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The University of Michigan Research Institute
Ann Arbor, Mich.

SECOND PROGRESS REPORT

TO

MATERIALS LABORATORY

WRIGHT AIR DEVELOPMENT CENTER

ON

EFFECT OF PRIOR CREEP ON MECHANICAL PROPERTIES OF AIRCRAFT STRUCTURAL MATERIALS

by

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Project 02902 Air Force Contract No. AF33(616)-6462

October 15, 1959

INTRODUCTION

This report, the second progress report to be issued under Contract AF33(616)-6462, covers the period from July 1, 1959 to September 30, 1959. The research is a study of creep damage to mechanical properties of aircraft structural materials.

The present research is an extension of that conducted under Contract AF33(616)-3368 in which a number of sheet materials were exposed to limited amounts of creep under fairly "normal" conditions. In the previous work, exposures were confined to the nominally useful temperature ranges for materials acceptable for service as being of generally stable structure. The exposure times were generally no longer than 100 hours, and the creep was limited to about 2 percent. The materials studied included 2024-T86 aluminum, C110M and Ti-16V-2.5Al titanium alloys, and 17-7PH stainless steel in the TH 1050 and RH 950 conditions. Short-time tests after creep-exposure consisted of tension tests, compression tests, and tension-impact tests conducted either at room temperature or the temperature of exposure. Examples of damage were found although the research was limited by the necessity of studying established sheet materials under more or less normal conditions of exposure.

It is the intention of the present investigation to extend these studies to materials presently available for use at the highest of operating temperatures and to orient the research so that the basic mechanism of creep damage to mechanical properties can be determined. Thus, instead of merely studying the effects of "normal" exposure conditions, efforts will be made to produce creep under conditions causing significant changes in properties. This may involve exposures to temperatures and stresses outside the normal service range of a material--possibly involving variable stress and/or temperature during the creep exposure. For the present, the research will be focussed on the interaction of creep and thermally induced structural changes to the exclusion, as far as possible, of surface damage and environmental effects.

Creep damage will be evaluated primarily by tension, compression, and impact tests. In contrast to the previous research, the present investigation will be conducted primarily on wrought bar stock. This will permit the introduction of conventional notch bar impact tests which are one of the most sensitive measures of damage. Wrought bar stock is also a convenient form for obtaining alloys with the desired response to creep. It also permits the study of the same alloy in the form of castings or sheet as well as allowing heat treatment or other prior processing variables to be included.

The research is to be conducted on three types of material. The first is René 41, a complex nickel-base heat resistant alloy. The second is a binary alloy of 80 percent Nickel and 20 percent Chromium as an example of a material relatively free from thermally-induced structural changes. The third is a binary alloy of molybdenum plus 0.5 percent titanium as an example of a high melting point material gaining in importance for future use.

TEST MATERIALS

Shortly after the beginning of this reporting period the test stock of both the 80Ni-20Cr alloy and the René 41 alloy were received. The specifications for these materials follow. The molybdenum alloy has not yet been procured.

80Ni-20Cr

Approximately 112 pounds of Chromel-A alloy were received from the Hoskins Manufacturing Company in the form of hot-rolled 1/2-inch diameter bar stock designated as being from Heat No. 1067. The following chemical analysis was furnished:

Element	Percentage (wt.) Nominal	Actual
Chromium	20.0	20.44
Nickel	78.0	77.48
Carbon	0.10	0.01
Silicon	1.4	1.41
Manganese	0.2	0.15
Iron	-----	0.31
(Others)	-----	0.20

The test stock was cut into four-inch long blanks and then subjected to annealing treatments to produce either large-grain or small-grain material. This is discussed in the section on Results (Page 8).

