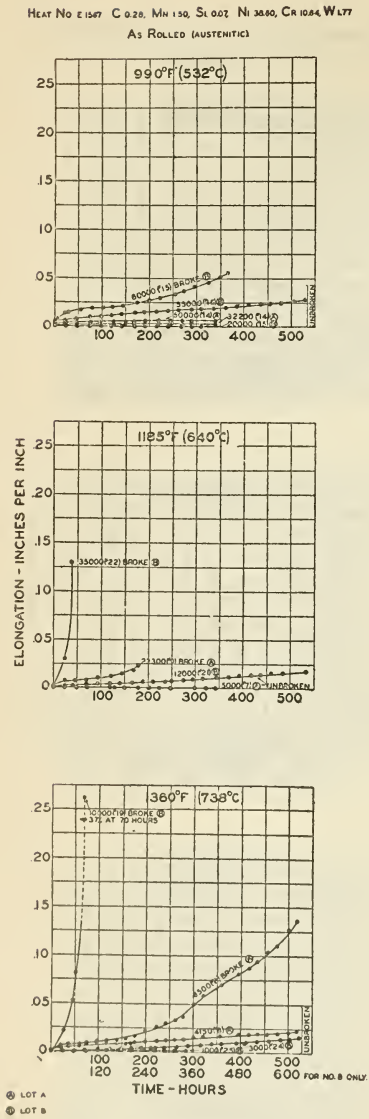


FIGURE 9.—*Time-elongation curves for the Ni-Cr-Fe alloy E1567*

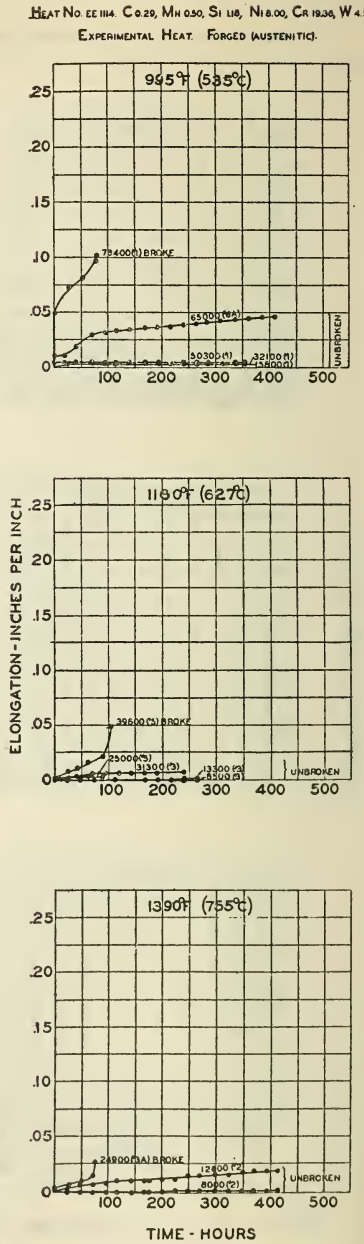
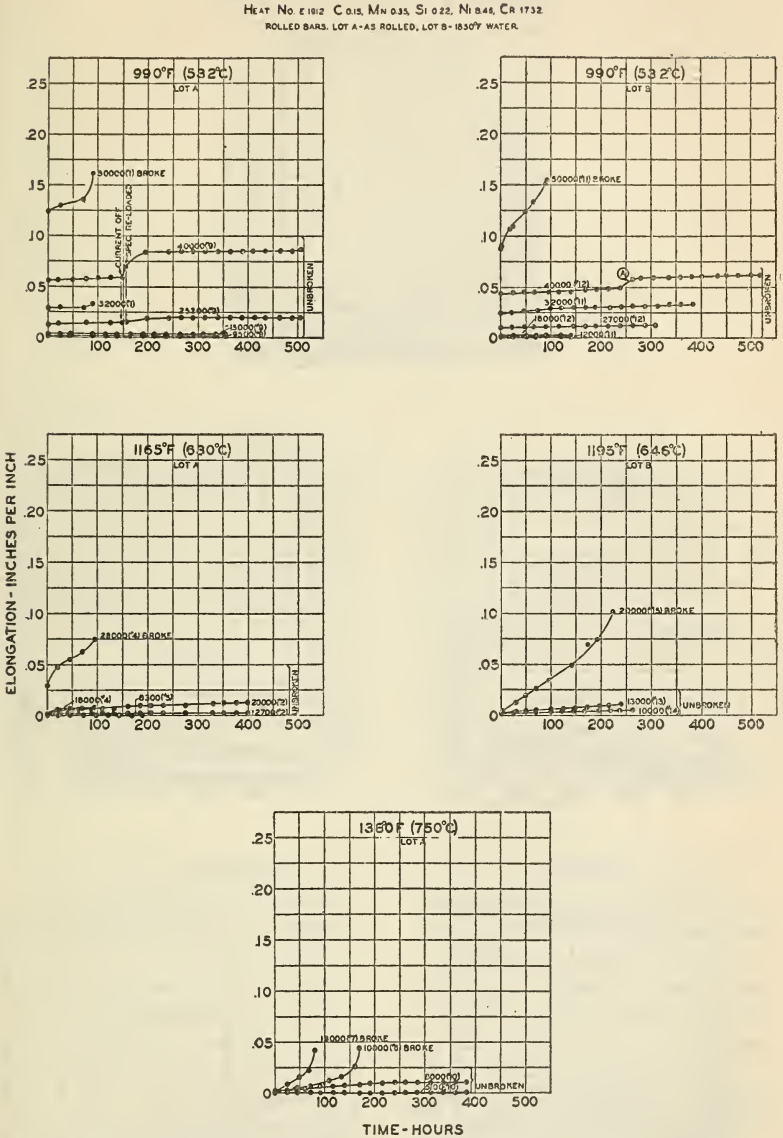


FIGURE 10.—*Time-elongation curves of the steel EE1114*



Ⓐ SPECIMEN PROBABLY SUBJECTED TO SHOCK AT THIS POINT DUE TO FRACTURE OF A SPECIMEN IN AN ADJOINING FURNACE.

FIGURE 11.—*Time-elongation curves of the steel E1912*

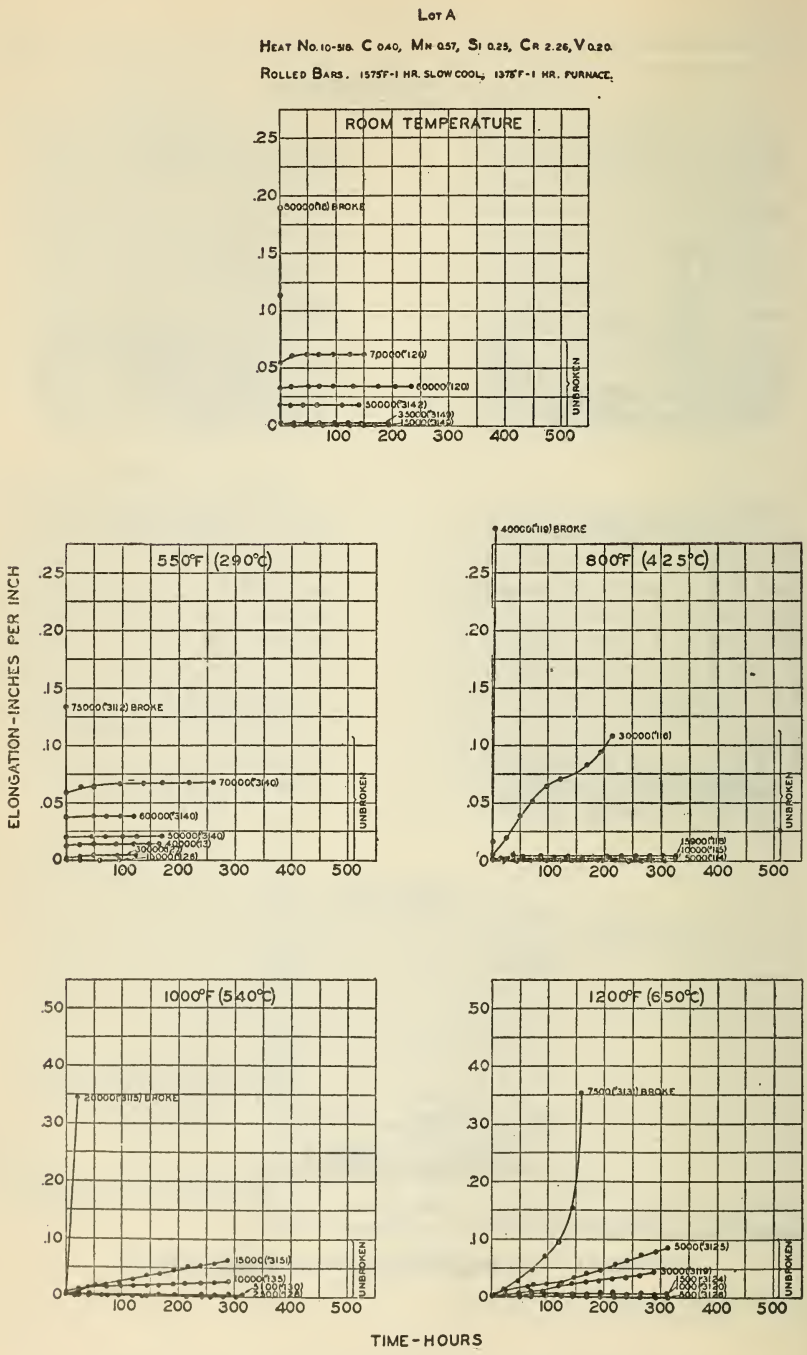


FIGURE 12.—*Time-elongation curves of steel 10–518, lot A*

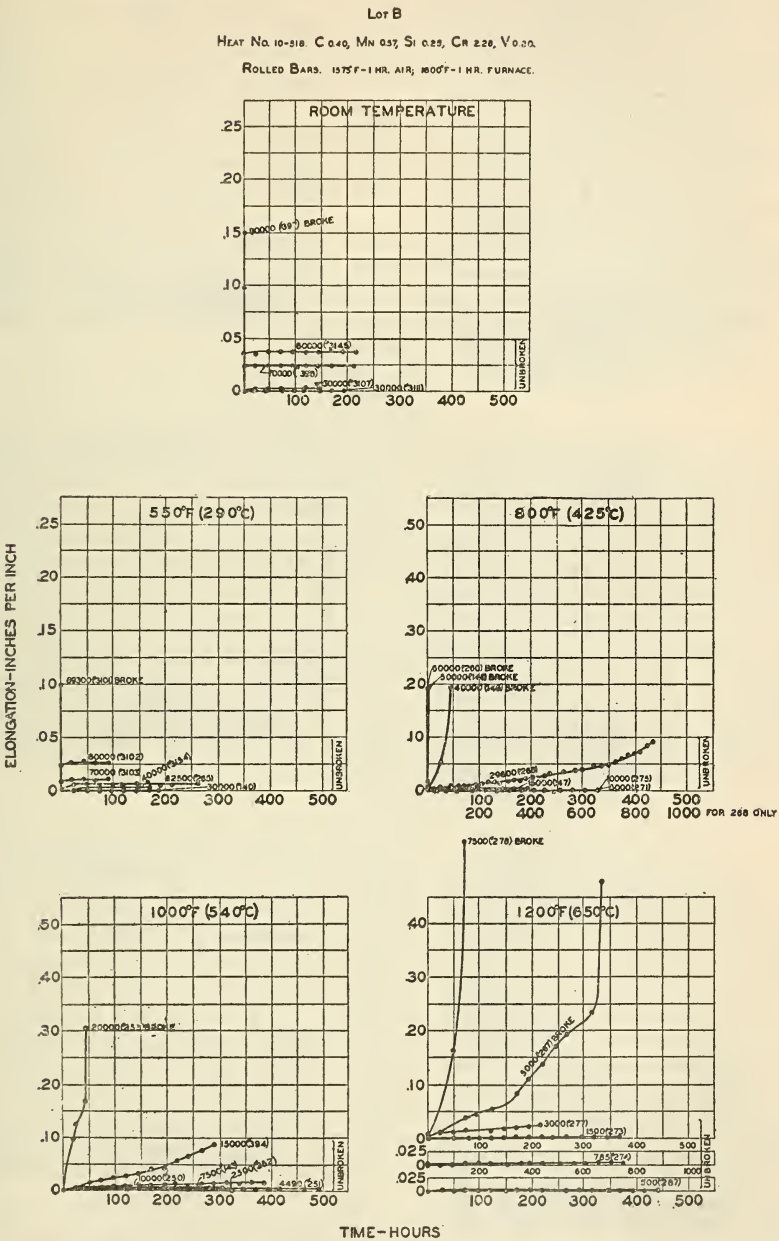


FIGURE 13.—*Time-elongation curves of steel 10–518 lot B*

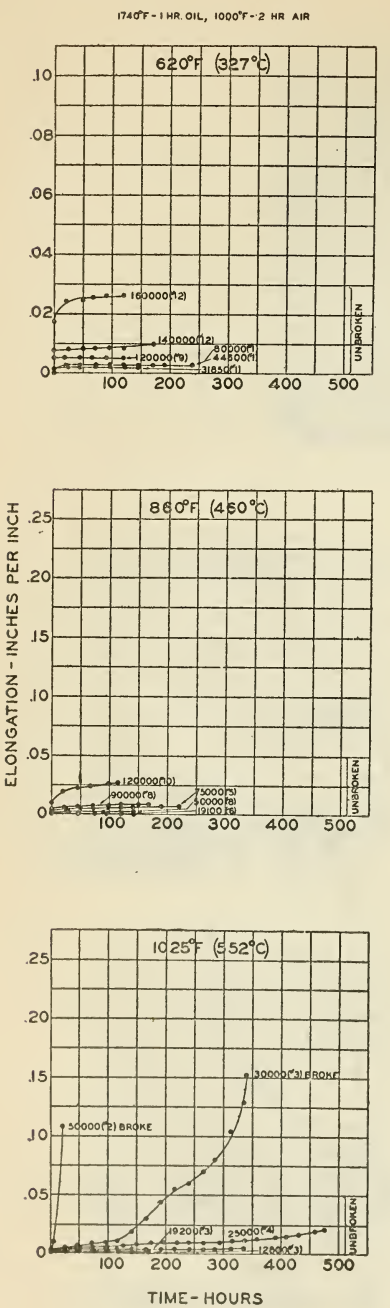


FIGURE 14.—*Time-elongation curves of steel EE1139*

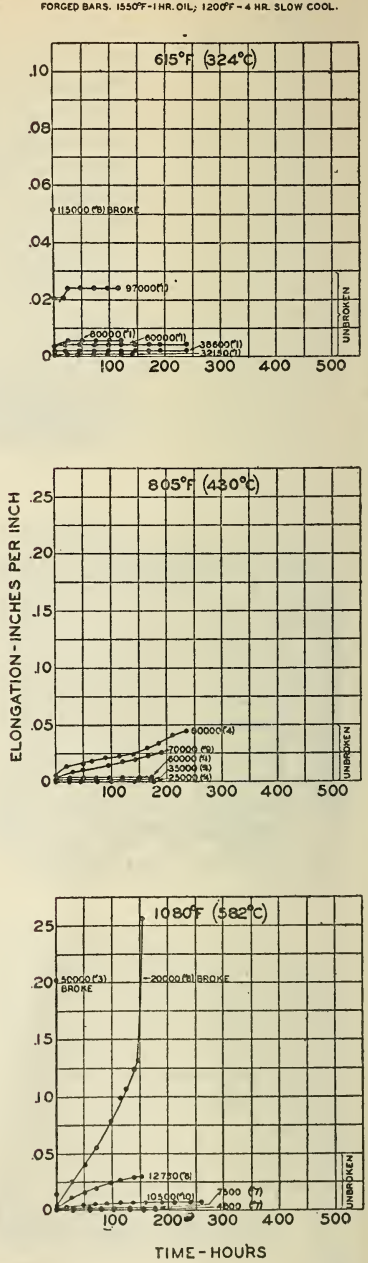


FIGURE 15.—*Time-elongation curves of the steel E1549*

At temperatures above those at which strain hardening is observed, any appreciable initial flow is followed by further and continuous deformation which may take place at approximately the same rate, a higher or a lower rate, depending upon the conditions of test. At such high temperatures the flow ordinarily increases with time and the allowable working stresses usually become a function of the rate of deformation subsequent to any initial changes in dimensions (secondary flow rates).

At intermediate temperatures, the time-elongation curves may show some of the characteristics of each of the two classes of curves mentioned. In other words, the transition from the relations typical of temperatures at which marked strain hardening is observed to the relations typical of much higher temperatures is most often gradual. The time-elongation curves may show appreciable initial deformation followed by decreases in flow rates, but the flow may be continuous so that fracture occurs in relatively short time.

In ductile materials appreciable elongation eventually results in appreciable contraction in area. This, in turn, results in stress concentration and the rates of flow are greatly increased just before fracture (final flow).

Different methods have been used in summarizing the results of flow tests, but probably the most acceptable to engineers are those which show the relations between deformation, stress, temperature, and time, since the selection of allowable working stresses is usually not solely a function of the time for fracture but demands consideration of the allowable deformation during any selected life. The desired life and the maximum allowable deformation will vary with different classes of structures and the viewpoints of individual designers and are likewise affected by the details of construction and operation. For this reason, the results are summarized in terms of per cent deformation per thousand hours at the different temperatures as is shown in Figures 30 to 41, inclusive, and in Table 2.

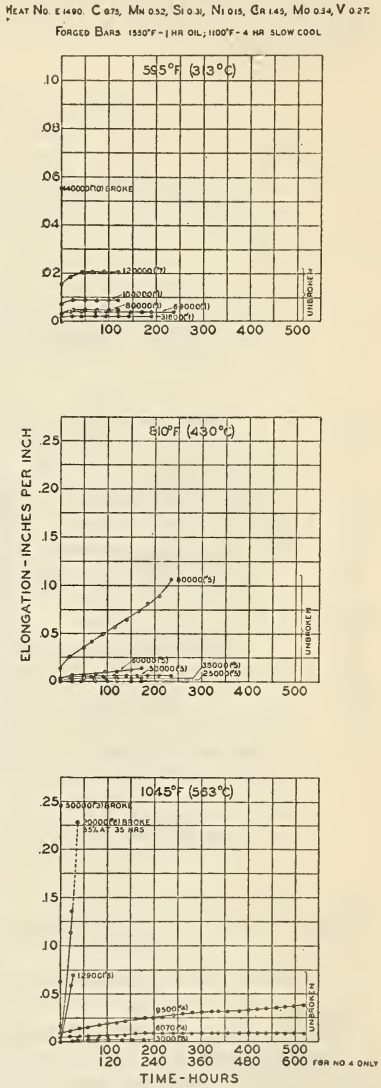


FIGURE 16.—*Time-elongation curves of the steel E1490*

The stresses producing the deformation rates shown in Figures 30 to 41 were determined from charts giving the relations between the applied load and the initial flow or secondary flow rates, shown in Figures 18 to 29, inclusive. The methods by which Figures 30 to 41 were obtained from data in Figures 18 to 29 and Table 2, and the assumptions involved, have been discussed in detail in reports already referred to.

