CREEP AND STRUCTURAL STABILITY OF NICKEL- CHROMIUM-IRON-ALLOYS AT 1,600° F.

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ABSTRACT

A study was made of the creep characteristics at 1,600° F. (870° C.) of 15 alloys covering a range from 1 to 75 percent nickel and from 3 to 55 percent chromium. The results were compared with those of a previous investigation at 1,000° F. (538° C.) on similar alloys.

In the investigation at 1,000° F. (538° C.) of the nickel-chromium-iron system, it was found that the alloys containing little or no iron, 50 to 80 percent nickel and 20 to 50 percent chromium exhibited the greatest resistance to creep. At 1,600° F. (870° C.), the strongest alloys are those containing approximately equal parts of nickel and chromium, and not more than 30 to 40 percent iron.

As part of a metallographic study the attempt was made to distinguish between the effect on structure of elevated temperature alone and of elevated temperature and stress combined. A comparison was made between the structure in specimens used in the creep test and that in the unstressed specimens of the same alloys annealed at 1,600° F. (870° C.) for periods ranging from 100 to 1,000 hours or quenched in iced brine from that temperature. In nearly all cases the quenched specimens were similar in structure to the annealed materials which indicates that these alloys were not readily heat treated.

Carbide precipitation and agglomeration of the carbide at the grain boundaries were most pronounced in both the binary iron-chromium alloys and the ternary iron-chromium-nickel alloys of higher chromium content. Prolonged heating, of both stressed and unstressed specimens, did not produce any pronounced changes in the structure of the binary iron-chromium alloys or the ternary alloys except those containing 50 percent or more of nickel.

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I. INTRODUCTION

The stresses producing creep of 1 percent in 1,000 hours in a number of cast nickel-chromium-iron alloys at 1,000° F. (538° C.) have been reported by French, Kahlbaum, and Peterson.¹ The present study

¹ H. J. French, Wm. Kahlbaum, and A. A. Peterson, Flow Characteristics of Special Fe-Ni-Cr Alloys and Some Steels at Elevated Temperatures, B.S. Jour. Research, vol. 5 (RP192), pp. 125-183, July 1930.

gives information on creep at 1,600° F. (870° C.) of similar materials, together with observations on the accompanying structural changes. To facilitate the comparison of the results of the earlier work with those of the present tests, the data of the earlier tests have been summarized graphically and included in this report to show the rates of creep at 1,000° F.

II. MATERIALS

The alloys used are listed in table 1. They cover a range from 1 to 75 percent nickel and from 3 to 55 percent chromium. Eight alloys (72 to 79, inclusive, table 1) were kindly prepared for this investigation by the Michiana Products Corporation, Michigan City, Ind. The preparation was similar to that employed at this Bureau for the corresponding alloys used in the tests at 1,000° F. (538° C.). Ingots 1½ inches in diameter and 6 inches long were cast in chill molds and were quartered longitudinally after heat-treatment (table 1). Specimens of 0.250 inch diameter were machined from the quarters. Four of the other materials (DH, OS, CA, and MS, table 1) were secured originally for use in "short-time" tensile tests at elevated temperatures. They represent the "as cast" materials. In addition to the cast alloys, one wrought material, representing a widely used commercial nickel-chromium heat-resistant alloy (76-20, table 1) was tested.

TABLE 1.—Composition and heat treatment of nickel-chromium-iron alloys tested for creep at 1,600° F.

Alloy designation	C	Mn	P	S	Si	Cr	Ni	Form of material	Heat treatment of alloys before the creep tests
	Per-cent	Per-cent	Per-cent	Per-cent	Per-cent	Per-cent	Per-cent		
72-----	0.41	0.17	-----	-----	0.50	12.91	1.36	1½-inch round ingots.	1,650° F., 1 hour, furnace cooled.
73-----	.19	.32	-----	-----	1.51	127.54	12.36	do-----	1,800° F., 2 hours, air cooled.
74-----	.37	.34	0.023	0.009	1.13	55.80	.82	do-----	1,900° F., 3 hours, air cooled.
75-----	.03	.28	.042	.005	1.54	17.20	24.00	do-----	2,000° F., 3 hours, air cooled.
76-----	.26	.27	-----	-----	1.10	130.94	133.00	do-----	1,900° F., 3 hours, air cooled.
77-----	.33	1.00	-----	-----	1.51	18.02	150.62	do-----	Do.
78-----	.22	1.30	.019	.036	1.01	18.00	72.80	do-----	Do.
79-----	.25	.31	.023	.022	.13	3.00	31.20	do-----	1,450° F., 1 hour, furnace cooled.
76-20---	.15	-----	-----	-----	-----	20.60	76.00	1½-inch round rod.	Mill annealed.
DH ¹ ---	.87	.85	-----	-----	1.10	13.72	58.45	1¼-inch round castings.	As cast.
OS ¹ ---	.95	.79	-----	-----	1.77	19.18	40.42	do-----	Do.
CA ¹ ---	.18	.96	-----	-----	1.16	16.70	74.62	do-----	Do.
MS ¹ ---	.62	.44	-----	-----	1.57	15.62	25.18	do-----	Do.