René 41

Approximately 107 pounds of René 41 alloy were procured. This material was produced by the Metallurgical Products Department, General Electric Co. in the form of 0.516-.520-inch diameter centerless ground bar stock. The material was all from Heat R-134 and was shipped in the solutioned condition as water quenched from 1975°F. The chemical analysis furnished by the producer follows:

Element	Percentage (wt.) Nominal	Actual
Nickel	52.5	55.32
Chromium	19.0	19.27
Cobalt	11.0	11.06

Analysis of René 41 (continued):

Element	Percentage (wt.) Nominal	Percentage (wt.) Actual
Molybdenum	9.75	9.06
Titanium	3.15	3.28
Aluminum	1.65	1.44
Carbon	0.09	0.12
Boron	0.005	0.004
Iron	-----	0.30
Sulfur	-----	0.006
Manganese	-----	0.07
Silicon	-----	0.07

The producer reported the grain size to be ASTM 3-6 and the Brinell Hardness to be 241-269.

Several batches of 4-inch long specimen blanks were heat treated in groups of 24 each according to the recommended schedule for the alloy:

1. Re-solution treatment--1950°F - 1/2 hour plus air cool (gas-fired furnace).

2. Aging treatment--1400°F - 16 hours plus air cool (electric resistance furnace).

Following this treatment the Vickers Hardness was 367 (equivalent to a Brinell Hardness of 347).

TEST SPECIMENS, EQUIPMENT, AND PROCEDURES

The primary creep exposures are to be conducted on specimens having a 0.350-inch gage section diameter. These specimens are machined from the 1/2-inch diameter bar stock and have a reduced gage section of approximately 2-inches. The specimen is gripped by threaded holders fitting 1/2-13 threads machined on the ends of the specimen. A drawing of the test specimen was presented in the First Progress Report (Ref. 1).

For tests of mechanical properties following creep-exposure the specimen is machined either to a tensile specimen having a gage diameter of approximately 0.3-inches, or to a Type-W subsized notched impact specimen. Remachining of the creep-exposure specimen permits the elimination of surface damage effects in subsequent mechanical property determination.

A description of the test equipment and procedures was presented previously (Ref. 1) and will not be repeated in detail. The creep-exposures are conducted in individual creep testing units. The load is applied by a third class lever system and extension is measured by a modified Martens optical extensometer system.

Tension and compression tests are conducted in a Baldwin-Southwark hydraulic tensile machine equipped with microformer-type strain gages for automatic stress-strain recording. The compression tests are conducted in a subpress which employs a loading ram acturated by the cross-head of the tensile machine. Impact tests are conducted in an Olsen testing machine.

RESULTS AND DISCUSSION

Rene' 41 Alloy

The initial tests of the Rene' 41 alloy consisted of tension and creep-rupture tests to establish the base properties. In addition these tests were used to confirm that the heat received had properties representative of the alloy.

The results of tensile tests at room temperature and several elevated temperatures are summarized in Table 1 and plotted as a function of test temperature in Figure 1. The specimens tested were all from the first batch of blanks that were heat treated. Additional tests are to be run on material from succeeding heat treatment batches in order to complete the establishment of representative base properties.

The data indicate that almost all the initial strength and ductility was retained at 1200°F but that the strength fell off rapidly as the temperature was increased to 1400 and 1600°F. On the other hand, the ductility first decreased as the test temperature was raised from room temperature to 1400°F and then showed a substantial increase at 1600°F.

The only comparative tension test data readily available was a curve presented by Jahnke and Frank (Ref. 2) showing the variation in the 0.02 percent offset yield strength with test temperature in the range from room temperature to 1300°F. This curve is included in Figure 1 although the data of the present investigation are too sparse to permit a valid comparison to be made. At room temperature there appears to be fairly good agreement between the two sets of data. The lack of test points in the present investigation between room temperature and 1400°F leaves the remainder of the comparison uncertain.