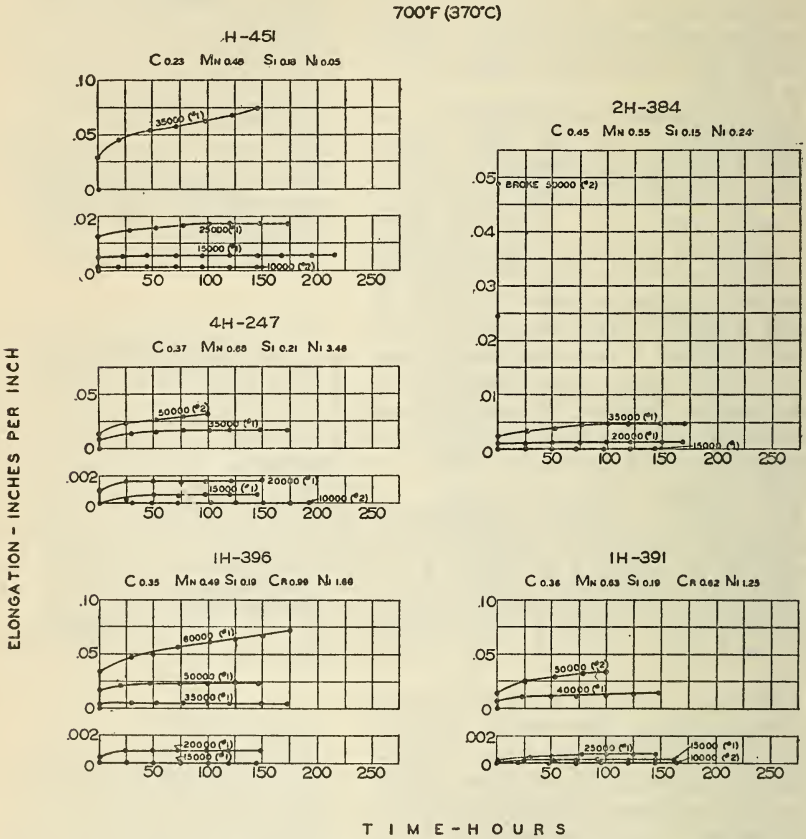


FIGURE 17.—*Time-elongation curves at 700° F. of two carbon and three alloy steels*

Table 1 contains details of chemical composition and preliminary heat treatments.

Where comparisons are made with the metals of Group IV, Table 1, the required flow data for these steels were taken from previously reported tests which were carried out under comparable conditions.[7]

One important point, which has not been given much consideration in the interpretation of flow tests, is that the numerical values obtained on one bar, lot, or melt of a given alloy may not coincide closely with the values obtained on other bars, lots, or melts. Similar variations in the properties of metals at atmospheric temperatures are well recognized and should likewise be given consideration in the

[7] See footnotes 2, 3, and 4, p. 126.

application of flow-test data. The extent of these variations is not now accurately known, but it has been shown [8] that the differences in load-carrying ability, from heat to heat of steel, may be large. Without additional data, it is not safe to assume that the reported values represent the average, maximum, or minimum of the range characteristic of a given metal and safety factors must still be employed.

TABLE 2.—*Flow-test data for five steels tested at 700° F.*

Steel No.	Type composition [1]	Load	Initial flow	Secondary flow	Stress producing flow per 1,000 hours of—	
					0.1 per cent	1 per cent
		Lbs./in.²	*in./in.*	*in./in./hr.*		
4H451	0.23 C	10,000	0.0012	0	9,500	19,500
		15,000	.0054	0		
		25,000	.017	0		
		35,000	.03	.0002		
2H384	0.45 C	15,000	0	0	19,000	[2] [38,000]
		20,000	.0012	0		
		35,000	.0046	0		
		50,000	Continuous.	----------		
4H247	0.37 C, 3.46 Ni	10,000	0	0	17,300	31,400
		15,000	.0006	0		
		20,000	.0016	0		
		35,000	.016	0		
		50,000	.021	.00011		
1H391	0.36 C, 1.25 Ni, 0.62 Cr	10,000	0	0	26,000	32,000
		15,000	.0002	0		
		25,000	.0006	0		
		40,000	.011	.00002		
		50,000	.026	[3] .00008		
1H396	0.35 C, 1.66 Ni, 0.99 Cr	15,000	0	0	20,500	38,000
		20,000	.0009	0		
		35,000	.0051	0		
		50,000	.022	.000015		
		60,000	.043	.00017		

[1] For details of chemical composition and heat treatment refer to Table 1.
[2] Bracketed values estimated.
[3] Cr less.

2. COMMERCIAL NICKEL-CHROMIUM-IRON ALLOYS

In Figure 42, comparisons are given at 700°, 1,000°, 1,125°, and 1,350° F. of the metals in Groups I and II, Table 1, and the five steels previously tested, Group IV. The stresses producing 0.1 and 1 per cent initial elongation and also 0.1 and 1 per cent secondary elongation (calculated per 1,000 hours) are represented by the lower and upper limits, respectively, of the blocks in the chart and serve as a basis of comparison of the flow characteristics of the different metals. Comparisons can be made at lower temperatures in some cases and likewise at higher rates of flow from data given in Figures 30 to 41, inclusive.

In the relation of stress to total deformation for alloys at certain temperatures, it is necessary to consider both the initial and the secondary flow. These differences can be studied in detail from data given in Figures 18 to 29 and Table 2.

[8] See footnote 3, p. 126.

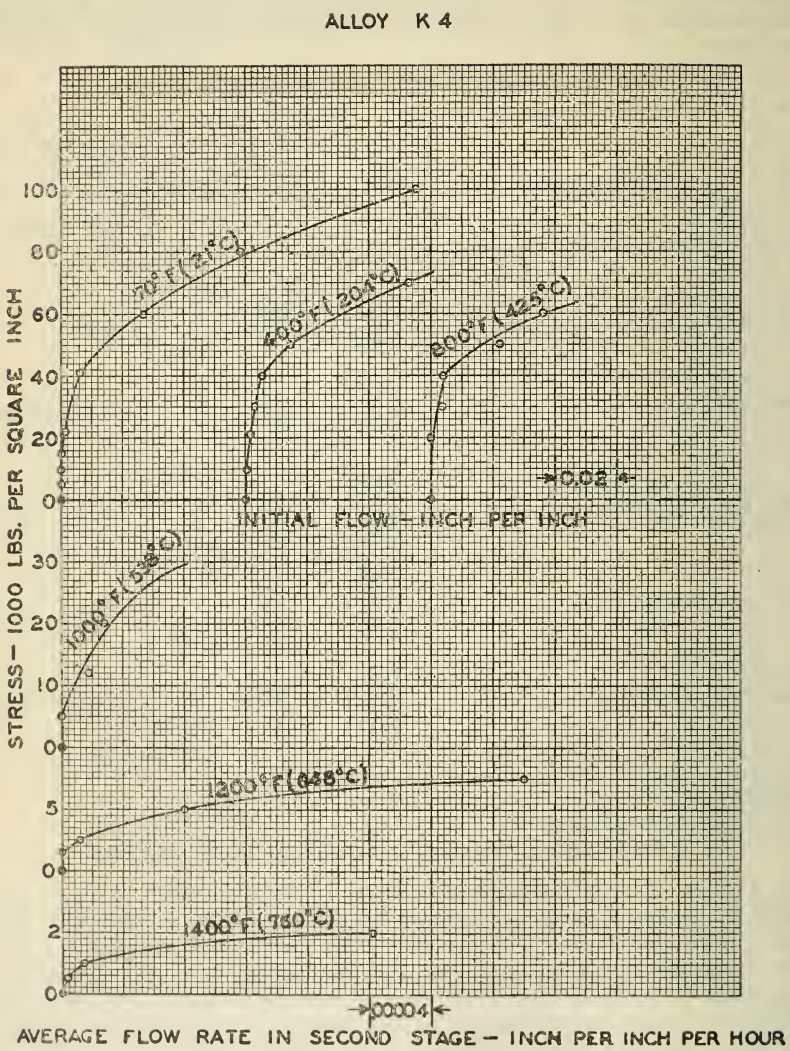


FIGURE 18.—*Flow data for Ni-Cr alloy K–4, at different temperatures*

Obtained from Figure 5.

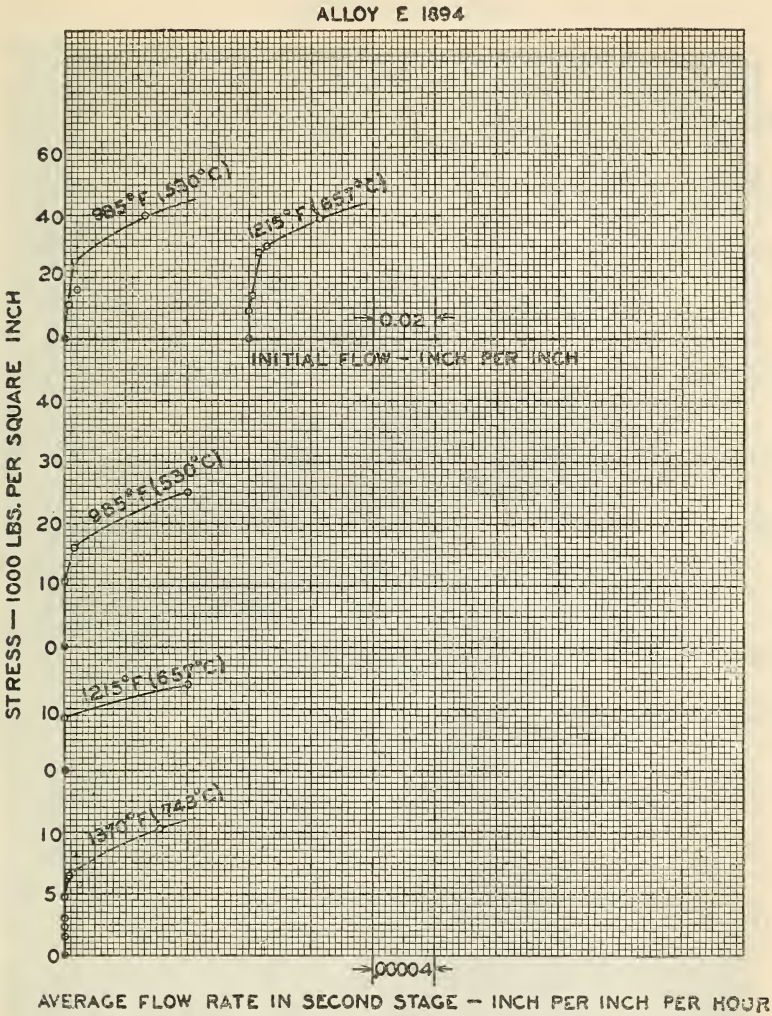


FIGURE 19.—*Flow data for Ni-Cr-Fe-W alloy E1894, at different temperatures*

Obtained from Figure 6.

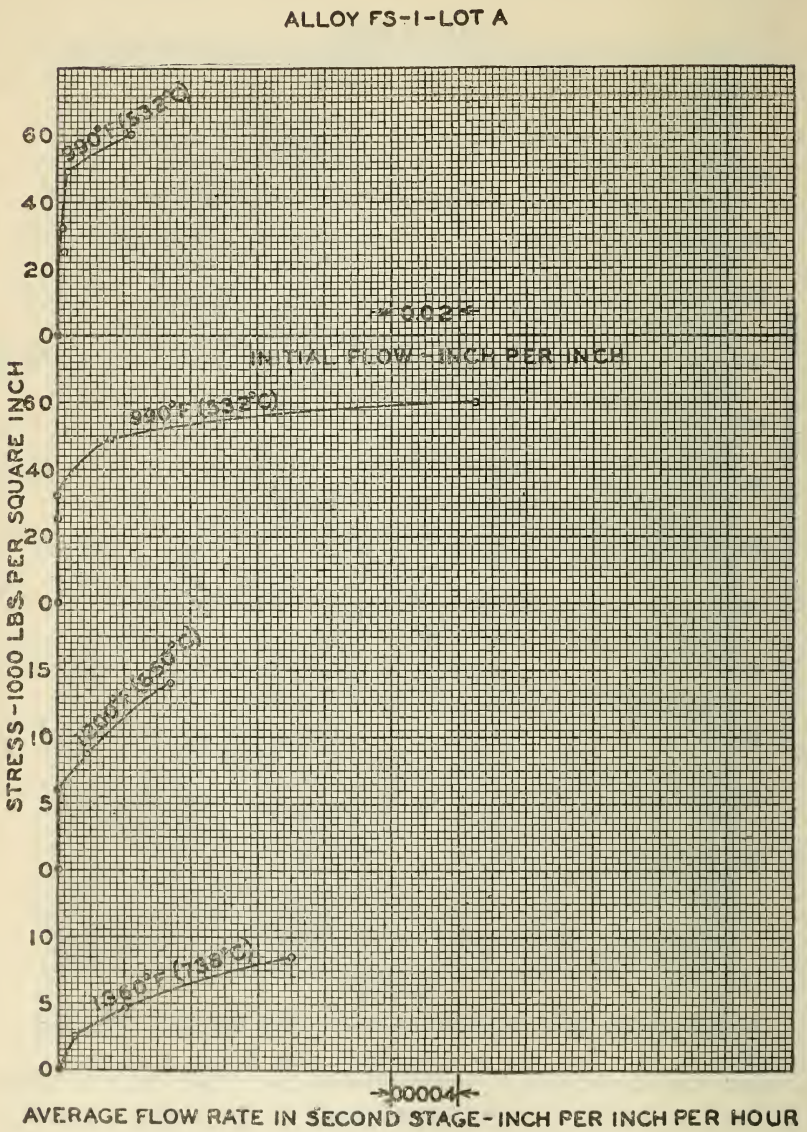


FIGURE 20.—*Flow data for the high Fe-Cr-Ni-W alloy FS-1, lots A and B, at different temperatures*

Obtained from Figure 7.

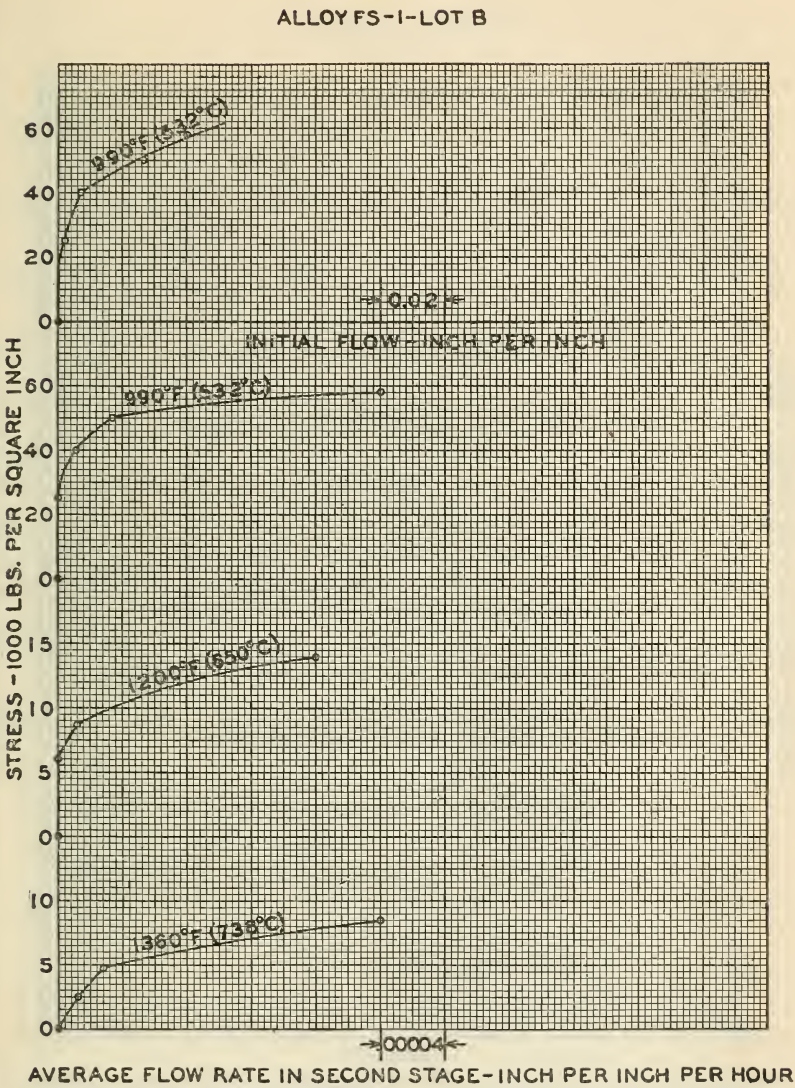


FIGURE 20.—*Flow data for the high Fe-Cr-Ni-W alloy FS1, lots A and B, at different temperatures*—Continued

Obtained from Figure 7.

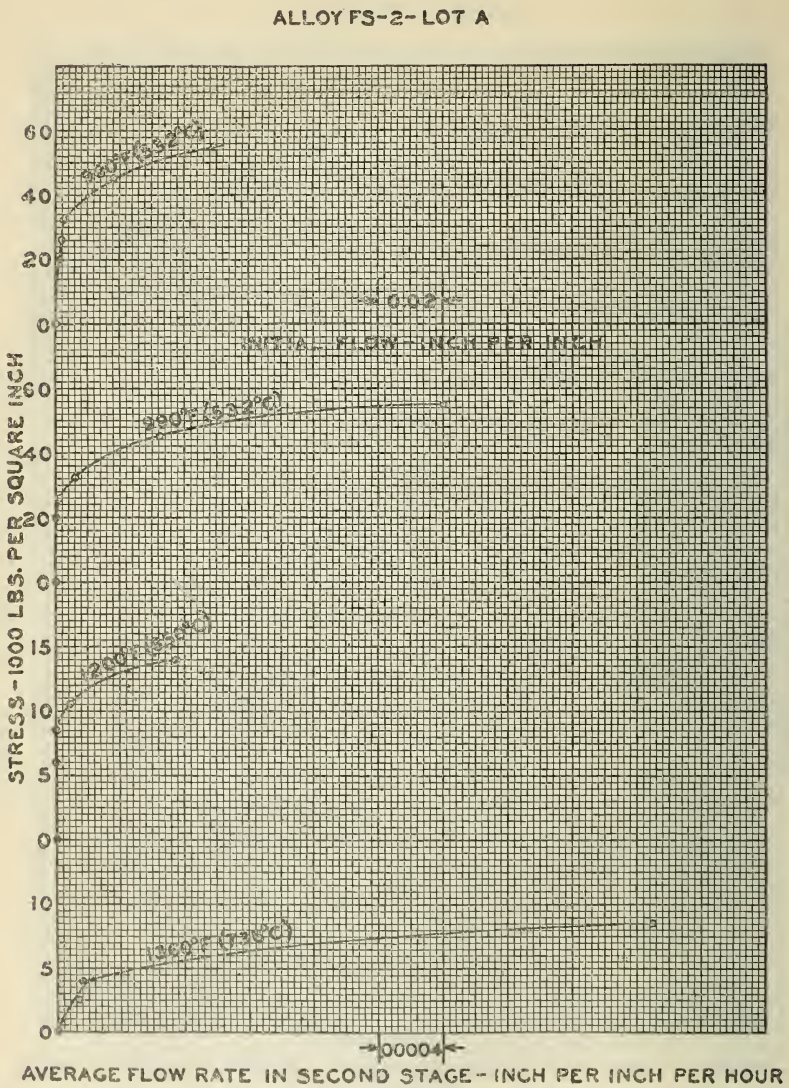


FIGURE 21.—*Flow data for the high Fe-Cr-Ni alloy FS-2, lots A and B, at different temperatures*

Obtained from Figure 8.