¹ Manufacturer's analysis; all others were made at the Bureau of Standards by H. A. Bright and H. M. Fowler.

² Secured originally from various sources for use in "short-time" tensile tests at elevated temperatures.

The compositions and heat-treatments of the alloys used in the tests at 1,000° F. are given in table 2.

TABLE 2.—Composition and heat treatment of nickel-chromium-iron alloys tested for creep at 1,000° F.¹

Alloy designation	C	Mn	Si	Cr	Ni	Form of material	Heat treatment of alloys before the creep tests
	Percent	Percent	Percent	Percent	Percent		
1,000.....	0.19	0.75	0.69	-----	-----	1½ - inch octagonal castings.	1,650° F., ½ hour, air cooled.
1,001.....	.25	.80	.89	-----	Balance.	do.	1,500° F., ½ hour, air cooled.
1,002.....	.24	.88	.52	-----	68.5	do.	1,650° F., ½ hour, air cooled.
1,003.....	.18	.75	.57	-----	30.6	do.	1,450° F., 1 hour, furnace cooled.
1,004.....	.24	.59	.39	14.6	-----	do.	1,650° F., 2 hours, furnace cooled.
1,005.....	.38	.73	.82	30.2	-----	do.	1,800° F., 2 hours, air cooled.
1,006.....	.49	.68	1.01	55.3	-----	do.	1,800° F., 2 hours, air cooled.
1,007.....	.51	.74	.75	18.3	78.2	do.	1,900° F., 3 hours, air cooled.
1,008.....	.24	.88	1.14	46.3	49.7	do.	Do.
1,009.....	.41	.53	.78	14.8	58.7	do.	Do.
1,010.....	.11	.54	.77	16.4	25.5	do.	2,000° F., 1 hour, air cooled.
1,011.....	.11	.59	.87	27.2	35.4	do.	1,900° F., 3 hours, air cooled.
1,024.....	Commercial nickel shot remelted and cast in ingots.					do.	1,500° F., ½ hour, air cooled.

¹ See footnote 1 (text), p. 851.

III. METHODS OF STUDY

1. CREEP TESTS

The method for determining creep was the same as previously described.² The specimen had a diameter of 0.250 inch and a gage length of 2 inches and was loaded as indicated in figure 1. The gage length was defined by means of fine platinum wires in grooves on the edge of the shoulder at each end of the reduced section. Elongation was measured by means of a traveling micrometer microscope.

At the middle of the gage length, the temperature at the surface of the specimen exceeded the temperature at the center of the specimen by 2° F. at 1,600° F. This was determined by two thermocouples. A platinum-platinum-rhodium thermocouple of 0.008 inch diameter wire covered with porcelain insulation was inserted in a very small hole extending radially to the center of a calibration specimen. Another thermocouple of 0.025 inch diameter chromel-alumel wire fastened to the surface of this specimen at the middle of the gage length indicated a temperature 2° F. higher than the one embedded in the metal. Further temperature measurements on the surface of the calibration specimen at the shoulder just outside of the reduced section indicated that the maximum temperature decrease along the surface of the specimen was 9° F. (5° C.). Thus, with surface temperature of 1,600° F. (870° C.) at the center of the gage length the temperature of the surface at each shoulder was 9° F. (5° C.) lower.

The creep tests made were of 500 to 700 hours' duration. The total creep during these periods was sufficient to permit the detection of rates of creep of the order of 10⁻⁶ inch per inch per hour.