The results of a limited number of creep-rupture tests are tabulated in Table 2 and time-elongation curves are plotted in Figure 2. To aid in the selection of test stresses a master-rupture curve was derived from a curve presented by Jahnke and Frank (Ref. 2) of the 100 hour rupture strength of Rene' 41 as a function of temperature. The Miller-Larson time-temperature parameter was used for the construction of this curve which is given in Figure 3. Test stresses for preliminary tests were selected to cause fracture in approximately 10 hours at 1400° and 1600°F. These tests, R-6 and R-7, ruptured in 17.3 and 27.7 hours respectively, indicating that a master rupture curve for the present heat would be displaced slightly to the right of the Jahnke-Frank curve. Additional tests were then planned at stresses intended to cause rupture in 20 hours at 1200° and 1300°F. The test at 1300°F, R-15, failed at 28.2 hours, however the 1200°F test was run at a slightly high stress and lasted only 4 hours. In order to give more information on the shape of the curve an additional test was then run at 1800°F.

As plotted in Figure 3 the results of the rupture tests confirm that the material from Heat R-134 was at least comparable in rupture strength if not slightly stronger than the material used to derive the Jahnke-Frank 100-hour rupture strength curve.

The time-elongation curves from these rupture tests are plotted in Figure 2. A gage factor based on elastic considerations was used to account for the fillets and shoulders included in the extension measurements. When sufficient additional creep data are available they will be used to calculate plastic gage factors and these curves will be corrected. Experience indicates that the true creep is about 10-20 percent greater than that calculated with the use of the elastic factor, however, the elastic factor does give results of the proper order of magnitude.

In the tests conducted at 1400°, 1600°, and 1800°F the creep rate increased ("third stage" creep) from the start of the tests. In the 1200° and 1300°F tests there was evidence of a short period of decelerating creep ("first stage" creep) at the beginning of the test period.

Based on the data of Figure 3, the first series of creep-exposure tests was initiated. As a starting point, the exposures were run for 10 hours at the nominal 20-hour rupture stress at 1400°, 1500° and 1600°F. In addition, specimens were exposed without stress for the same time period at 1400°, 1600° and 1800°F. Time-elongation data was taken for all the exposures. Following the exposures, tension tests were conducted at room temperature.

The results of the tests are tabulated in Table 3, the time-elongation curves for the unstressed exposures are plotted in Figure 4, and the time-elongation curves for the creep-exposures are plotted in Figure 5. The results of the room temperature tension tests are plotted as a function of the exposure temperature in Figure 6.

Figure 4 shows that a slight shrinkage occurred over the time of exposure for the samples exposed without stress at 1400° and 1600°F, with a somewhat greater effect noted at 1600°F. Exposure without stress at 1800°F caused a slight expansion over the period of the test. It should be noted, however, that the curves in Figure 4 do not include the four hour preheat period. During the major portion of this period the specimen was heating up to the test temperature and then settling out on temperature. Thus, the curves of Figure 4 do not account for changes that might have occurred during this period.

The time-elongation curves for the 10 hour creep-exposures (Figure 5) were similar for all three test temperatures. Accelerated creep occurred after 4 to 5 hours of the exposure period. Figure 4 suggests that the dimensional change due to temperature alone contributed little, if any, to the net creep plotted in Figure 5.

The short-time tensile tests showed that both the strength and ductility of the material was reduced by the exposure to temperature alone. The effect was greater as the exposure temperature was increased. Exposure under stress slightly reduced the ductility while the ultimate tensile strength and tensile yield strength were affected differently depending on the exposure temperature. With respect to the effect of temperature alone, the ultimate tensile strength was increased by creep at 1400°F, apparently unchanged by creep at 1500°F, and decreased by creep at 1600°F. This behavior is an indication of stress-accelerated aging. Furthermore, residual stresses from creep could result in a Bauschinger effect that increased the tensile yield strength over that which might be expected solely on the basis of the stress-accelerated structural change.

Electron micrographs of representative samples of Rene' 41 are presented in Figures 7 through 12. In the as-treated condition (Figures 7 and 8) the structure consisted of a very fine dispersion of gamma prime phase in the matrix and carbide particles in the boundaries.