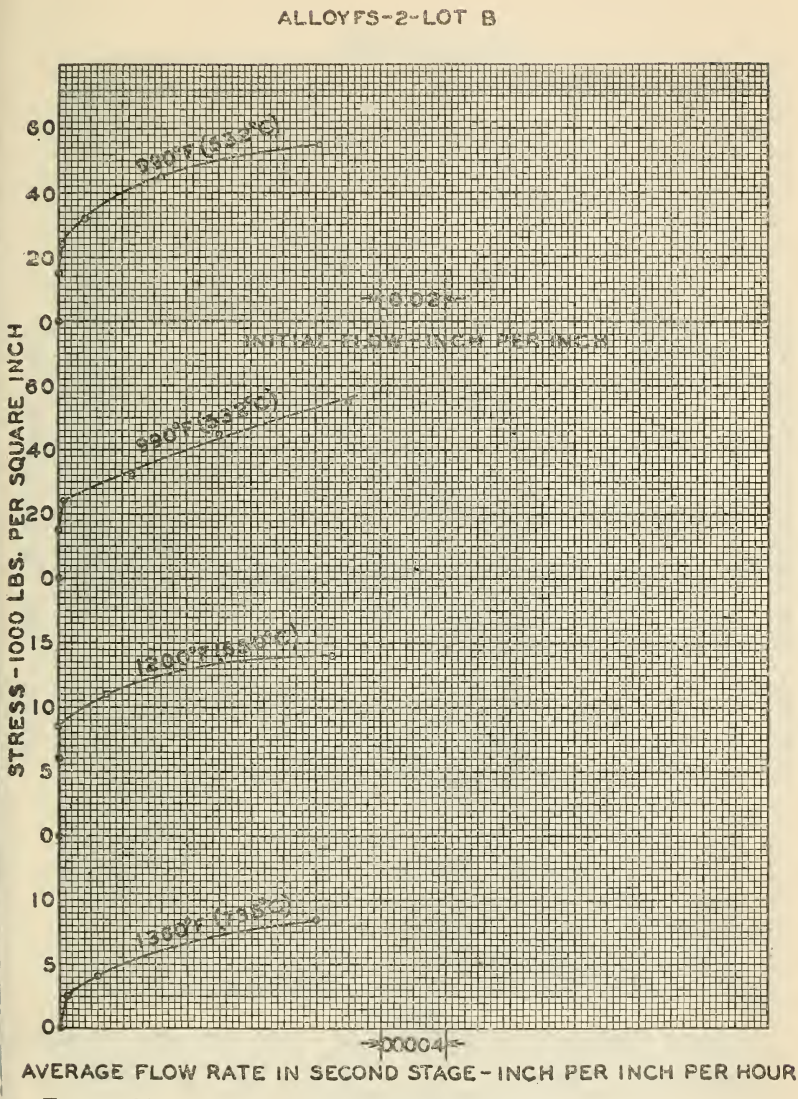


FIGURE 21.—*Flow data for the high Fe-Cr-Ni alloy FS-2, lots A and B, at different temperatures*—Continued

Obtained from Figure 8.

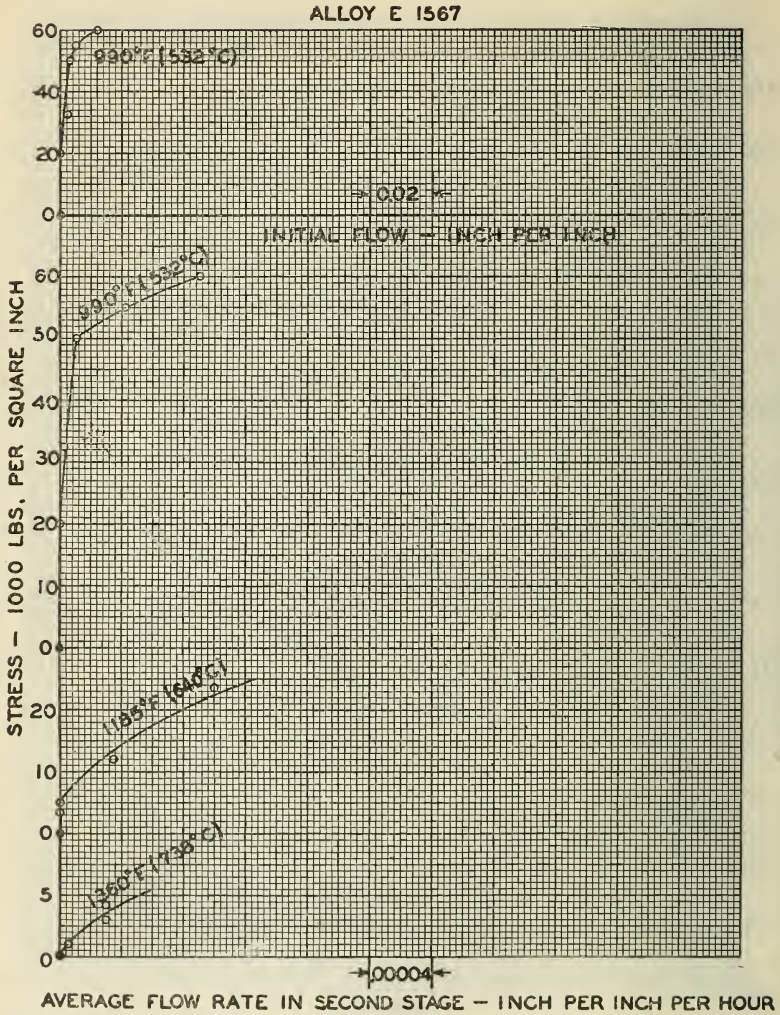


FIGURE 22.—*Flow data for Ni-Cr-Fe-W alloy E1567, at different temperatures*

Obtained from Figure 9.

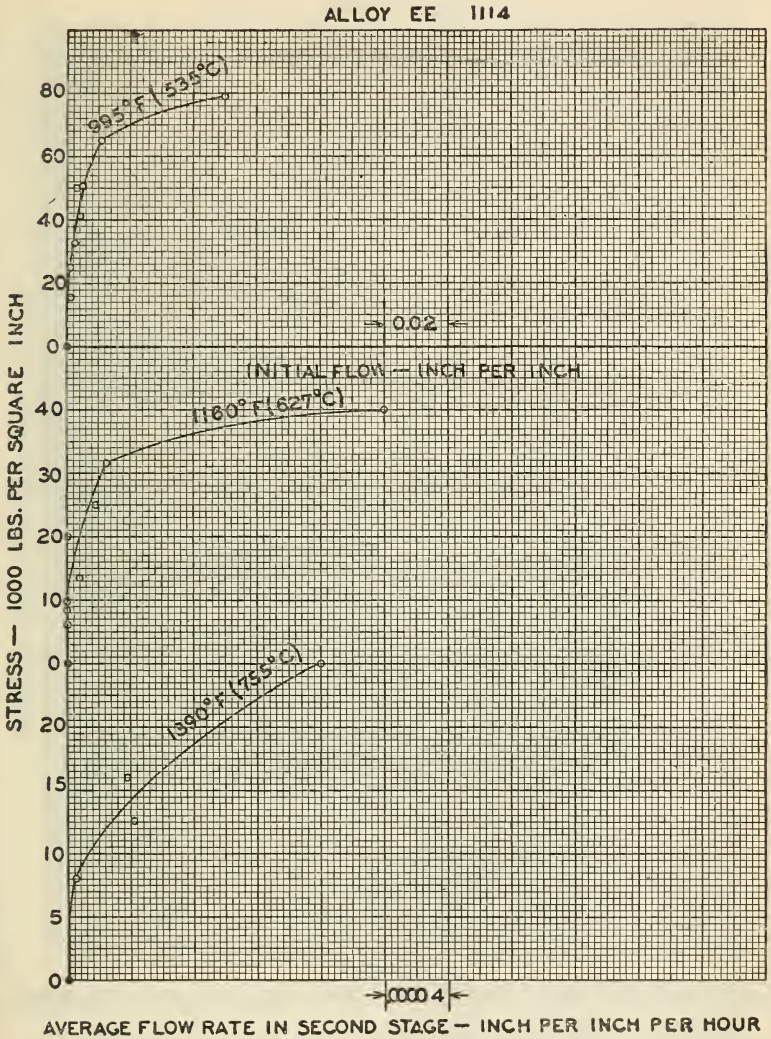


FIGURE 23.—*Flow data for the high chromium-nickel-tungsten steel EE1114, at different temperatures*

Obtained from Figure 10.

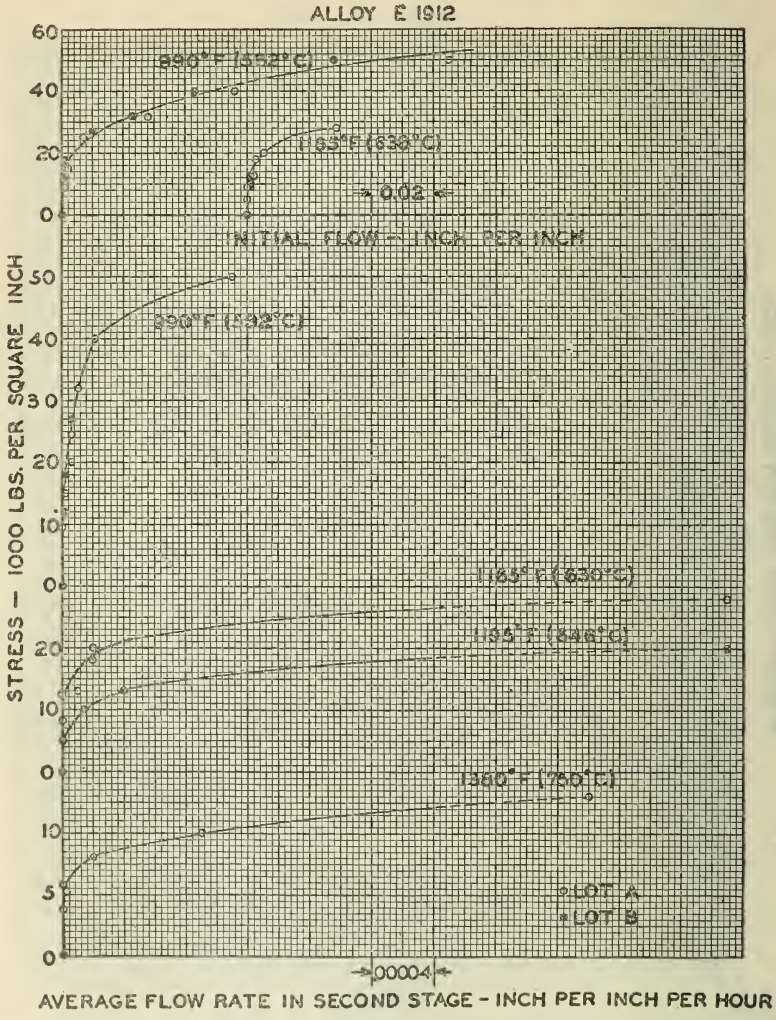


FIGURE 24.—*Flow data for the high chromium-nickel steel E1912, at different temperatures*

Obtained from Figure 11.

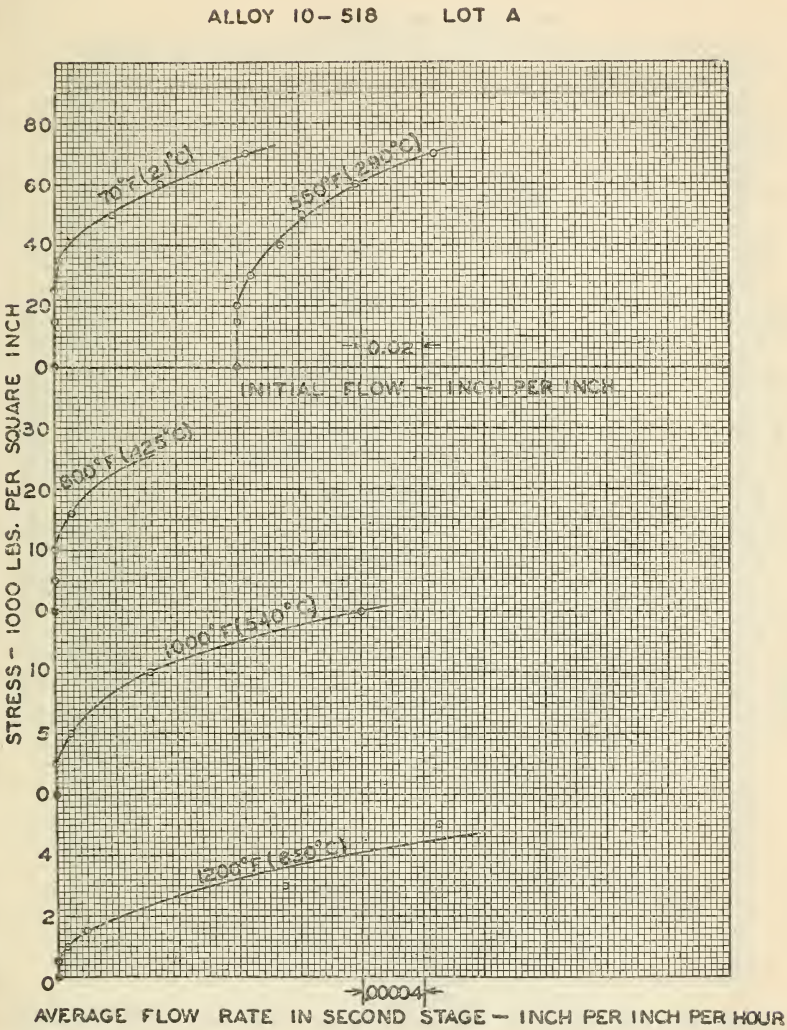


FIGURE 25.—*Flow data for the Cr-V steel 10–518, lot A, at different temperatures*

Obtained from Figure 12.

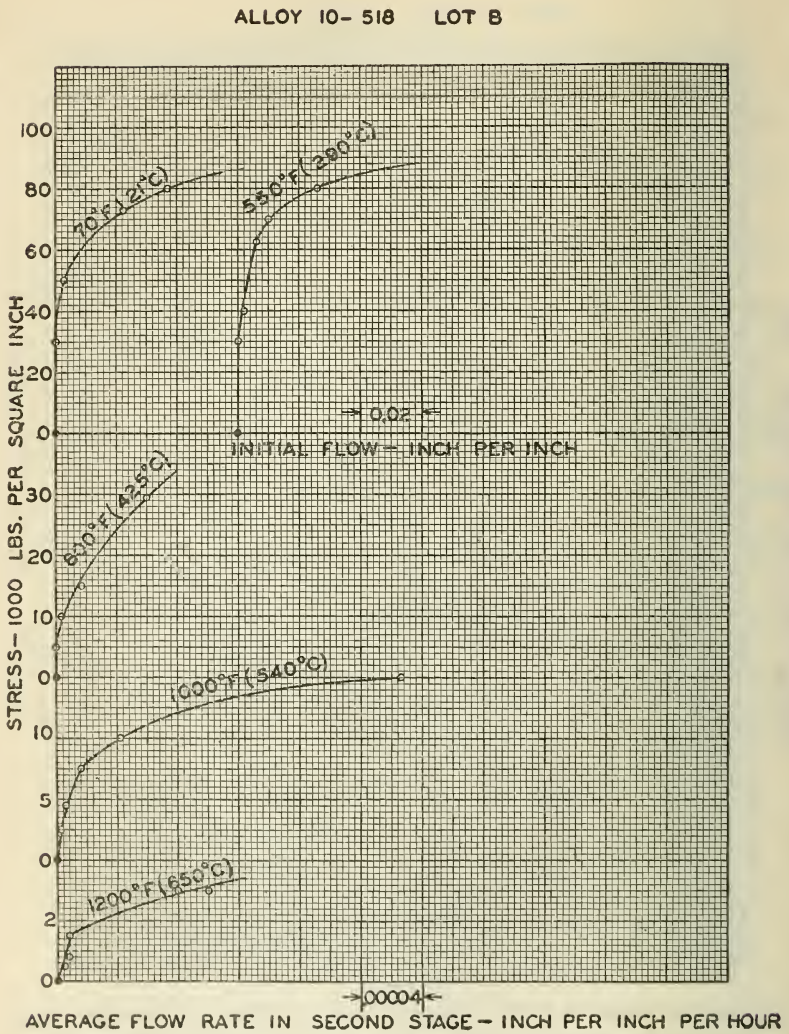


FIGURE 26.—*Flow data for the Cr-V steel 10–518, lot B, at different temperatures*

Obtained from Figure 13.

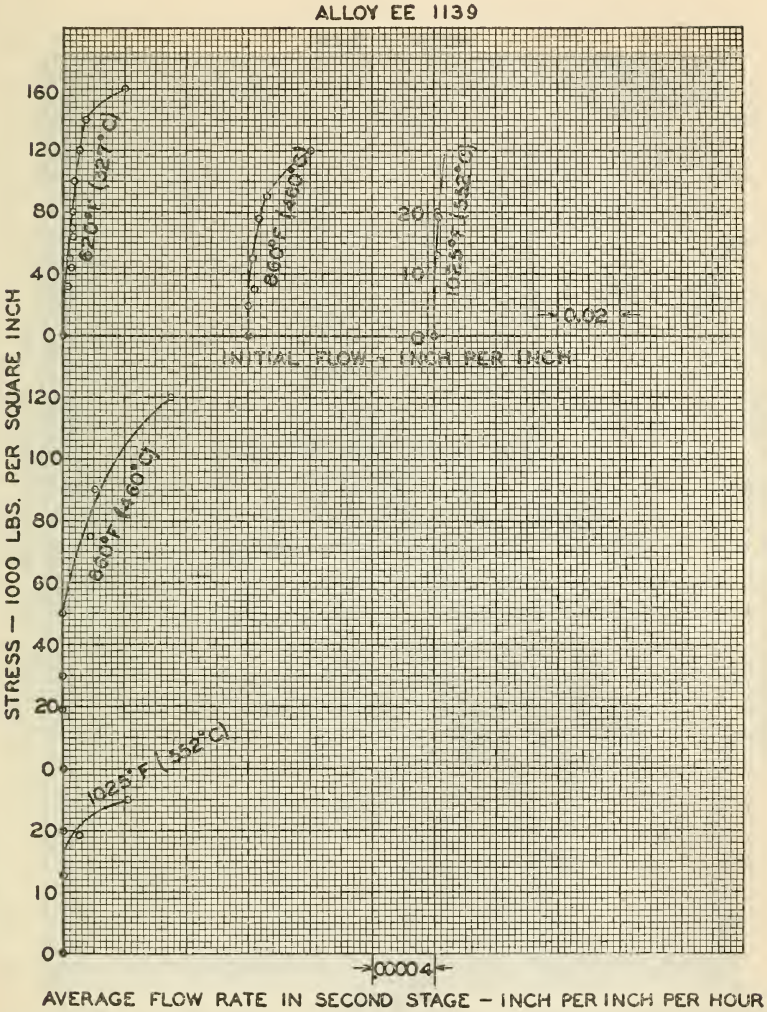


FIGURE 27.—*Flow data for the Cr-V-W steel EE1139, at different temperatures*

Obtained from Figure 14.