² Wm. Kahlbaum and Louis Jordan, Creep at Elevated Temperatures in Chromium-Vanadium Steels Containing Tungsten or Molybdenum, B.S. Jour. Research, vol. 9 (RP481), p. 441, September 1932.

2. MICROSTRUCTURAL EXAMINATION

A metallographic study was made of specimens representative of the materials before and after the creep tests. In addition to the determination of the structural changes occurring as result of creep, an attempt was made for the purpose of ascertaining whether or not the rate of structural changes in these alloys might be accelerated by stress, and to distinguish between the effect on structure of elevated temperature alone and of elevated temperature and stress combined.

Townsend has observed that, in the case of lead sheath, the precipitation and coalescence of antimony from solid solution are accelerated

FIGURE 1.—Diagram of vertical test unit for creep tests at elevated temperatures.

A, traveling micrometer microscope; B, illuminator; C, thermocouple which actuates automatic controller; D, specimen temperature recording thermocouple; E, asbestos packing to minimize convection currents within the furnace.

by strain. Some authorities believe a similar condition exists in duralumin. A precipitation of CuAl_2 along the slip planes has been observed in portions of duralumin propellers which have been subjected to high stresses.

The metallographic specimens representative of the structural condition after creep were cut from the reduced sections of the test bars which had undergone creep at several loads and for different periods of time. Comparison specimens of the same alloys, protected from oxidation by being packed in sand and charcoal, were heated in an automatically controlled electric muffle furnace at $1,600^\circ \text{F. (870}^\circ \text{C.)}$ for periods varying from 100 to 1,000 hours. Two specimens of

each alloy were removed after each successive 100-hour heating period up to 1,000 hours. One specimen was quenched in iced brine; the other was transferred to another furnace at the same temperature ($1,600^{\circ}$ F.) and allowed to cool slowly in the furnace. The treatment selected was intended to retain the structure existing at the high temperature

FIGURE 2.—Time-elongation curves of nickel-chromium-iron alloys tested at $1,600^{\circ}$ F. (870° C.).

The number over each curve indicates the stress in lb./in.² at which the creep test was made. The arrows terminating some of the curves indicate the direction of the next point which was not included in the chart.

in the first case and in the other to produce a structure more nearly representative of that resulting in service from slow cooling.

IV. RESULTS

1. RATES OF CREEP

The time-elongation curves for the alloys tested at $1,600^{\circ}$ F. and at the various loads are shown in figures 2 and 3 and the average rates of creep in figure 4.

Data are not given for the creep of the alloy containing 13 percent chromium and 1.4 percent nickel (no. 72) nor for the one containing 31 percent nickel and 3 percent chromium (no. 79). Neither alloy had sufficient resistance to oxidation at 1,600° F. (870° C.) to permit the carrying out of the creep tests. After several hundred hours at 1,600° F. (870° C.) the entire cross section of the 0.250-inch test bars was almost completely converted to oxides.

FIGURE 3.—Time-elongation curves of nickel-chromium-iron alloys tested at 1,600° F. (870° C.).

The number over each curve indicates the stress in lb./in.² at which the creep test was made. The arrows terminating some of the curves indicate the direction of the next point which was not included in the chart.

The remaining alloys showed excellent resistance to oxidation at 1,600° F. (870° C.). The oxide was confined to a slight discoloration of the surface in most cases. Alloys of the 25 percent nickel-15 percent chromium type (75 and MS, table 1) were practically without any oxide discoloration on the surface at the end of 700 hours.

Figure 5 shows the rates of creep of the nickel-chromium alloys tested at 1,000° F. in the earlier work.

2. MICROSTRUCTURAL CHANGES

The conclusions concerning the factors which influence the structural changes during creep at elevated temperatures were based upon

FIGURE 4.—Average rates of creep in "second stage" of nickel-chromium-iron alloys tested at 1,600° F. (870° C.).

FIGURE 5.—Average rates of creep in "second stage" of nickel-chromium-iron alloys tested at 1,000° F. (538° C.).

the observations made on alloys 72 to 78 (table 1). Representative micrographs are shown (figs. 6, 7, and 8).

The specimens heated at 1,600° F. without stress showed very similar structural features in nearly all cases regardless of whether

they had been cooled slowly from the annealing temperature or had been quenched in iced brine.