Figures 9 and 10 show the effects of creep-rupture testing at 1600 and 1800°F respectively. As the test temperature and time were increased, the gamma prime phase in the matrix was agglomerated and showed considerable growth. In figure 10 the fine particles in the matrix are gamma prime that re-precipitated on cooling from the exposure temperature. In addition, there appeared to be changes in the grain boundary particles that were quite marked over the as-treated condition.

Two specimens exposed with or without stress for 10 hours at 1600°F are shown in Figure 11 and 12. Both of the 10 hour samples showed less change in the gamma prime phase over the as-treated condition than did the sample shown in Figure 9 which had been exposed for 27.7 hours. There was no particularly significant difference between the two 10-hour samples despite the application of stress to the exposure. As Table 3 shows there was also little difference in the mechanical properties of the two 1600°F samples, however, the exposure at 1600°F which resulted in agglomeration and other structural changes, did reduce both the ultimate tensile strength and the ductility below that of the as-produced condition.

The effects of exposure temperature, time and the amount and type of creep will be explored by further testing over the range between 1200° and 1800°F. Efforts will be made to produce large amounts of creep in a search for maximum effects and exposure times will be extended to 100 hours.

80 Ni-20 Cr

In the studies of the 80 Ni-20Cr alloy, also designated as Chromel-A, the creep-exposure tests are to be conducted on both small grain and large grain material. As reported in Reference 1, the as-hot rolled material had an average ASTM grain size of 10.4 (an average diameter of 0.0109 mm) and it was found that annealing for 1 hour at 2100°F produced an average ASTM grain size of 4.1 (an average diameter of 0.098 mm). Through the use of micro-hardness traverses a hardness gradient was discovered between the surface and center of the as-hot rolled bar stock. This gradient which indicated the presence of a strain gradient was responsible for germination effects resulting in zones of widely varying grain size when annealing was conducted at 2000°F. Apparently 2100°F was high enough to overcome this tendency and fairly uniform grains were obtained throughout the cross-section.

The grain sizes of approximately 10 and 4 were felt to represent a sufficient spread in size from small grains to large grains for the purposes of the investigation, however, it was desired that the hardness gradient be removed. Accordingly, a series of specimens were annealed at 1550°F for time periods of 1, 4, and 24 hours. After the 24 hour anneal the grain size increased only to ASTM 9.5. Micro-hardness surveys indicated that the four hour anneal removed the gradient.

These studies of metallographic slugs also indicated that the over-all hardness level was increased slightly during short-time annealing treatments at 1550°F. Electron microscope examination of the specimens indicated that the slightly increased hardness was related to an increased number of particles (possibly carbides) appearing at the grain boundaries.

On the basis of these studies it was concluded that an annealing treatment of 4 hours at 1550°F would remove the hardness gradient from the as-hot rolled condition but would not increase the grain size unduly. However, in view of the evidence indicating a slight overall hardening effect during annealing at 1550°F, a further study was made of the effect of annealing time on the mechanical properties. Accordingly, room temperature tension tests were conducted on material annealed for one, four and twenty-four hours at 1550°F.

The test results are summarized in Table 4 and the mechanical properties are plotted versus annealing time in Figure 13. Also included in Figure 13 is the Vickers Hardness data taken on the metallographic slugs used for the grain size studies.

These data indicate that annealing the as-hot rolled material at 1550°F slightly decreased the ultimate tensile and yield strengths but had little if any effect on the ductility. The greatest change in strength resulted from the one and four hour anneals with little further change being observed upon increasing the annealing time to 24 hours. The increased hardness previously observed after annealing for up to 2 hours did not correlate with the mechanical property changes.

On the basis of the mechanical properties and micro-hardness data, the four hour annealing treatment at 1550°F was then selected to provide the relatively strain-free, fine-grain material for the creep-exposure tests. This treatment was coded "C1". The one hour annealing treatment at 2100°F previously chosen to provide large grain material was coded "C2".