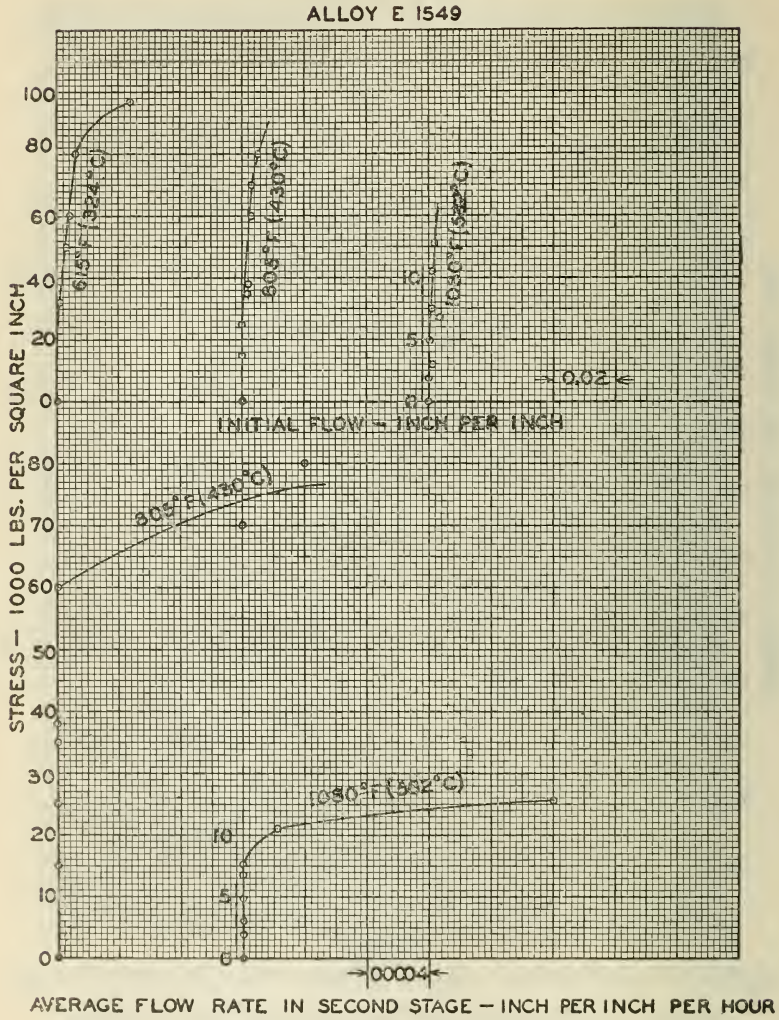


FIGURE 28.—*Flow data for the Cr-Mo steel E1549, at different temperatures*

Obtained from Figure 15.

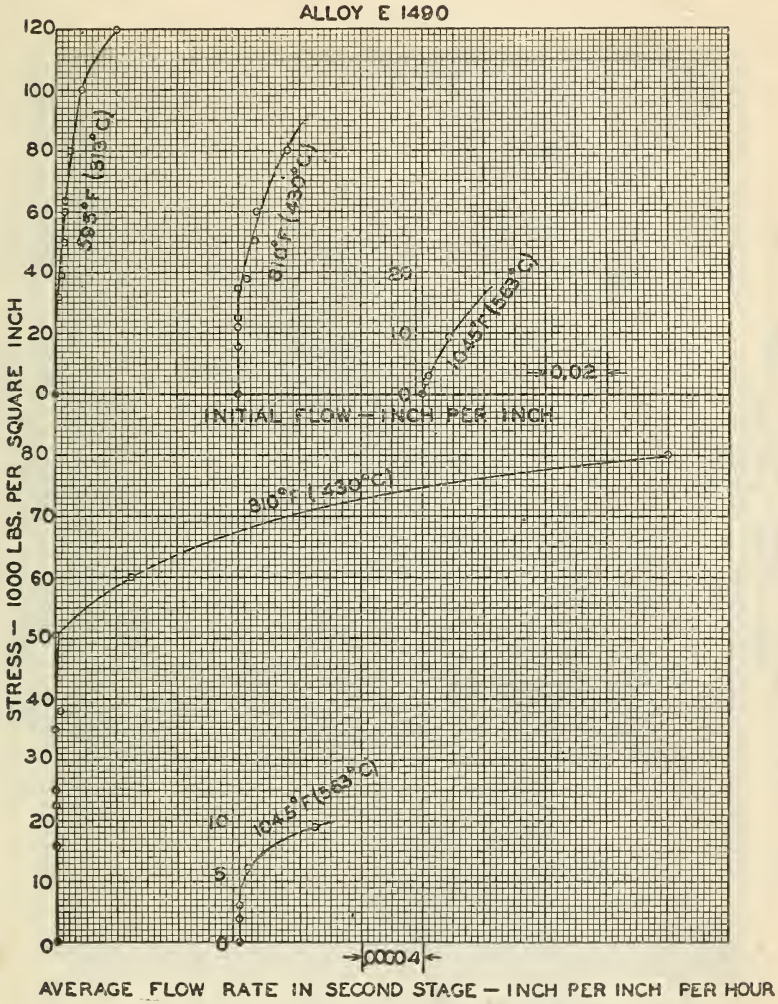


FIGURE 29.—*Flow data for the Cr-Mo-V steel E1490, at different temperatures*

Obtained from Figure 16.