The etching reagents used for alloys 72 to 78 differed somewhat with the different compositions of the alloys. Two reagents were used satisfactorily on alloy 72. The first reagent contained 2 parts glycerine, 2 parts hydrochloric acid, and 1 part nitric acid. The second reagent was aqua regia which had been prepared at least 20 hours prior to application. Both revealed the same structural characteristics. Alloys 73 and 74, having higher chromium contents and no appreciable amount of nickel, were etched with difficulty. A hot 50 percent aqueous solution of hydrochloric acid gave the most satisfactory results. The structures of alloys 75 to 78 were brought out with solutions similar to those used for alloy 72, the aged aqua regia solution being less satisfactory, however, than the other. As the nickel was increased, the alloys were less difficult to etch even in the presence of relatively large amounts of chromium.

All of the solutions used revealed the general structural characteristics. Murakami's reagent which consists of 10 g potassium ferricyanide, 10 g sodium hydroxide, and 100 ml water was used in an effort to reveal the carbides, but only a part of the precipitated material could be shown by this solution. Considerably fewer precipitated particles were observed in a specimen which was repolished and etched with Murakami's reagent, after it had been etched with either one of the other reagents to show general structural features.

V. DISCUSSION

1. CREEP

The time-elongation curves (figs. 2 and 3) show a distinct difference between the low-nickel and the high-nickel cast nickel-chromium-iron alloys at 1,600° F., namely, a difference in the abruptness of the transition from the so-called "second stage" of creep to the "third stage" as the stresses are increased with constant temperature. In the low-nickel cast alloys, 73 and 74, the transition was rather gradual. The slope of time-elongation curves changed progressively from the rather gentle one characteristic of "second stage" creep to the steep slope characteristics of the third or final stage of creep which precedes fracture of the specimen. The other cast alloys, which contain nickel in proportions from 25 to 75 percent, showed a very abrupt change from the second to third stage. A similar difference is apparent in comparing the wrought alloy (76-20) with two cast alloys of similar composition (78 and CA). The wrought alloy showed the gradual transition, whereas both the cast alloys showed an abrupt change in the rate of creep as the stress was increased on different specimens.

It is also noteworthy that the rate of creep, in the tests at 1,600° F. in which the stresses were sufficient to produce creep, was more or less uniform from the start of the test. Ordinarily a relatively rapid rate of creep takes place in the first few hours of test which is generally designated as the "first stage" or "initial creep." The rate gradually decreases as the test proceeds. This stage, "secondary creep", is intermediate between the initial rapid elongation immediately following the application of the load and the rapid rate of creep immediately preceding fracture.

FIGURE 6.—Structure of nickel-chromium-iron alloys relatively low in nickel and high in chromium.

Alloy 73: A, original condition; B, annealed at 1,600° F. for 1,000 hours; and C, broken in creep test after 314 hours at 1,600° F. and 1,500 lbs./in.²

Alloy 74: D, original condition; E, annealed at 1,600° F. for 1,000 hours; and F, tested in creep for 448 hours at 1,600° F. and 1,000 lbs./in.²

Etchant, hot 50 percent aqueous solution of hydrochloric acid Magnification, 500 ×

FIGURE 7.—Structure of nickel-chromium-iron alloys containing approximately equal amounts of nickel and chromium.

Alloy 75: *A*, original condition; *B*, annealed at 1,600° F. for 1,000 hours; and *C*, tested in creep for 700 hours at 1,600° F. and 2,500 lbs./in.²

Alloy 76: *D*, original condition; *E*, annealed at 1,600° F. for 1,000 hours; and *F*, tested in creep for 696 hours at 1,600° F. and 5,000 lbs./in.²

Etchant, aqua regia (see text). Magnification, 500 ×.

FIGURE 8.—Structure of nickel-chromium-iron alloys containing relatively high amounts of nickel and intermediate amounts of chromium.

Alloy 77: A, original condition; B, annealed at 1,600° F. for 1,000 hours; and C, tested in creep for 689 hours at 1,600° F. and 4,000 lbs./in.²

Alloy 78: D, original condition; E, annealed at 1,600° F. for 1,000 hours; and F, tested in creep for 689 hours at 1,600° F. and 4,000 lbs./in.²

Etchant, aqua regia (see text). Magnification, 500 X.