The results of a room temperature tensile test on "C2" material are included in Table 4 and show that this treatment produced a slightly lower ultimate strength, a considerably lower yield strength, and appreciably increased ductility over both the as-hot rolled and "C1" materials.

Several batches of test blanks were than annealed to each condition and preliminary creep-rupture tests were initiated to provide information on the deformation characteristics of the material. In order to provide a variation in strain rate the tests were run at stresses expected to cause fracture in approximately 5 or 100 hours at temperatures between 1000° and 1800°F. Stresses were selected with the aid of a master-rupture curve derived from data presented by Shahinian and Achter (Ref. 3), for rupture tests of sheet material of similar composition having an average grain diameter of 0.09 mm. This grain size was close to the 0.098 mm diameter of the "C2" material from the present investigation.

The creep-rupture data are summarized in Table 5, the master rupture curves are plotted in Figure 14, and the time-elongation curves are plotted in Figure 15. The data plotted in the creep curves of Figure 15 have been corrected for all elastic and plastic deformation occurring in the fillets, shoulders, and threads.

Examination of Table 5 reveals that the large grain material ("C2") was appreciably stronger in creep-rupture tests than the fine grain material although it was previously noted in Table 4 that the fine-grain material had somewhat better room temperature tensile properties. The master-rupture curve obtained for the large grain material agreed quite well with that derived from the data of Shahinian and Achter (Figure 14) for material of almost the same grain size. The curve derived for the small grain material was displaced toward lower parameter values (shorter time to fracture at a given temperature and stress) and the individual test points exhibited more scatter at the parameter values corresponding to the higher temperature, longer time tests. Metallographic studies to be discussed later indicated that this scatter was probably due to grain growth during testing. In several of the tests reported in Table 5 the elongation on fracture exceeded the reduction of area. This was due to extensive interior cracking.

The creep curves presented in Figure 15 show that the large grain "C2" condition had an appreciably greater creep resistance than the small grain "C1" condition at all test temperatures. Rapid and extensive creep necessitating frequent resetting of the extensometer system was encountered in all of the creep tests. With the exception of one test at 1000°F the creep rate accelerated through out the test period.

Optical micrographs at 100x magnification of representative specimens following fracture are presented in Figures 16 through 21. These specimens were from tests conducted at 1200°, 1600° and 1800°F. In the originally small grain samples (Figures 16, 18 and 20) extensive intergranular cracking occurred and in the specimen tested at 1800°F (Figure 20) considerable grain growth was observed. The cracks in these specimens appeared to link together.

Intergranular cracking was also observed in the specimens of the large grain condition (Figures 17, 19 and 21). However the cracking did not appear to be so extensive and there was less tendency for individual cracks to link together. There was a slight possibility that additional grain growth occurred in the sample tested at 1800°F (Figure 21).

In both sets of samples a considerable amount of surface cracking was also observed. The fractures were intergranular.

The initial creep-exposure tests of Chromel-A were run on samples of "C2" material at 1200° and 1400°F and the results are summarized in Table 6. The time-elongation curves for these exposures are plotted in Figure 22. These exposures were conducted for 5 hours at the stress that would cause rupture in approximately 10 hours. The restriction of the exposure period to 5 hours was made in view of the rapid creep of the material. Including the 4 hour preheat period prior to loading, the entire test could be conducted during a standard working day, thus facilitating the frequent resetting of the extensometer system.

Examination of Figure 22 shows that the creep portions of the curves for these exposures were quite similar although the specimen tested at 1200°F had a considerably greater amount of loading deformation. An accelerating rate was noted after approximately three hours.