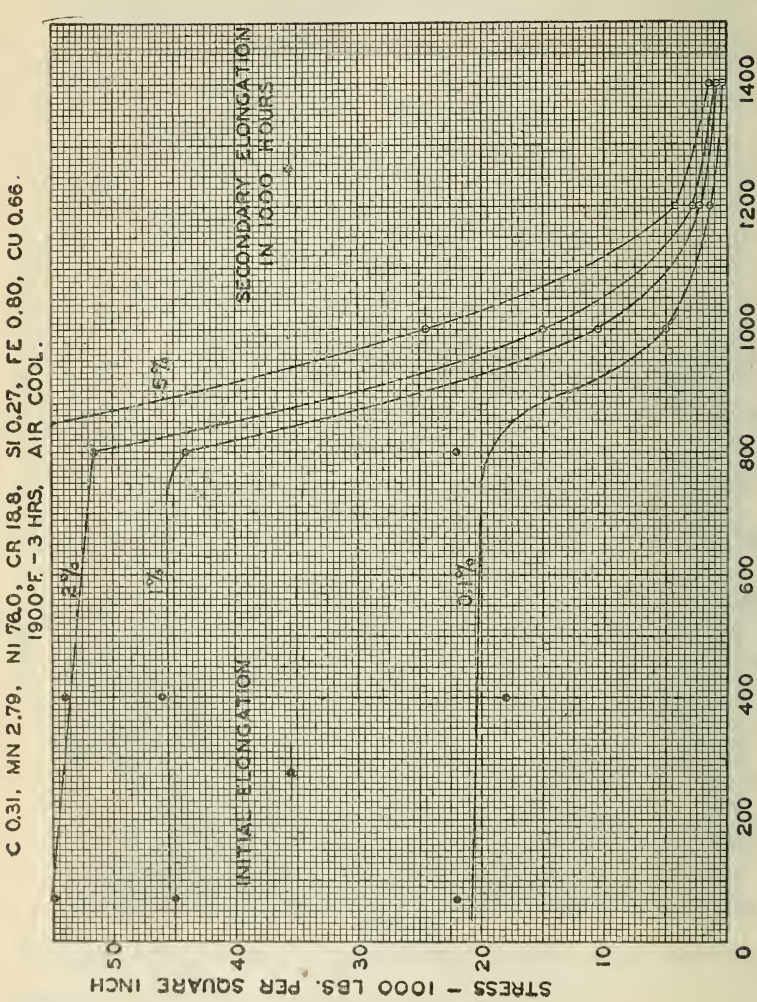


FIGURE 30.—*Flow chart for alloy K-4*

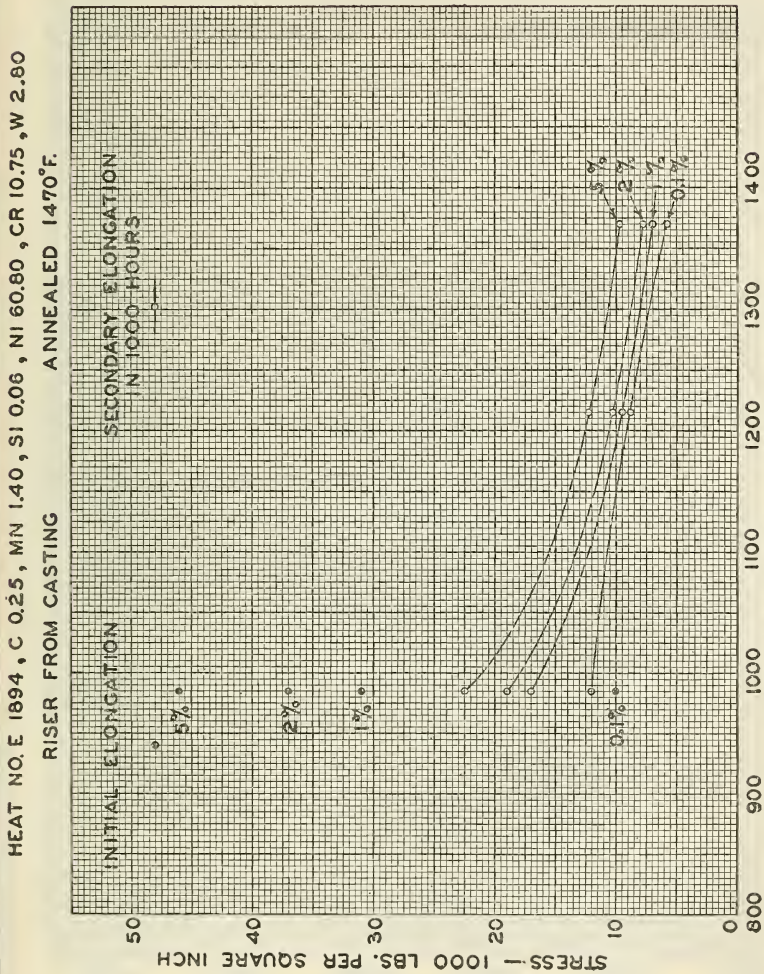


FIGURE 31.—*Flow chart for alloy E1894*

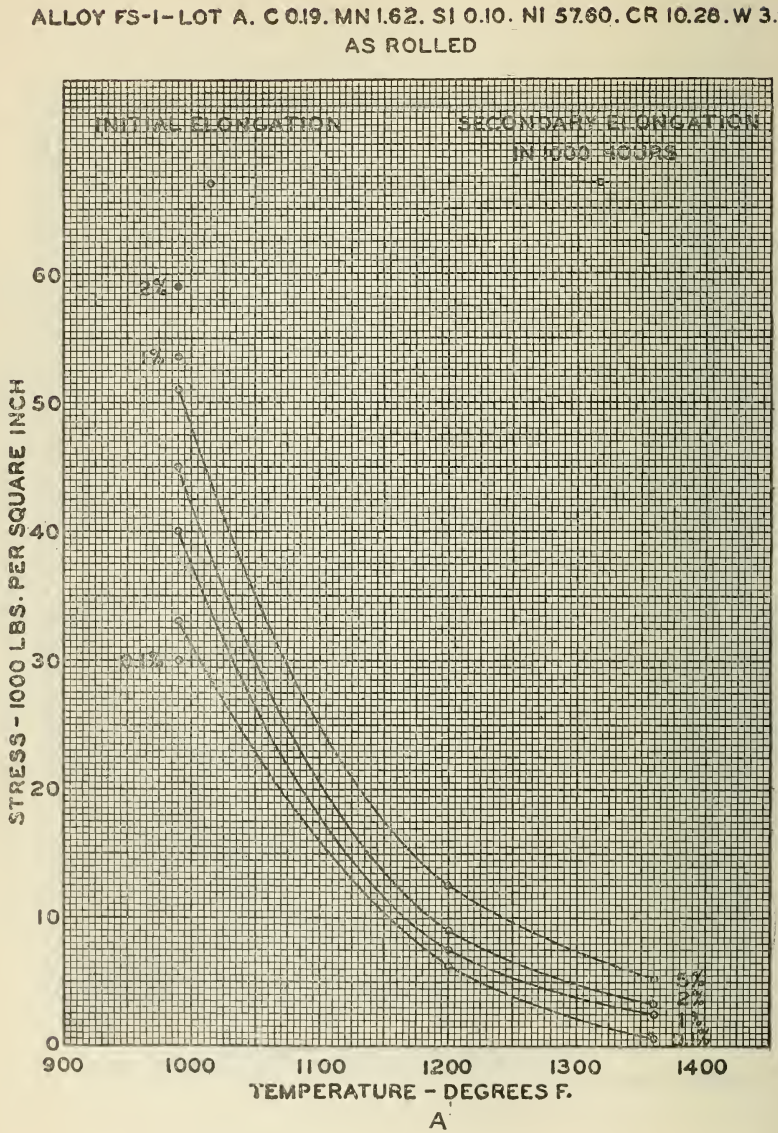


FIGURE 32.—*Flow data for alloy FS-1, lots A and B*

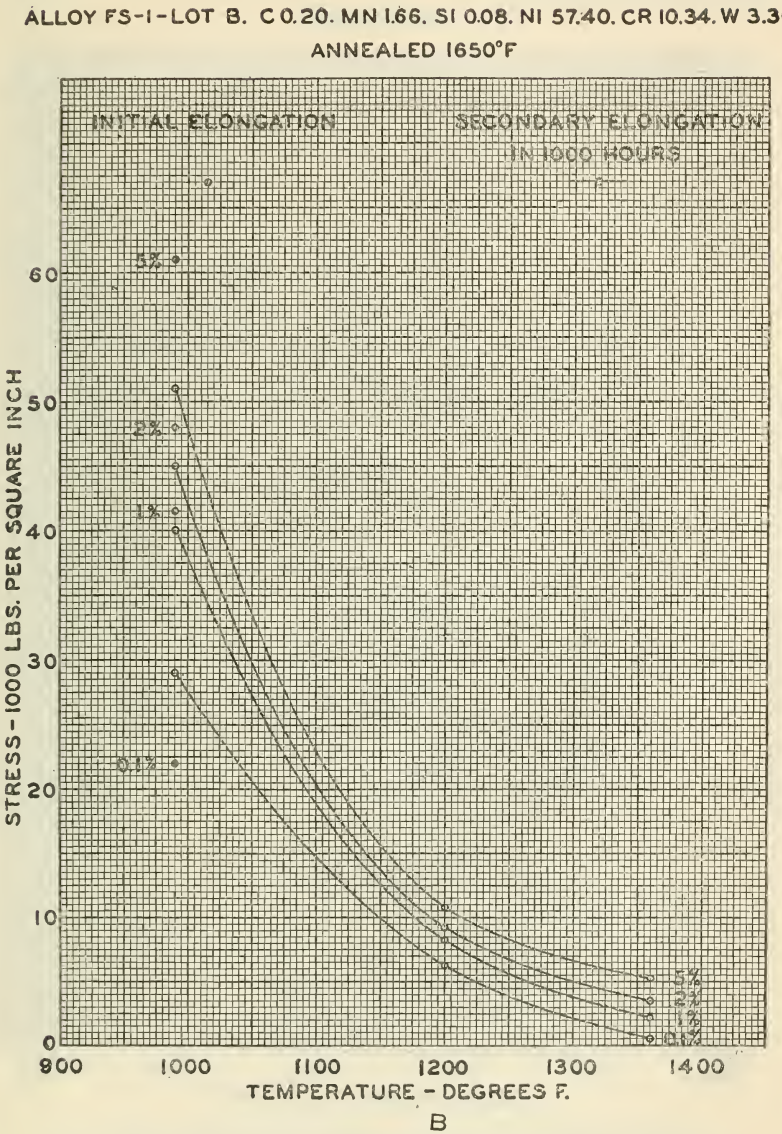


FIGURE 32.—*Flow data for alloy FS-1, lots A and B*—Continued

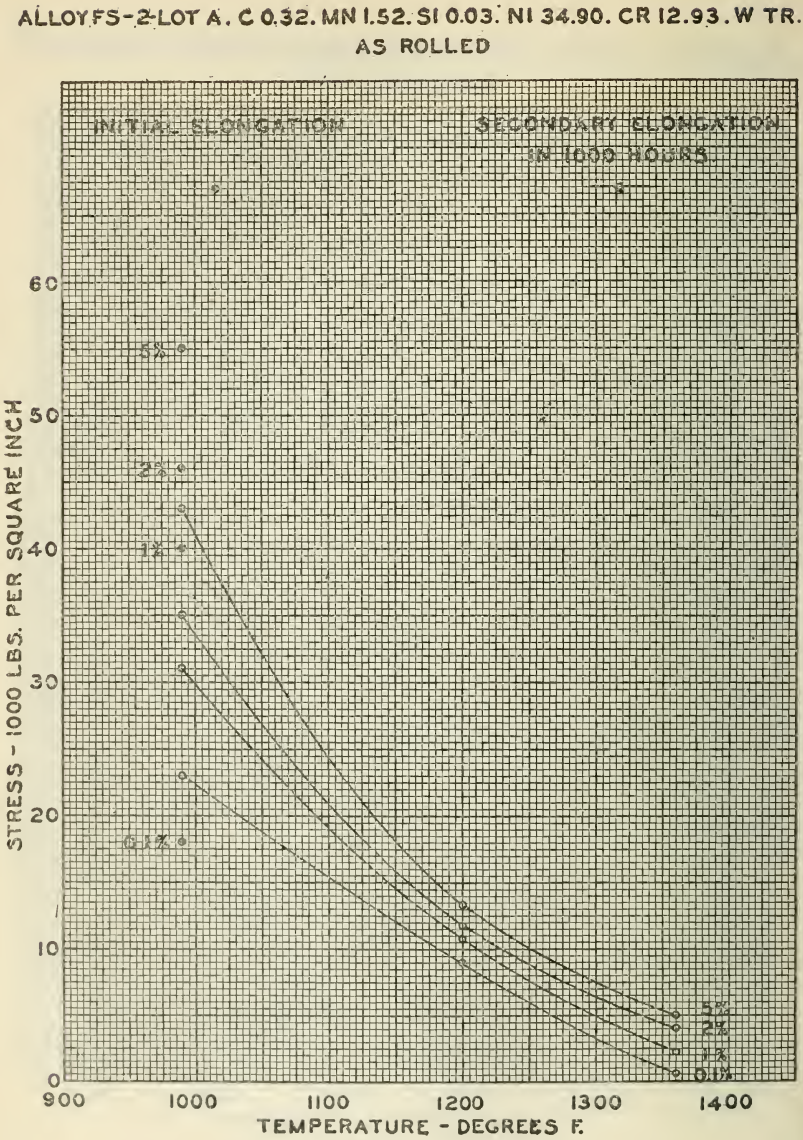


FIGURE 33.—*Flow data for alloy FS-2, lots A and B*

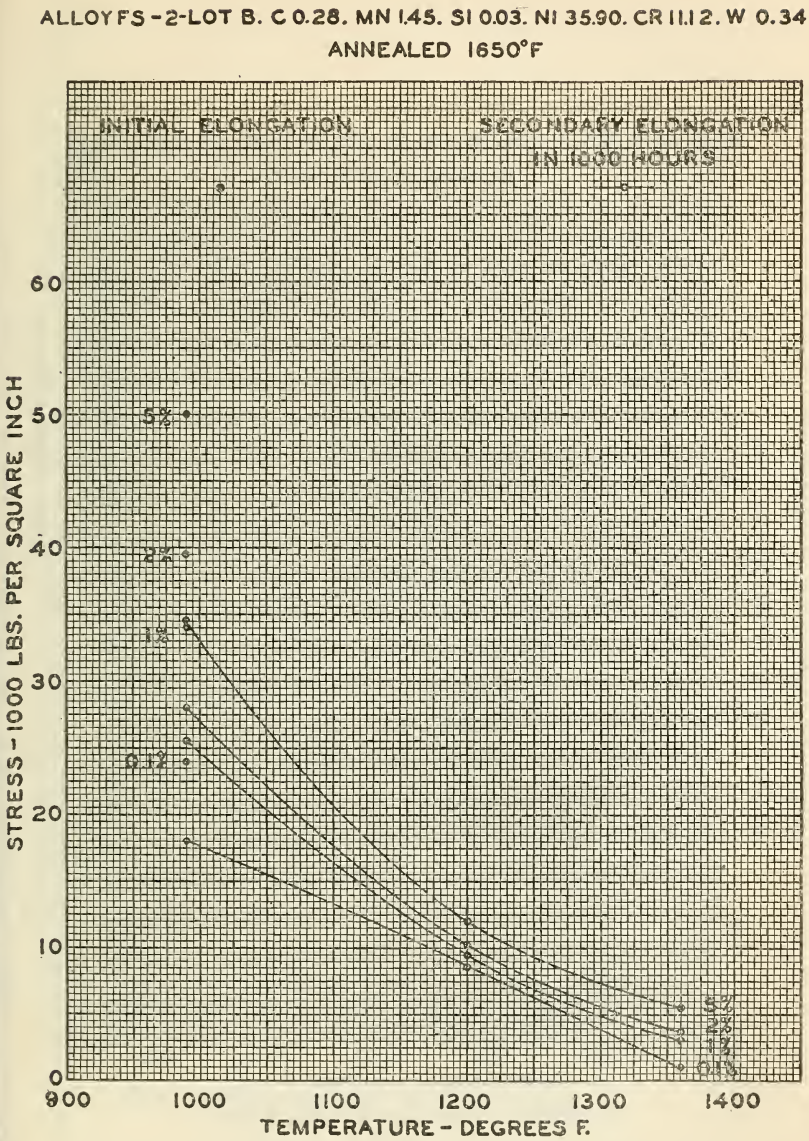


FIGURE 33.—*Flow data for alloy FS–2, lots A and B*—Continued

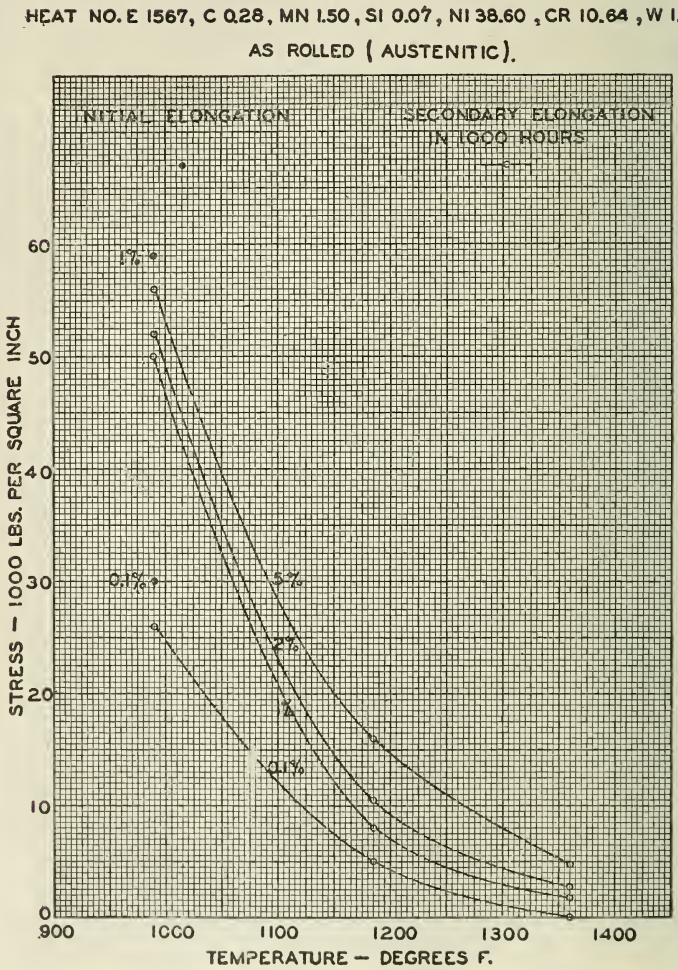


FIGURE 34.—*Flow chart for alloy E1567*

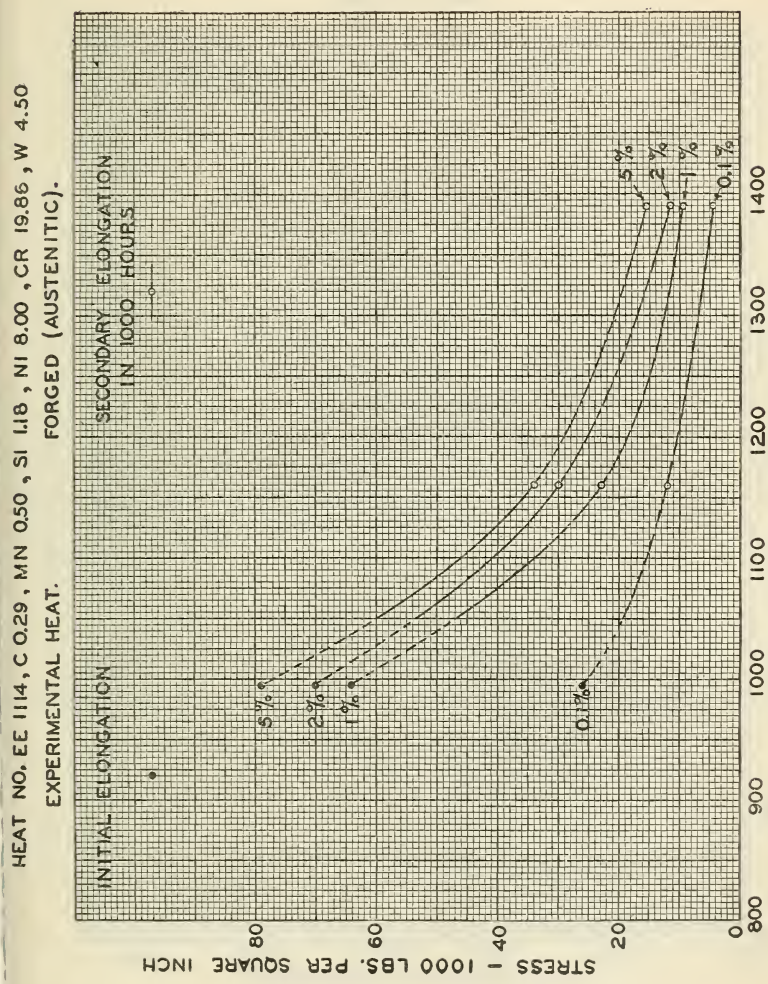


FIGURE 35.—*Flow chart for steel EE1114*

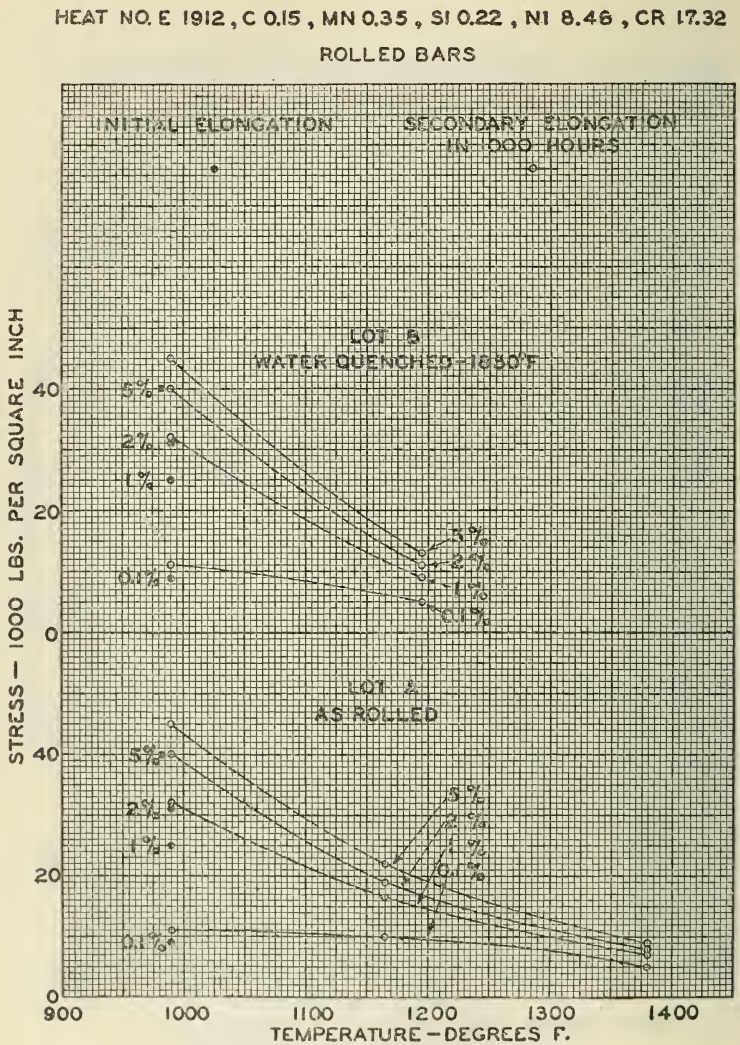


FIGURE 36.—*Flow chart for steel E1912*

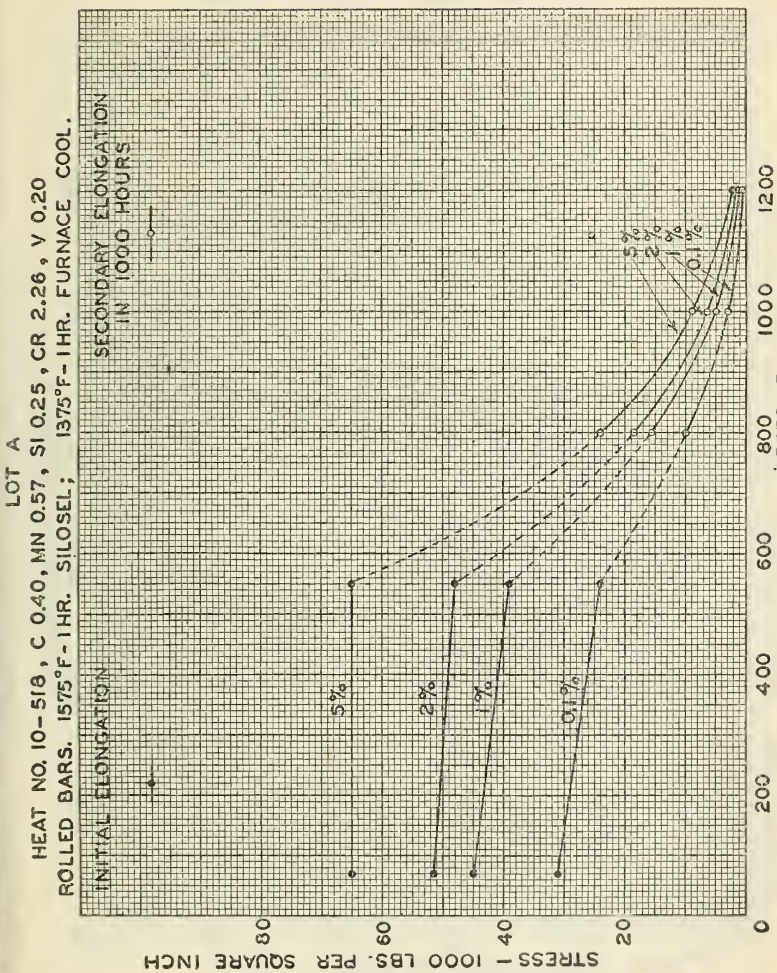


FIGURE 37.—*Flow chart for steel 10-518, lot A*

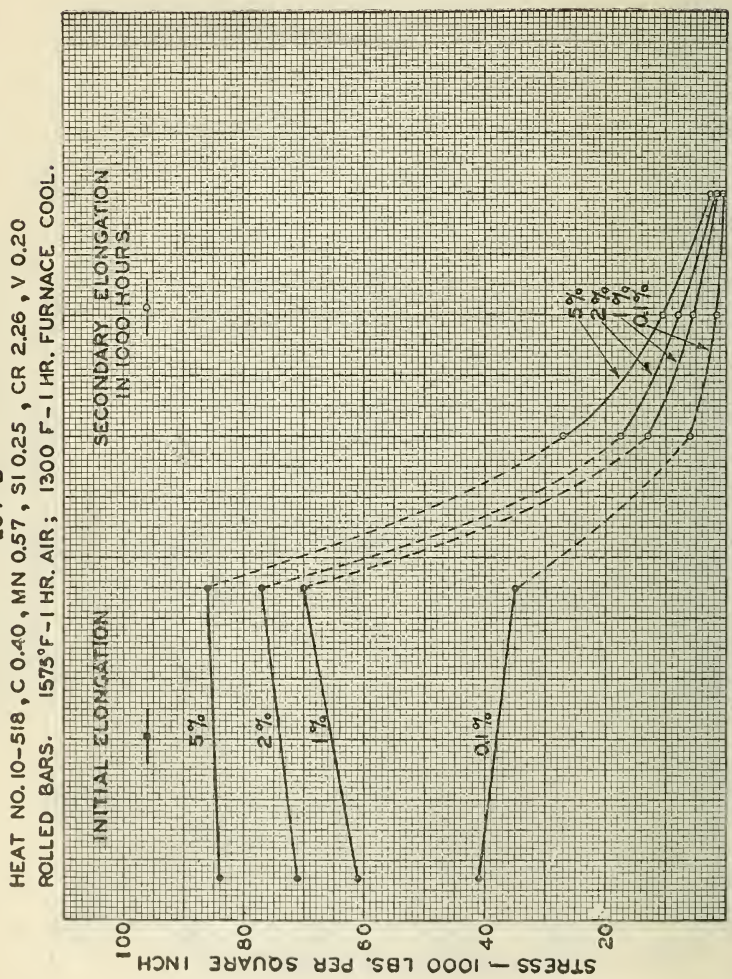


FIGURE 38.—*Flow chart for steel 10-518, lot B*

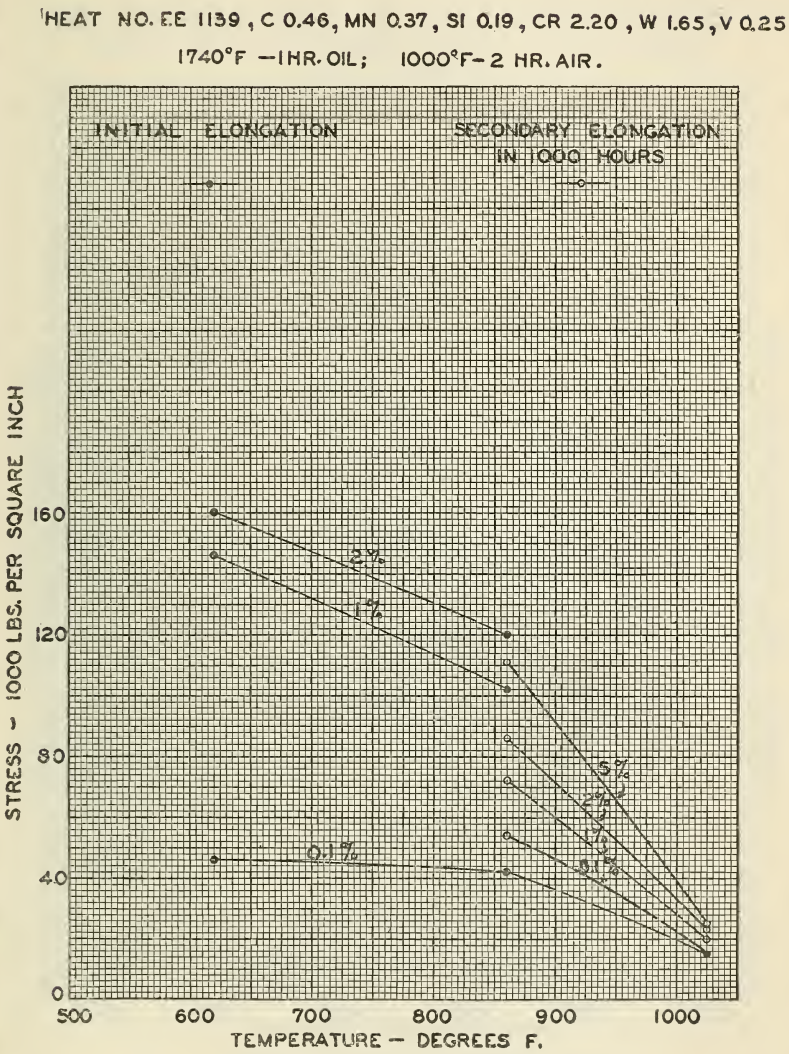


FIGURE 39.—*Flow chart for steel EE1139*

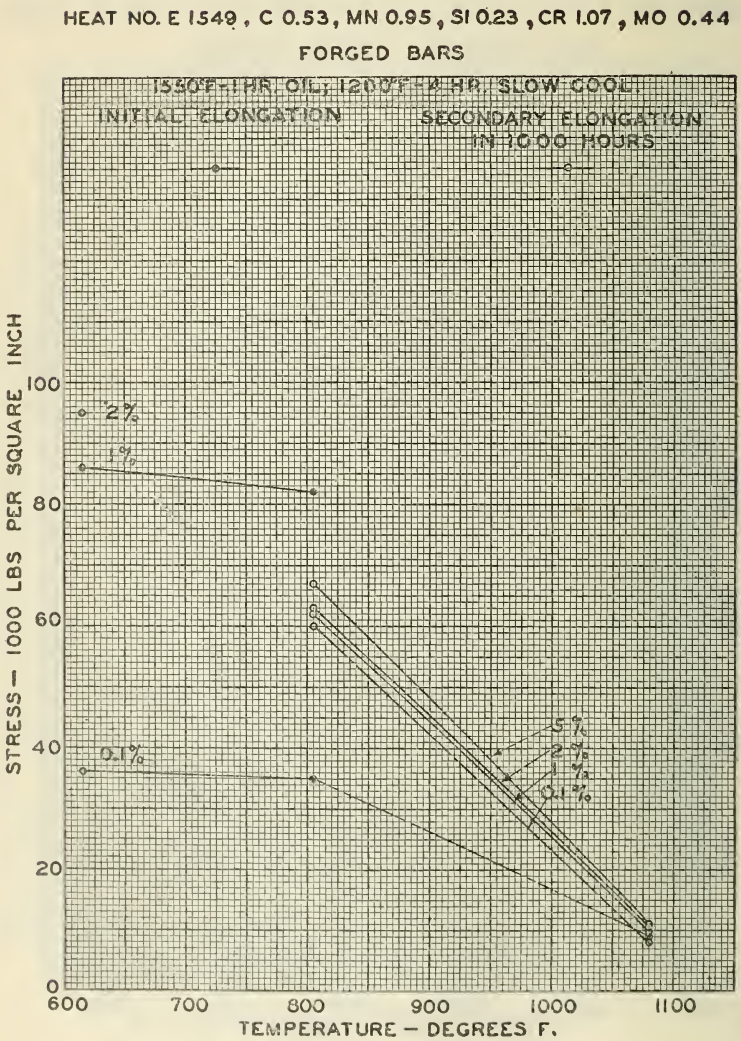


FIGURE 40.—*Flow chart for steel E1549*

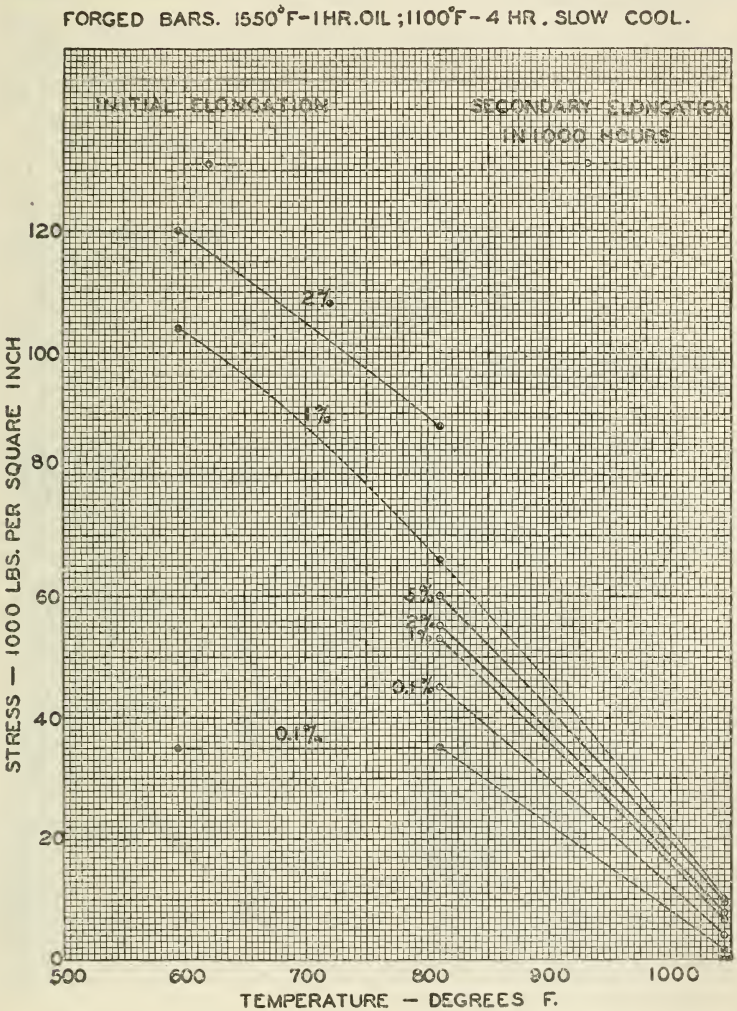


FIGURE 41.—*Flow chart for steel E1490*

The data given in Figure 42 confirm some of the facts developed from practical experience, but, in addition, show certain features which have not been given much, if any, attention. At temperatures between 1,125° and 1,350° F., the high nickel-chromium steels were generally superior to the carbon and low-alloy steels, but if the deformation per thousand hours at the higher temperatures is limited to 1 per cent or less, the maximum allowable stresses drop to low values even for the high-alloy steels.

The outstanding alloy of the group at temperatures between 1,000° and 1,350° F. was the one containing about 0.3 per cent carbon, 1 per cent silicon, 20 per cent chromium, 8 per cent nickel, and 4.5 per

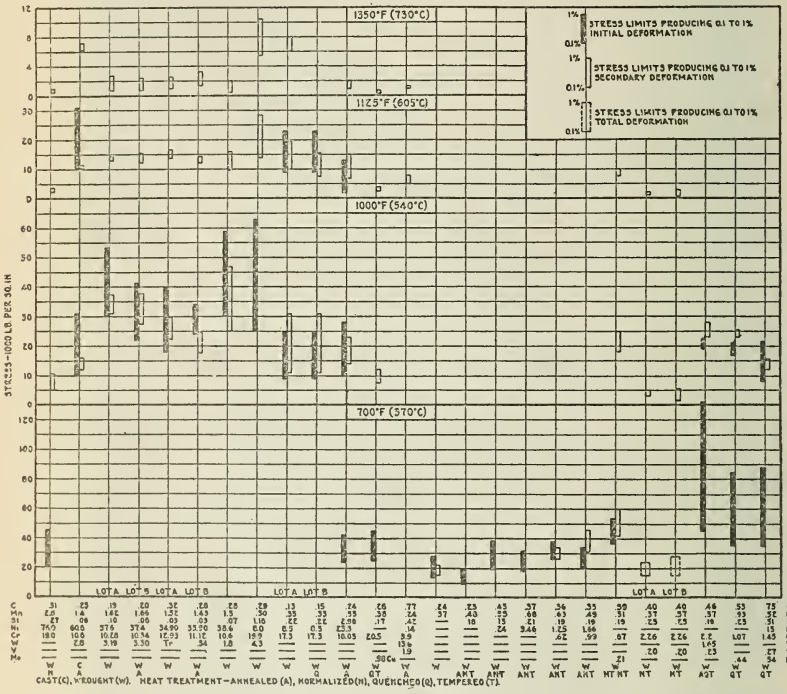


FIGURE 42.—*Comparisons of alloys on the basis of the stresses producing both initial and secondary deformation*

NOTE.—Secondary deformation is over period of 1,000 hours.

cent tungsten; it showed as high or higher load-carrying ability than any of the other alloys. Its superiority was most marked at 1,350° F., but tended to decrease with decrease in the permissible rates of flow and with decrease in temperature.

With this one exception, alloys showing superior properties at 1,350° F. did not necessarily show superiority at lower temperatures. At 1,350° F. superior load-carrying ability was shown by the alloys, 20 Cr, 8 Ni, 1 Si, 4.5 W; 18 Cr, 8 Ni; and 61 Ni, 11 Cr, 2.8 W; at 1,000° F. superiority was shown by the alloys 20 Cr, 8 Ni, 1 Si, 4.5 W; 38 Ni, 11 Cr, 1.8 W, and 57 Ni, 10 Cr, 3 W (FS–1 lot A; as rolled).

These different alloys all represent compositions used industrially for service at different temperatures and it was not practicable to

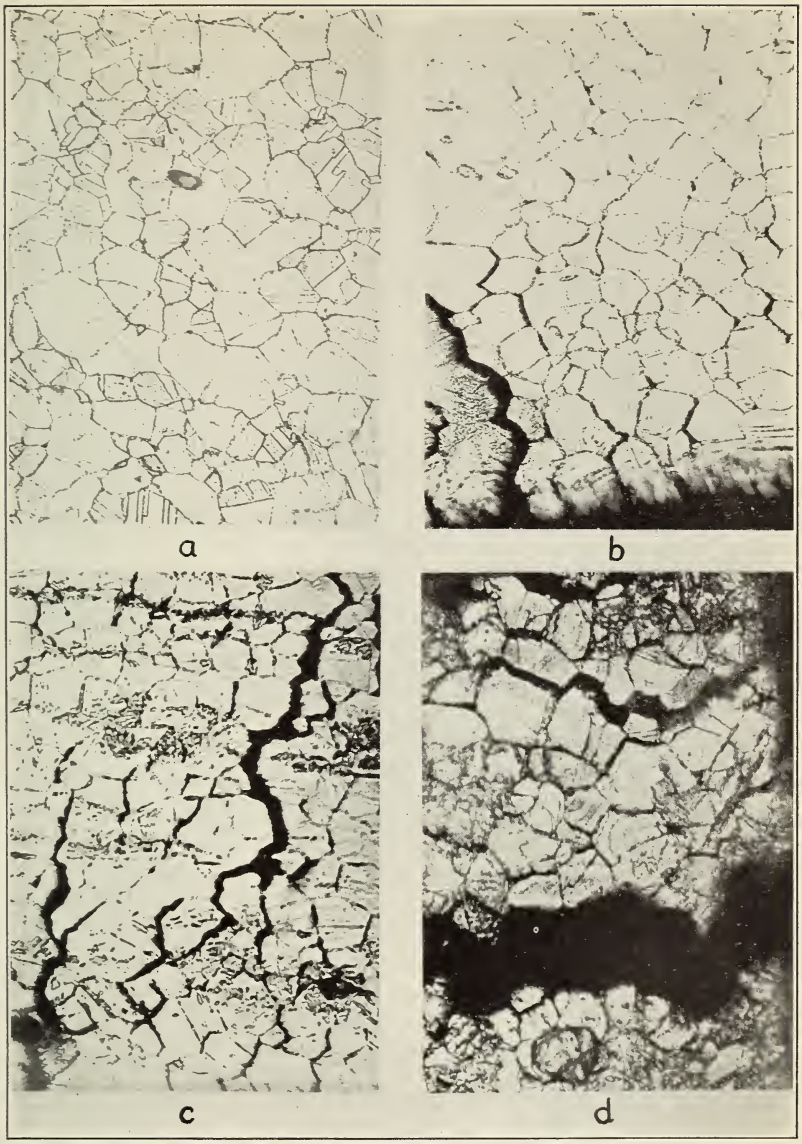


FIGURE 43.—*Structures of the rolled bars (lot A) of alloy E1912, after test at different temperatures, × 250*

a, 40,000 lbs./in.^{2} at 990° F. for 560 hours; *b*, 50,000 lbs./in.^{2} at 990° F. for 90 hours; metal ⅛ inch back of fracture at surface of specimen Total elongation, 15.5 per cent; *c*, 28,000 lbs./in.^{2} at 1,165° F. for 93 hours; metal ⅛ inch back of fracture at surface of specimen. Total elongation, 7.7 per cent; *d*, 10,000 lbs./in.^{2} at 1,380° F. for 168 hours; metal ⅛ inch back of fracture at surface of specimen. Total elongation, 4.4 per cent. Etched with 2 parts concentrated HCl, 1 part concentrated HNO_3, 1 part H_2O_2 and 2 parts glycerin.

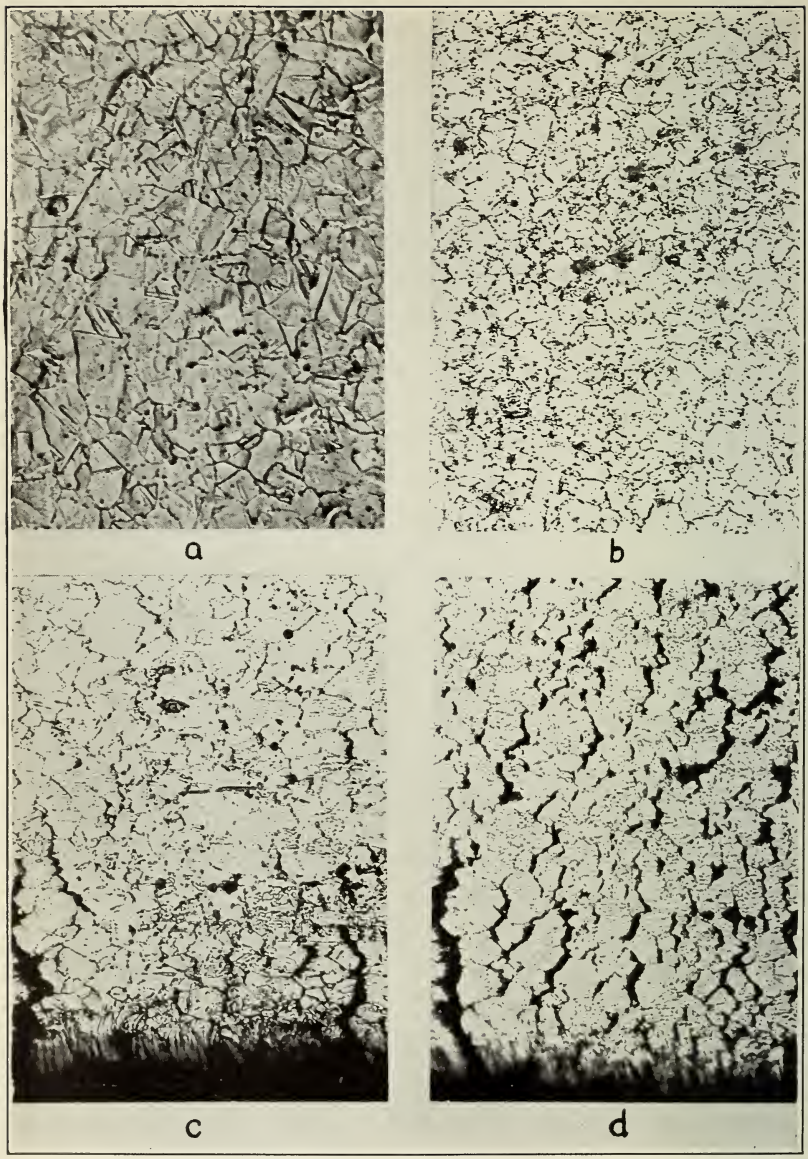


FIGURE 44.—*Structures of the water quenched bars (lot B) of alloy E1912 before and after test at different temperatures*

a, Original quenched bar; *b*, 40,000 lbs./in.^{2} at 990° F. for 520 hours, unbroken with 6.1 per cent elongation; *c*, 50,000 lbs./in.^{2} at 990° F. for 93 hours; metal ⅛ inch back of fracture at surface of specimen. Total elongation, 15.5 per cent; *d*, 20,000 lbs./in.^{2} at 1,195° F. for 223 hours, metal ⅛ inch back of fracture at surface of specimen. Total elongation, 10.1 per cent. Etched as indicated in Figure 43.

attempt to determine the effects of variations in important elements, such as nickel, chromium, and silicon upon their high temperature flow characteristics, since in only a few cases were the differences in composition of any two alloys restricted to a single element. For example, the effect of tungsten on the alloy nominally containing 18 per cent chromium and 8 per cent nickel can not be established from data in Figure 42, since the alloy with tungsten contains about twice the carbon and five times the silicon in the alloy without tungsten. Such circumstances do not affect the usefulness of the flow-test data, but made it necessary to depend upon the experimental melts, Group III, Table 1, to show the general trends in the system, nickel-chromium-iron.