These three stages of creep were not so pronounced at 1,600° F (870° C.) as at the lower temperatures. If the applied load was sufficient to produce appreciable elongation at the beginning of the test, the rate in most cases continued fairly constant throughout the duration of the test. The very low loads which produced no measurable elongation in 700 hours showed practically no initial deformation upon application of the load.

The difference in the resistance to creep (which was of the order of 0.1 percent in 1,000 hours at 1,600° F.) of alloys of different chemical composition is shown in figure 9.³ The ternary alloys containing approximately equal proportions by weight of nickel and chromium and not more than 30 to 40 percent iron showed the highest resistance to creep. In the binary iron-chromium alloys the resistance to creep was found to increase as the chromium content is increased from about 20 to 60 percent. An addition of nickel up to 30 percent increased the resistance to creep of iron-chromium alloys containing between 15 and 40 percent chromium. An increase above 30 percent might, however, have little effect on the resistance to creep of iron-nickel-chromium alloys containing between 10 and 25 percent chromium.

Alloys having a composition which places them in the vicinity of the "pure iron corner" of the ternary diagram and for some distance from pure iron on the iron-nickel side of the diagram (alloys 72 and 79) do not resist oxidation and scaling in air at 1,600° F. as well as do the other alloys studied.

These experimental results are in accord with the prediction by Dean⁴ that " * * * alloys in the vicinity of equal percentages of iron, nickel, and chromium and those in the iron-chromium series between 20 and 40 percent chromium with varying amounts of nickel * * * will furnish the alloys of the future, where conditions of economy, excellent mechanical and physical properties, and extreme resistance to high temperature oxidation must be fulfilled." This prediction was not based on the results of creep tests, but was made as a result of determinations of hardness, thermal expansion, electrical resistivity, and resistance to oxidation. Dean also stated that alloys to the right of a line (dotted line, fig. 9) drawn from 100 percent nickel to 20 percent chromium in the iron-chromium series are resistant to oxidation at 1,830° F. (1,000° C.). In the present work both cast and wrought alloys of the 75 nickel-20 chromium type were tested. The resistance to creep of the cast alloys (CA and 78, fig. 4) was very considerably greater than that of the wrought alloy (76-20, fig. 4).

In the previous investigation⁵ of alloys it was found that alloys containing little or no iron, 50 to 80 percent nickel, and 20 to 50 percent chromium exhibited the greatest resistance to creep at 1,000° F. (538° C.). The greatest resistance to creep was obtained in castings containing about 50 percent each of nickel and chromium. Such an alloy might be expected to offer difficulties in the foundry and has the serious disadvantage of being extremely brittle. A summary of the results of the earlier work is given in figure 10, which shows the

³ In order to make figure 9 more complete and accurate in the "pure nickel corner" and on the nickel-chromium side a very limited number of creep tests were made at 1,600° F. on nickel (alloy 1024, table 2) and on an alloy containing approximately equal parts of nickel and chromium (alloy 1008, table 2). Test specimens of these two materials were taken from material used in the investigation at 1,000° F.

⁴ An investigation of some of the physical properties of the iron-nickel-chromium system, Walter A. Dean. Rensselaer Polytechnic Institute, Engineering and Science Series No. 26, June 1930, pp. 31-55.

⁵ See footnote 1, p. 851.

FIGURE 9.—Stresses in lb./in.² required to produce 0.1 percent creep in 1,000 hours at 1,600° F. (870° C.) in the nickel-chromium-iron ternary system
Compositions of the alloys tested are indicated.

FIGURE 10.—Stresses in lb./in.² required to produce 0.1 percent creep in 1,000 hours at 1,000° F. (538° C.) in the nickel-chromium-iron ternary system
Compositions of the alloys tested are indicated.

approximate stresses producing creep of the order of 0.1 percent in 1,000 hours at 1,000° F. (538° C.).

The compositions of the alloys possessing the greatest load-carrying ability at 1,000° F. are not identical with the corresponding alloys at 1,600° F. (870° C.). The changes are most clearly demonstrated by comparing figures 9 and 10. At 1,600° F. (870° C.) the strongest alloys were those containing approximately equal parts of nickel and chromium, and not more than 30 to 40 percent iron. Neither chromium nor nickel alone appeared to contribute to its alloys with iron superior resistance to creep.

The stresses which at 1,600° F. fail to produce creep exceeding 10^{-6} inch per inch per hour in 700 hours range from about 2,500 lb./in.² for the alloy containing equal parts of nickel, chromium, and iron to about 400 lb./in.² for the 28 percent chromium alloy. This gives some indication of the extremely low loads at which creep takes place at 1,600° F. (870° C.) for the group of materials investigated.

All of the alloys of the present study that broke during creep tests failed with very little elongation, 7 percent or less, and practically no reduction of area.

2. STRUCTURE

The structural changes resulting from heating were not pronounced in either the unstressed or stressed specimens of the cast nickel-chromium-iron alloys.

An increase in the chromium content of the binary iron-chromium alloys causes an increase in the stability of the structural constituents. This stability is at a maximum in alloy 74 (fig. 6, (d), (e), and (f)). No marked difference in the amount or location of the carbide constituent could be seen in the structures of the original, annealed, or stressed specimens.

Prolonged heating in the absence of stress did not produce any marked changes in the structure of the ternary alloys of intermediate and high chromium-content (fig. 7, (a), (b), (d), and (e)).

The ternary alloys having an intermediate chromium content and 50 to 75 percent nickel showed slight structural changes after being subjected to a prolonged annealing (fig. 8, (a), (b), (d), and (e)). As the nickel content is increased the structural stability is decreased and the carbide particles are agglomerated to a greater extent.

The effect of stress at 1,600° F. has, generally speaking, a tendency to accelerate the rate of structural changes in the entire group of alloys studied. This effect is perhaps most readily illustrated in figure 6, (b), and (c). The stressed specimen, C, was loaded so that fracture occurred after 314 hours. The structure shows very coarse agglomerated carbide particles. The structure of the specimen, B, annealed at the same temperature for 1,000 hours resembles very closely that of the stressed specimen. The structure of specimens annealed at 1,600° F. for different periods up to 700 hours did not possess the degree of agglomeration which is observed in the stressed specimen or the specimen annealed for 1,000 hours. The application of stress apparently had accelerated the structural change in this alloy to a very marked extent. Approximately one third of the time at the same temperature was needed to produce a similar structure in the stressed specimen as in the unstressed specimen. The accelerating effect of stress was noticeable in all the alloys except alloy 74.

The rate of diffusion and agglomeration was increased in all the alloys studied, excepting alloy 74, to such a degree that the stressed specimens more closely approached an equilibrium condition than the unstressed specimens which had been annealed for several hundred hours longer than the duration of the creep test.

VI. SUMMARY

The creep characteristics at 1,600° F. (870° C.) of 15 different alloys, covering a range of chemical composition from 1 to 75 percent nickel and from 3 to 55 percent chromium, were determined. The results of these determinations are compared with those of a previous investigation at 1,000° F. (538° C.) on similar alloys.

In the previous investigation it was found that those alloys containing little or no iron, 50 to 80 percent nickel, and 20 to 50 percent chromium exhibited the greatest resistance to creep. At 1,600° F. (870° C.) the strongest alloys are those containing approximately equal parts of nickel and chromium and not more than 30 to 40 percent iron.

A metallographic study was made to determine what structural changes took place during creep. The attempt was made to distinguish between the effect on structure of elevated temperature alone and of elevated temperature and stress combined. A comparison was made between the structure in specimens used in the creep test and that in unstressed specimens of the same alloys annealed at 1,600° F. (870° C.) for periods ranging from 100 to 1,000 hours or quenched in iced brine from that temperature. In nearly all cases materials quenched in iced brine after heating were similar in structure to the annealed materials which indicates the extreme lack of susceptibility of alloys of this type to heat treatment.

An increase in the chromium content of both the binary alloys of iron and chromium and the ternary alloys results in an increase in the carbide precipitation and a greater agglomeration at the grain boundaries. The changes in structure which occurred after prolonged annealing were noticeable in the binary alloys containing up to 30 percent chromium and in the ternary alloys with large amounts of nickel.

The combination of prolonged heating and stressing caused structural changes in all the alloys with the exception of alloy 74. There is a distinct indication that the effect of stress had accelerated the rate of diffusion and agglomeration of the carbides. The structures in the stressed specimens indicate that these specimens approached an equilibrium condition at a rate sometimes three times as great as that in the corresponding specimens annealed at the same temperature.

WASHINGTON, April 18, 1933.