The two lots of alloy E1912, containing about 18 per cent chromium and 8 per cent nickel with 0.15 per cent carbon offer some interesting comparisons. It was originally intended to test this alloy only in the hot-worked condition as represented by lot A, Table 1. However, more samples were required before the tests were completed and the bars of the second lot (B) were found to have a higher tensile strength at atmospheric temperatures than bars of lot A, due quite probably to a somewhat lower finishing temperature in rolling. Therefore, lot B was softened by water quenching from 1,850° F. and subsequently tested although its room temperature tensile strength was still somewhat higher than that of lot A. Also, the grain size of the quenched samples was smaller than that of the hot finished samples as is shown in Figures 43 and 44.

At 990° F., these two lots of alloy E1912 exhibited about the same load carrying ability but at 1,180° F. the fine-grained (water quenched) steel was weaker than the coarse-grained material. (Fig. 36.) Comparisons of the two lots were not made at higher temperatures, but the evidence available gives interesting confirmation of the view that fine-grained metals having more intercrystalline material than corresponding coarse-grained metals should be stronger at atmospheric temperatures, but weaker at high temperatures.

There is some evidence, however, that coarsely crystalline metals may be dangerous from other viewpoints. While they may flow at lower rates than corresponding fine-grained metals, fracture may occur with less total elongation. There is also the possible added disadvantage of weakness in resisting shock at high temperatures as well as at atmospheric temperatures.

In the case of the steel nominally containing 18 per cent chromium and 8 per cent nickel, a marked intercrystalline weakness was observed at temperatures between 1,165° and 1,380° F. and to some extent also at 990° F., in both fine-grained and coarse-grained samples, though the latter seemed to show the more marked tendency in this direction. When the specimens were allowed to remain under load at 1,165° to 1,195° or 1,380° F., until fracture occurred the fracture was intercrystalline and grain separations were to be observed at some distance back of the fractures, especially at the surface. These fractures are shown in Figures 43 and 44. There is no clear evidence that this intercrystalline weakness is associated with carbide precipitation at the grain boundaries.

According to one manufacturer [9] there is decided difference in behavior of this nickel-chromium steel which depends upon whether

[9] Private communication.

the carbon content is below or above 0.07 per cent. Quenching from around 2,100° F. has been recommended to bring the carbides in solution, but if subsequently reheated to above 990° F. embrittlement of steels with over 0.07 per cent carbon has been reported to occur and has been attributed to the reprecipitation of carbides at the grain boundaries.

The steel containing about 0.3 per cent carbon, 1 per cent silicon, and 4.5 per cent tungsten, in addition to 20 per cent chromium and 8 per cent nickel, showed intercrystalline weakness, 1,160° and 1,390° F., but, so far as could be determined from the usual metallographic examination, this was less marked than in the 0.15 per cent carbon steel with 18 per cent chromium, 8 per cent nickel, and no tungsten. (Figs. 43, 44, and 45.)

Intercrystalline weakness, possibly associated in some cases with grain growth, was observed in two of the samples of the alloy E1567 containing 38 per cent nickel, 11 per cent chromium, and 1.8 per cent tungsten when subjected continuously to stress at 1,185° F. (Fig. 46.) No similar effects were found in the alloy, E1894, containing about 60 per cent nickel, 11 per cent chromium, and 2.8 per cent tungsten which was tested in the cast (annealed) condition. The structure of this latter alloy was exceedingly coarse, as is shown in Figure 47 and in tests at 1,370° F. there was evidence of either carbide precipitation or the formation of a eutectic at the grain boundaries. (Fig. 47 (*b*) and (*c*).) Further attention to constitutional changes and intercrystalline weakness of the high-nickel chromium alloys when subjected continuously to stress at high temperatures with comparisons of the alloys nominally containing 18 per cent chromium and 8 per cent nickel with both more and less than 0.07 per cent carbon, would seem to be merited.

3. CARBON AND LOW ALLOY STEELS

If the load-carrying ability is judged by the stresses producing 0.1 to 1 per cent deformation in 1,000 hours, as in Figure 42, the low-alloy steels show promising properties at 700° to 1,000° F. and even up to 1,125° F.

Figure 42 shows a number of factors which tend to improve the load-carrying ability of carbon and low-alloy steels. The first is increase in carbon content. The steel with 0.45 per cent carbon showed much better load-carrying ability than that with 0.23 per cent carbon and resisted flow at 700° F. about as well as the steel with 0.35 per cent carbon and either 3½ per cent nickel or a combination of 1¼ to 1¾ per cent nickel and ½ to 1 per cent chromium.

A comparison of the stresses producing 0.1 to 1 per cent deformation in 1,000 hours for 0.35 per cent carbon steel obtained by interpolation of values for the 0.23 and 0.45 per cent carbon steels with the load-carrying ability of the nickel and nickel chromium steels of similar carbon content indicates that the addition of 3½ per cent of nickel or 1¼ to 1¾ per cent nickel and ½ to 1 per cent chromium is relatively ineffective in increasing the resistance to flow at 700° F. At least the load-carrying ability was no higher than that of a plain carbon steel of somewhat higher carbon content (0.45 per cent) when the metal was placed in a "soft" condition corresponding to that in

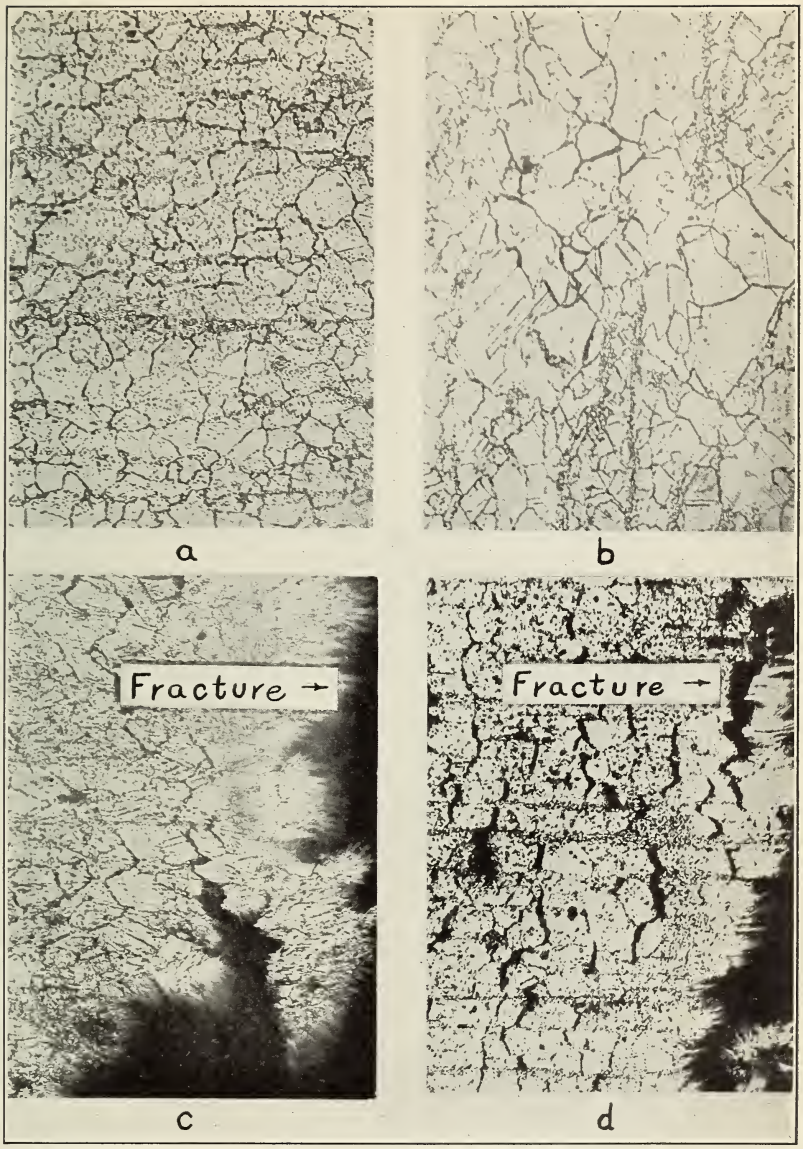


FIGURE 45.—*Structures of the forged bars of alloy EE1114, after test at different temperatures, × 250*

a, 78,400 lbs./in.² at 995° F. for 79 hours; metal ⅛ inch back of fracture near center of bar. Total elongation, 10.2 per cent; *b*, 25,000 lbs./in.² at 1,160° F. for 106 hours. Unbroken with total elongation of 0.32 per cent; *c*, 39,800 lbs./in.² at 1,160° F. for 106 hours; section at fracture. Total elongation, 4.9 per cent; *d*, 24,900 lbs./in.² at 1,390° F. for 77 hours; section at fracture. Total elongation, 2.7 per cent. Etched as indicated in Figure 43.

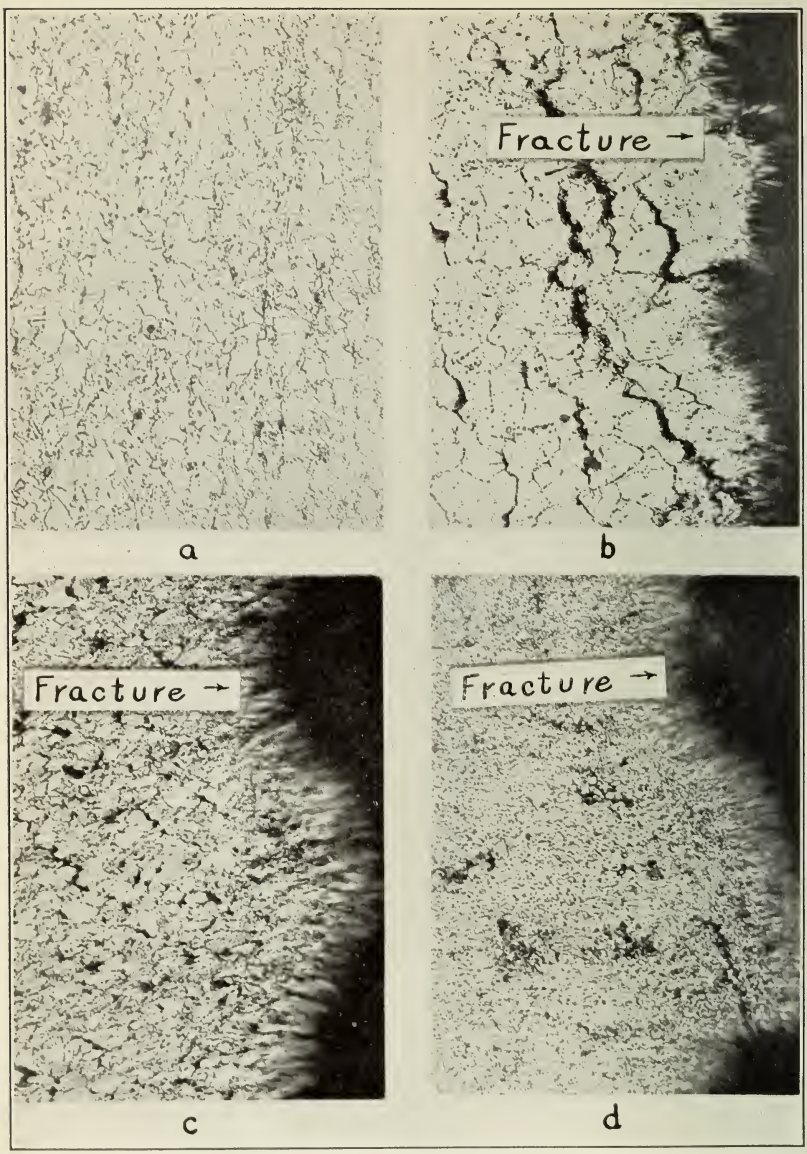


FIGURE 46.—*Structures of the rolled bars of alloy E1567, before and after test at different temperatures, × 250*

a, Original bar of lot B; *b*, 23,300 lbs./in.² at 1,185° F. for 180 hours; metal at fracture. Total elongation, 2.4 per cent (lot A); *c*, 35,000 lbs./in.² at 1,185° F. for 38 hours; metal at fracture. Total elongation, 13 per cent; *d*, 10,000 lbs./in.² at 1,360° F. for 70 hours; metal at fracture. Total elongation, 37 per cent. Etched as indicated in Figure 43.

large forgings. However, other characteristics of the alloy steels may give them superiority, such, for example, as superior resistance to grain growth on recrystallization which results from deformation and subsequent heating in cyclic temperature operations.

The outstanding feature with respect to the low-alloy steels is the effectiveness of quenching in raising the resistance to flow at temperatures around 700° to 1,000° F. It may be said, a priori, that quenching should be followed by tempering at temperatures at, or preferably above, those of subsequent operation if stability is to be expected, but it is significant that at 700° and 1,000° F. (in one case at 1,125° F.), the quenched and tempered steels showed load-carrying ability proportionately much higher than that produced by small additions of any of the alloying elements considered. It is largely for this reason that it was considered impracticable to attempt to develop the magnitude of the effects of tungsten additions to the chromium or other alloy steels (fig. 42) since the heat treatments were not all comparable.

One other item of interest is to be found in the comparison of the results obtained on the chromium-vanadium steel, No. 10–518, Table 1, subjected to two different preliminary heat treatments. At atmospheric and slightly elevated temperatures the samples with the higher tensile strengths, as determined at room temperature, showed the higher load-carrying ability but at 1,200° F. the order of superiority was reversed although the differences between the two sets of samples were not marked. It is probable that this reversal is analogous to that found in the high chromium nickel steel, E1912, Table 1, already discussed. Once again evidence has been obtained to indicate that high tensile strength at ordinary temperatures does not necessarily signify high load-carrying ability at high temperatures.

4. EFFECT OF PROLONGED STRESS AT DIFFERENT TEMPERATURES ON HARDNESS AND IMPACT RESISTANCE AT ATMOSPHERIC TEMPERATURES

One question which may arise in the practical application of metals at high temperatures is whether prolonged loading will produce appreciable changes in their properties at either atmospheric or elevated temperatures. Aside from precipitation of carbides, claimed to embrittle high chromium or high nickel chromium steel similar to E1912, Table 1, deformation at high temperatures followed by cooling and reheating, which may be encountered in cyclic operation of high-temperature equipment, may result in grain growth and changes in impact resistance or other properties.[10]

Recently Rosenhain and Hanson[11] reported an appreciable increase in the Brinell hardness of mild steel strips containing 0.11 per cent carbon when subjected for about five years at 570° F, to loads equivalent to one-third to two-thirds of their tensile strength determined at ordinary temperatures. This hardening was observed despite the fact that the samples were reported to have undergone only a very small amount of deformation in the specified interval.

No satisfactory explanation was offered for these effects, but if appreciable hardening can take place generally in steels without

[10] F. P. Fischer, Rekristallisationsversuche Allgemeiner Art und zahlenmässige Feststellungen über Festigkeitseigenschaften rekristallisierten Flusseisens (Weicheisens) Kruppsche Monatshefte, **4**, p. 77; 1923.
[11] W. Rosenhain and D. Hanson, The Behavior of Mild Steel Under Prolonged Stress at 300° C., J. Iron & Steel Inst., **116**, p. 117; 1927.

deformation, when they are subjected to prolonged stresses at high temperatures, this matter must be considered in the interpretation of flow-test data. On this account hardness and notched bar impact tests were made on samples of the chromium-vanadium steel, No. 10–518, Table 1, after they had been stressed for long periods in the flow tests.

The impact specimens were prepared from the reduced sections of the flow-test specimens, the notch being placed in the center of the gage length. On account of the small size of the specimens used in the flow tests (0.25-inch diameter) a standard impact test specimen could not be obtained. Instead, specimens were prepared for a low-range Charpy impact testing machine and had a length of 2.1 inches, a thickness of 0.1 inch and widths varying from 0.14 to 0.2 inch, depending upon the diameters of the tested flow test specimens. Whenever possible, specimens having a width of 0.2 inch were used. However, the results were all converted [12] to equivalent values for specimens having a width of 0.2 inch.

Rockwell hardness tests were also made on the broken impact specimens, a 1/16-inch ball and 100 kg load (B scale) being used. The results are summarized, together with pertinent flow test data in Tables 3 and 4.

TABLE 3.—*Effect of prolonged stress at different temperatures on subsequent hardness and impact resistance at atmospheric temperatures of the Cr–V steel, No. 10–518, Lot A, Table 1*

[1,575° F., slow cool; 1,375° F., furnace cool]

Specimen No.	Flow test		Duration of flow test	Final elongation in flow test	Reduction of area in flow test	Tests at room temperatures subsequent to flow tests	
	Temperature	Load				Impact resistance	Rockwell (B scale) hardness
	° F.	*Lbs./in.²*	*Hours*	*Per cent*	*Per cent*	*Ft./lbs.*	
3149	70	25,000	96	----------	----------	5.10	85.6
3149	70	35,000	195	0.17	----------	5.00	95.9
3142	70	50,000	140	1.87	----------	4.68	87.4
120	70	60,000	94	3.47	----------	4.55	90.5
120	70	70,000	148	6.24	----------	4.48	98.4
126	550	20,000	96	----------	----------	4.97	83.3
127	550	30,000	121	.43	----------	4.93	86.1
13	550	40,000	164	1.40	----------	5.11	86.0
3140	550	50,000	168	2.07	----------	4.22	90.8
3140	550	60,000	121	3.84	----------	3.08	94.0
3140	550	70,000	168	6.40	----------	3.53	98.8
C114	800	5,000	308	----------	----------	4.85	85.1
C115	800	10,000	327	----------	----------	5.07	93.3
C118	800	15,900	327	.06	----------	3.23	86.1
116	800	30,000	218	10.13	14.6	3.58	88.5
C128	1,000	2,500	305	----------	----------	5.26	84.5
C130	1,000	5,100	313	----------	----------	5.30	84.5
C135	1,000	10,000	291	1.89	2.04	4.45	85.2
C138	1,000	15,000	194	4.10	4.50	4.23	85.7
3151	1,000	15,000	288	6.24	5.30	4.36	84.9
C3126	1,200	500	315	----------	----------	5.21	83.4
C3120	1,200	1,000	313	----------	----------	5.11	84.5
3124	1,200	1,500	312	----------	----------	5.21	82.7
3119	1,200	3,000	288	----------	----------	4.99	81.9
C3125	1,200	5,000	315	7.8	----------	5.18	83.9

[12] Since the thickness of the specimens was the same in all cases, the impact values vary directly with the width.

TABLE 4.—*Effect of prolonged stress at different temperatures on subsequent hardness and impact resistance at atmospheric temperatures of the Cr–V steel, No. 10–518, Lot B, Table 1*

[1,575° F., air cool; 1,300° F., furnace cool]

Specimen No.	Flow test		Duration of flow test	Final elongation in flow test	Reduction of area in flow test	Tests at room temperatures subsequent to flow tests	
	Temperature	Load				Impact resistance	Rockwell (B scale) hardness
	° F.	*Lbs./in.²*	*Hours*	*Per cent*	*Per cent*	*Ft./lbs.*	
C3111	70	30,000	194	0.08	----------	5.12	95.0
3107	70	50,000	143	.38	----------	4.47	98.0
C3105	70	70,000	143	.39	----------	4.84	97.3
398	70	70,280	214	1.77	1.20	4.21	97.8
C3148	70	80,000	216	3.13	3.15	3.88	98.5
140	550	30,000	187	----------	----------	4.18	98.3
C142	550	37,750	187	.02	----------	4.13	97.9
3154	550	40,000	168	----------	----------	4.22	93.0
C265	550	62,500	260	.33	----------	4.25	96.4
C3103	550	70,000	91	.74	----------	4.10	97.7
C3102	550	80,000	91	2.19	----------	3.20	100.6
266	800	5,000	308	----------	----------	2.74	97.2
271	800	5,000	327	----------	----------	3.42	95.7
C262	800	9,440	197	----------	----------	2.20	97.1
C275	800	10,000	327	.10	----------	2.46	97.3
C147	800	15,000	191	.18	----------	2.61	97.2
C259	800	22,000	282	.55	----------	2.50	96.6
C268	800	29,600	866	8.99	1.43	3.78	95.4
252	1,000	2,500	322	.33	----------	4.19	98.2
C251	1,000	4,490	489	.10	----------	4.47	96.7
C143	1,000	7,500	305	.52	----------	4.65	95.3
C250	1,000	10,000	383	1.49	----------	4.45	97.1
C394	1,000	15,000	288	8.52	13.06	4.46	95.7
287	1,200	500	441	.18	----------	4.95	92.3
C274	1,200	785	750	1.13	----------	5.25	88.7
C273	1,200	1,500	367	.57	----------	4.92	90.1
C277	1,200	3,000	218	2.77	----------	5.06	93.4

No measurable changes were found in the hardness or impact resistance at atmospheric temperatures so long as no appreciable deformation was produced in the previous flow tests. Deformation at temperatures at which strain hardening occurs in the flow tests was accompanied quite generally by an increase in the hardness and a decrease in the resistance to impact. In all cases, however, the changes were small. At higher temperatures, 1,000° to 1,200° F., no measurable changes were produced in the impact resistance or hardness by deformation in the flow tests. The flow tests were not continued for such long periods as in the tests reported by Rosenhain and Hanson and a steel of very different composition was studied. The results indicated, however, that no changes occurred other than those which might normally be expected from strain hardening.

5. TRENDS AT 1,000° F. IN THE SYSTEM NI-CR-FE

In the tests of the commercial alloys of nickel, chromium, and iron, it was impracticable to determine the effects of variations in nickel or chromium on the load-carrying ability of the alloys at high temperatures, since the variations in composition were not restricted to these individual metals. It was largely on this account that the 12 metals of Group III, Table 1, were prepared. Their

approximate locations in the nickel-chromium-iron ternary diagram are shown in Figure 48.

The flow tests were not continued for such long periods as those made on the commercial alloys, since the principal object was to determine general trends in the system, nickel-chromium-iron, rather than to secure numerical values of the load-carrying ability of the different alloys.

The metals were melted in zirconia crucibles in a high-frequency induction furnace, cast in iron molds (preheated to approximately 390° F.), and subsequently heat treated as indicated in Table 1. The heat treatments were selected to produce at least a partial grain

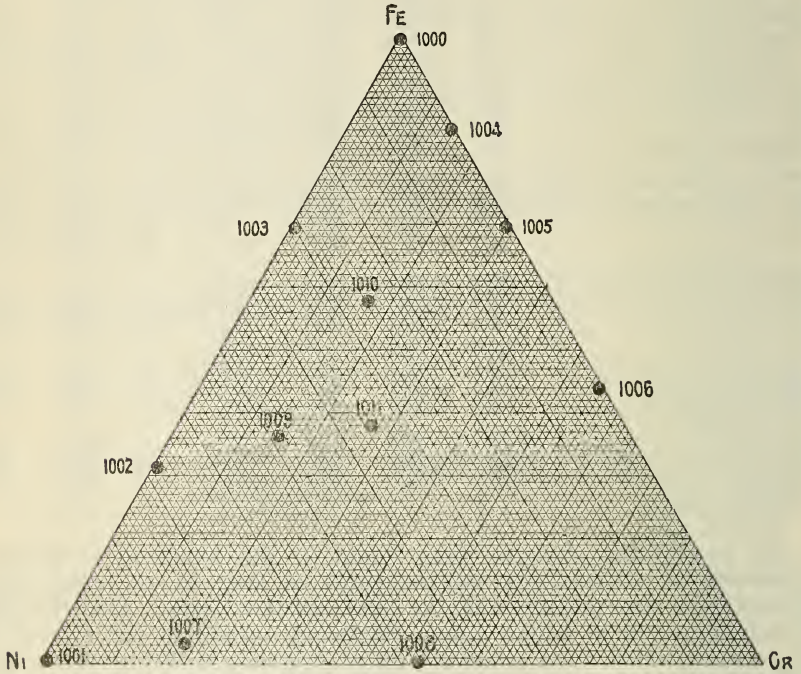


FIGURE 48.—*Locations of the alloys of Group III, Table 1, on the nickel-chromium-iron ternary diagram*

The melt numbers given in the chart correspond to those given in Table 1.

refinement, promote diffusion, and leave the alloys in a "softened" condition.

The alloys tested were not pure in the sense that they were free from all elements except nickel, chromium, and iron, since intentional additions were made of carbon, silicon, and manganese. The presence of appreciable proportions of the last three elements probably exerted a pronounced effect upon numerical values of the flow at 1,000° F., and by acting in different ways in different alloys may have modified somewhat the magnitude of the changes existing in the pure nickel-chromium-iron system. However, it is hardly probable that the general trends were upset by the presence of the carbon, silicon, or manganese and, since most industrial alloys castings of this general

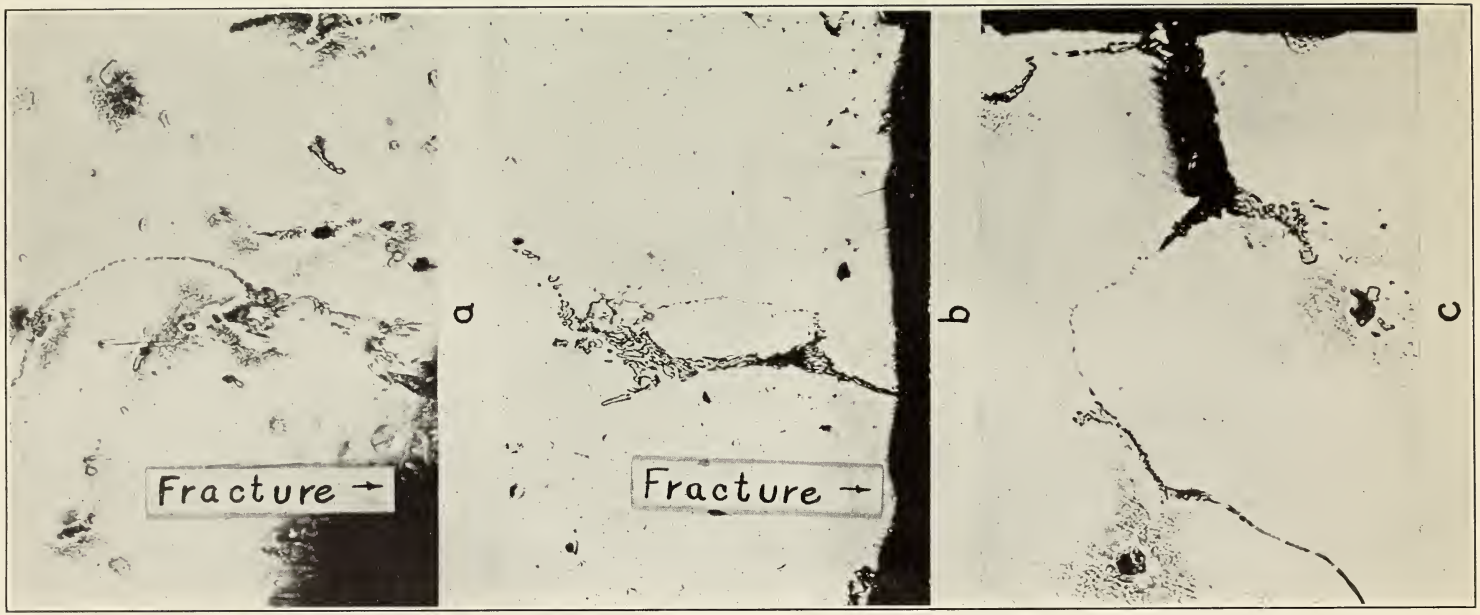


FIGURE 47.—*Structures of the cast and annealed specimens of alloy E1894 after test at different temperatures, × 100*

a, 28,000 lbs./in.² at 1,215° F. for 64 hours; metal at fracture. Total elongation 18 per cent; *b*, 14,000 lbs./in.² at 1,370° F. for 41 hours; metal at fracture. Total elongation 35.4 per cent; *c*, same as *b*, but at surface ⅛ inch back of fracture. Etched as indicated in Figure 43

type contain appreciable amounts of these three metals, the results are probably closer to those obtainable in practice than would be the case with pure metals.

Table 1 shows that not all of the alloys contained the desired amounts of carbon, silicon, and manganese. The carbon contents were 0.20 to 0.35 per cent in most cases, but some of the alloys contained as much as 0.50 per cent or as little as 0.11 per cent. The manganese was between 0.6 and 0.9 per cent, but the silicon varied from about 0.5 to 1.1 per cent. These variations probably affected the numerical values of the flow appreciably, but, in general, may be disregarded since only the major trends in the nickel-chromium-iron system are to be considered.

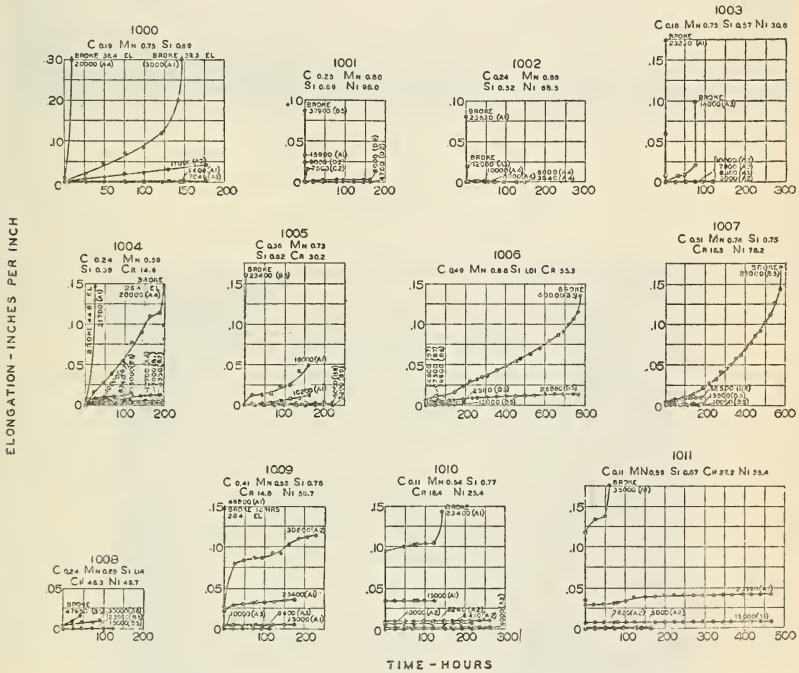


FIGURE 50.—*Time-elongation curves from tests at 1,000° F. of the alloys of Group III, Table 1*

The specimens for the flow tests were cut from the castings at points midway between the outside and the center in the direction of the long axis. The Brinell hardness values subsequent to the recorded heat treatments are given in Table 1, and have been used as the basis of the 3-dimension model in Figure 49 to give a better picture of the conditions in which the metals were tested. The time-elongation curves from the flow tests at 1,000° F., are given in Figure 50 while the relations between the flow and the applied loads are summarized in Figure 51.

As in the case of the alloys of Groups I and II, Table 1, the load-carrying ability may be represented by the stresses producing 1 per cent elongation in the first thousand hours and a comparison of the metals on this basis is given in the 3-dimension ternary model in

Figure 52. Figure 52 shows that the addition of nickel to the iron, containing about 0.2 per cent carbon, etc. (Table 1), resulted in no marked changes in the stresses producing 1 per cent elongation in the first thousand hours.

The addition of chromium to iron containing about 0.2 per cent carbon, etc. (Table 1), did not improve the load-carrying ability at 1,000° F. appreciably until the chromium content was in the neighborhood of 50 per cent. In fact, the iron alloy with 30 per cent chromium showed the lowest resistance to flow of all of the alloys tested and that with 14 per cent chromium, representing the composition of "stainless steel," was about on a par with steel containing no chromium.

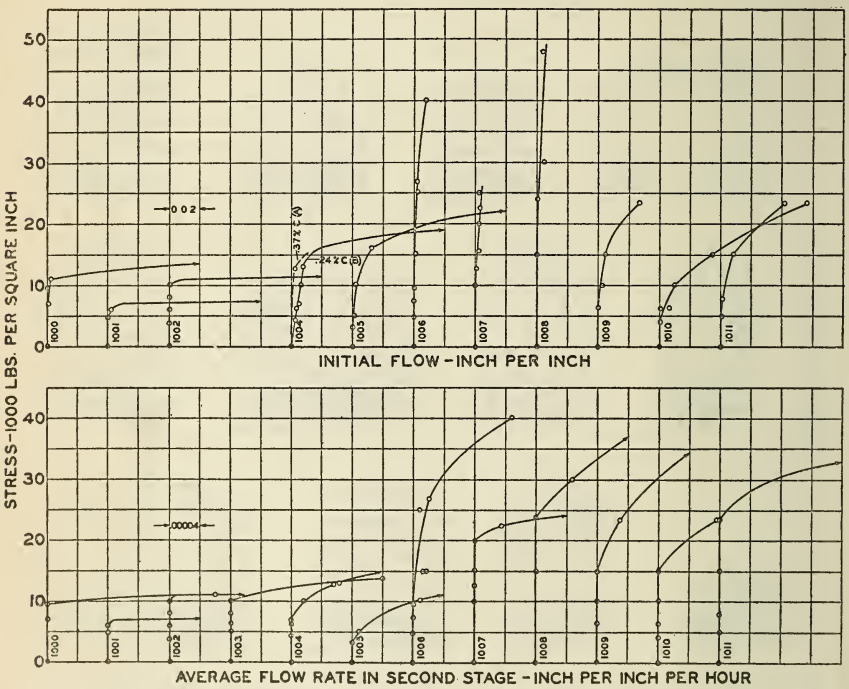


FIGURE 51.—*Flow data for tests at 1,000° F. on the alloys of Group III, Table 1*

Obtained from Figure 50.

On the other hand, the addition of a little chromium to the iron alloys with 40 per cent or more of nickel produced a marked increase in the load-carrying ability. The most effective proportions of chromium were between 5 and 20 per cent; higher proportions produced further increases, but not in the same degree.

These results explain in part the popularity of the commercial iron-nickel-chromium casting alloys containing about 60 to 65 per cent of nickel and 10 to 20 per cent of chromium. This composition is in the range of high load-carrying ability, although it does not have the best resistance to flow.

The strongest of the alloys at 1,000° F. were those with little or no iron, 50 to 80 per cent nickel, and 50 to 20 per cent chromium. The

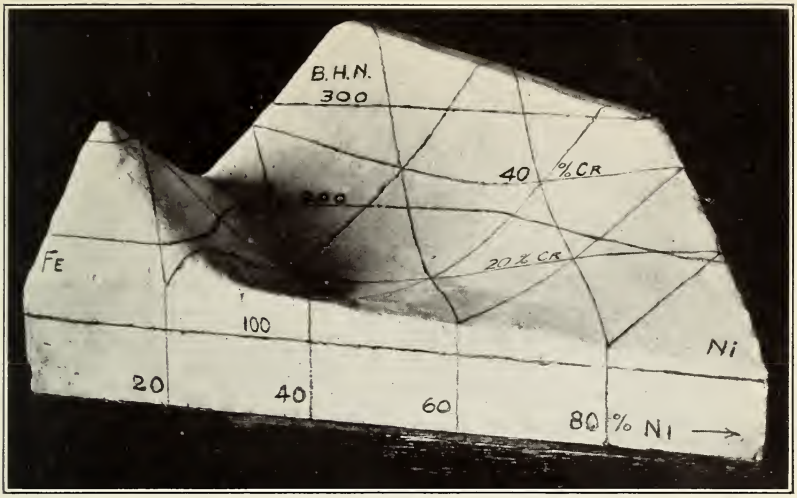


FIGURE 49.—*Summary of the Brinell hardness of the alloys in Group III, Table 1, in the conditions tested*

This model is based on data given in Table 1.

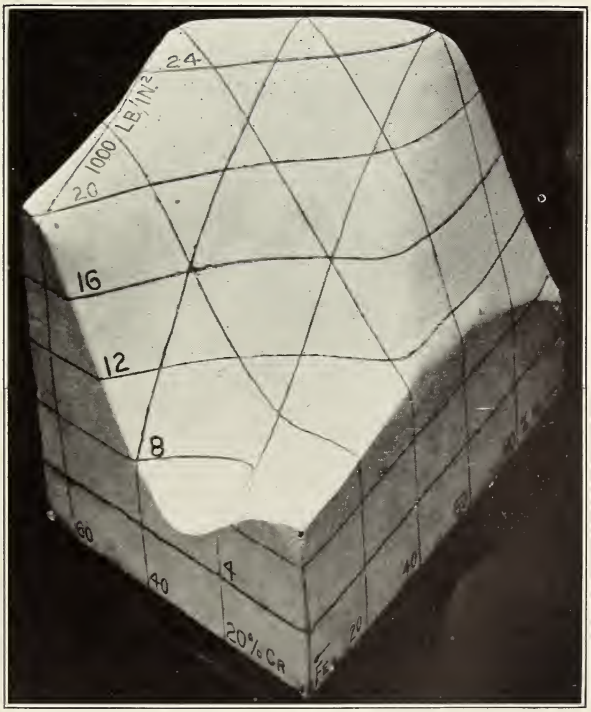


FIGURE 52.—*Stresses producing 1 per cent elongation in the first 1,000 hours at 1,000° F. in cast alloys of the system, nickel-chromium-iron*

As explained in the text, this model is intended only to show the general trends in the system.

highest load-carrying ability was obtained in the castings containing about 50 per cent each of nickel and chromium (alloy 1008, Table 1), but this alloy would be expected to offer difficulties in the foundry and had the serious disadvantage of fracturing with low elongation. (Fig. 50.) The remedy for this latter condition may be in decrease in the impurities, but foundry difficulties would be expected to persist under such conditions. A more practical solution of the problem of securing higher resistance to flow at high temperatures would probably be in additions of other elements to the alloys containing 60 to 65 per cent of nickel, 10 to 20 per cent of chromium. Tungsten is one of the additions used industrially for this purpose as is shown by the composition of the commercial alloys of Group I, Table 1.

In the alloys containing 50 per cent or more of nickel and 10 to 20 per cent of chromium, it would seem to be advisable to keep the chromium close to 20 per cent, since a decrease to 15 per cent or less brings the metal into a range of rapidly decreasing load-carrying ability as is shown in Figure 52. This means that the composition variations ordinarily encountered in commercial production would result in wider variations in properties in the nickel-iron alloys with 5 to 15 per cent chromium than in those with 15 to 20 per cent. Furthermore, lowering the chromium would also tend to lower the oxidation resistance of the metal.

It is of interest to note that the iron-nickel-chromium alloy having the nominal composition of 18 per cent chromium and 8 per cent nickel, which is now so widely used in the wrought condition, is in the field of low load-carrying ability at 1,000° F. It can not compete with some of the other alloys in castings for service requiring high resistance to flow, but is attractive on account of excellent resistance to oxidation and because it can be formed either hot or cold.

While this and some of the other alloys in the nickel-chromium-iron system were found to have relatively low resistance to flow at 1,000° F., it should be recognized that improvement may be obtained through modifications in heat treatment or by varying the proportions of elements, such as carbon, silicon, etc. An example is found in the iron alloy containing 14 per cent chromium. Tests on two different ingots containing, respectively, 0.24 and 0.37 per cent carbon showed (fig. 51) that the alloy with 0.37 per cent carbon had a much better resistance to flow at 1,000° F. than the alloy with 0.24 per cent carbon.

It should be recognized that variations in the general structure (cast or wrought metal), in heat treatment, or in the proportions of elements, such as carbon and silicon, may affect the load-carrying ability to a greater degree than appreciable variations in the proportions of nickel, chromium, or iron at least in some parts of the system. (Fig. 52.)

V. SUMMARY

Flow tests were made at different temperatures on three groups of alloys. The 11 metals of the first group comprised 1 nickel-chromium alloy, 6 nickel-chromium-iron alloys, with or without tungsten, and 4 low chromium steels containing also vanadium, tungsten, or molybdenum. The flow characteristics of these metals are summarized in charts given in the report.

Two carbon steels, two low nickel-chromium steels, and a 3½ per cent nickel steel comprised the second group of metals which were

tested at 700° F. When annealed so as to reproduce the conditions existing in large forgings the plain carbon steel containing 0.45 per cent carbon showed better load-carrying ability than that with 0.23 per cent carbon and resisted flow at 700° F. about as well as the steels with 0.35 per cent carbon and either 3½ per cent nickel or a combination of 1¼ to 1¾ per cent nickel and ½ to 1 per cent chromium.

The third group of metals consisted of nickel-chromium-iron alloy castings melted in a high-frequency induction furnace. Their chemical compositions were selected to cover a broad area in the nickel-chromium-iron system, and the tests of these metals were made at 1,000° F. after annealing or normalizing to produce softening, grain refinement, and diffusion.

It was found that the addition of nickel to iron containing about 0.20 per cent carbon, 0.75 per cent manganese, and 0.7 per cent silicon resulted in no marked changes in the stresses required to produce 1 per cent elongation in the first 1,000 hours. The addition of chromium to the iron did not greatly improve its load-carrying ability until the chromium content reached about 50 per cent. In fact, the iron alloy with 30 per cent chromium showed the lowest resistance to flow of all of the alloys tested at 1,000° F. and the one with 14 per cent chromium, representing the composition of "stainless steel," was about on a par with steel containing no chromium.

On the other hand, the addition of a little chromium to the iron alloys with about 40 per cent or more of nickel produced a marked increase in the load-carrying ability. The most effective amounts of chromium were between 5 and 20 per cent; higher proportions produced further increases, but these were not commensurate with the increases produced by additions below 20 per cent.

The highest load-carrying ability was obtained in the castings containing about 50 per cent each of nickel and chromium, but this alloy would be expected to offer difficulties in the foundry and, with the proportions of carbon, silicon, and manganese present, had the serious disadvantage of low ductility.

In the case of the wrought commercial alloy containing 0.15 per cent carbon, 18 per cent chromium, and 8 per cent nickel, intercrystalline weakness was observed at temperatures between 1,165° and 1,380° F. and to some extent also at 990° F. This was noted in both fine-grained and coarse-grained samples, although the latter seemed to show the greater tendency in this direction. A similar tendency, but in a smaller degree, was observed at 1,160° and 1,390° F. in the alloy containing 0.3 per cent carbon, 1 per cent silicon, 4.5 per cent tungsten, 20 per cent chromium, and 8 per cent nickel, and at 1,185° F. in an alloy containing 38 per cent nickel, 11 per cent chromium, and 1.8 per cent tungsten.

In the case of the wrought alloy containing about 0.15 per cent carbon, 18 per cent chromium, and 8 per cent nickel, fine-grained and coarse-grained samples showed about equal load-carrying ability at 990° F., but the fine-grained samples were weaker than the coarse-grained at 1,180° F. This should not be taken as a recommendation of coarse-grained metals for high-temperature service, since fracture may occur with less total elongation than in the corresponding fine-grained metals and so counteract any advantages from lower rates of flow. There is also the possible added disadvantage of weakness in resisting shock.

With one exception the wrought commercial alloys of nickel, chromium, and iron which showed superiority at about 1,380° F. did not necessarily show superiority at lower temperatures. This exception was the alloy containing about 20 per cent chromium, 8 per cent nickel, 4.5 per cent tungsten, 0.3 per cent carbon, and 1 per cent silicon, which had the highest load-carrying ability of all of the alloys of Group I.

A study was made of the effect of deformation in the flow tests at different temperatures on the hardness and impact resistance of a chromium-vanadium steel at ordinary temperatures. No marked changes were found in the hardness or impact resistance so long as no measurable deformation was produced in the prior flow tests. At temperatures at which strain hardening occurs, deformation in the flow tests produced a small increase in the hardness and a decrease in the impact resistance of the steel at atmospheric temperatures; deformation in the flow tests at higher temperatures did not affect these properties at atmospheric temperatures.

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