Following creep-exposure, the room temperature ultimate strength and yield strength of both specimens were increased and the ductility was decreased over the as-treated condition. (Table 6) In specimen C2-9 which was subjected to 8.60 percent total plastic strain at 1200°F, the tensile yield strength was more than doubled. In this specimen almost 40 percent of the total plastic strain was obtained during loading. The increase in tensile yield strength for specimen C2-8 which was subjected to 3.85 percent total plastic strain at 1400°F was about 45 percent over the base condition. In this specimen all of the plastic strain was obtained during creep. The changes in the ultimate strength and ductility of both samples were within 20 percent of the base values and were mainly due to strain hardening. The increased yield strengths were the result of Bauschinger effects. Metallographic examination of these specimens is not yet complete.

Additional testing for longer times is comtemplated at temperatures between 1000° and 1800°F in the search for significant amounts of damage.

FUTURE WORK

Work planned for the next three month period includes the following:

1. Continuation of tension tests to find damaging creep-exposures.
2. Metallographic studies of completed exposure specimens.
3. Procurement of the molybdenum-base alloy.
4. Introduction of impact tests to the damage studies.

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1. Gluck, J. V. and Freeman, J. W., "Effect of Prior Creep on Mechanical Properties of Aircraft Structural Materials", First Progress Report to Materials Laboratory, Wright Air Development Center on Air Force Contract AF33(616)-6462, July 15, 1959.

2. Jahnke, L. P. and Frank, R. G., "High Temperature Metallurgy Today", Metal Progress, v. 74, No. 6 (December 1958), p. 88.

3. Shahinian, P. and Achter, M. R., "Temperature and Stress Dependence of the Atmosphere Effect on a Nickel-Chromium Alloy", Transactions of the American Society for Metals, v. 51 (1959), p. 244-255.

Table 1

Tensile Test Data for Solution Heated and Aged René 41 Alloy

Spec No.	Test Temp (°F)	Ultimate Tensile Strength (psi)	.02% Offset Yield Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%)	Reduction of Area(%)	Modulus, E x 10^6 (psi)
R-1	Room	187,400	117,000	125,800	19.6	26.2	31.0
R-2	Room	187,000	123,000	128,000	20.3	28.2	29.9
	Average	187,200	120,000	126,900	20.0	27.2	30.4
R-22	1200	182,000	-------	-------	18.1	18.0	25.3
R-16	1400	132,800	101,000	113,100	12.7	17.0	24.8
R-17	1600	82,000	48,200	79,800	25.8	47.4	24.1

Table 2

Rupture Test Data for Solution Treated and Aged René 41 Alloy

Spec No.	Test Temp (°F)	Stress (psi)	Rupture Time (hours)	Elongation (%)	Reduction of Area(%)
R-18	1200	140,000	4.0	8.3	10.2
R-15	1300	100,000	28.2	2.6	11.3
R-6	1400	80,000	17.3	25.5	28.9
R-7	1600	35,000	27.7	26.2	41.0
R-14	1800	8,000	116.1	41.4	54.3

Table 3

Creep Exposure Test Data for Solution Treated and Aged René 41 Alloy

Exposure Conditions

Spec. No.	Temp (°F)	Time* (hrs)	Stress (psi)	Total Load Def. (%)	Plastic Load Def. (%)	Creep Def. (%)	Total Plastic Def. (%)	Total Def. (%)
R-11	1400	10.0	None	----	---	----	----	-.006**
R-8	1400	10.0	80,000	0.36	nil	2 (est)	2 (est)	2.36 (est)
R-13	1500	10.0	55,000	0.30	nil	1.05	1.05	1.35
R-10	1600	10.0	None	----	---	----	----	-.017**
R-9	1600	10.0	35,000	0.18	nil	0.96	0.96	1.14
R-12	1800	10.0	None	----	---	----	----	.02**

Room Temperature Tensile Properties After Exposure

	Ultimate Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%)	Red. of Area(%)	Modulus, E x 10^6 (psi)	Hardness -VHN
R-11	183,500	126,800	14.7	18.7	29.7	---
R-8	192,400	152,600	16.0	17.2	30.1	367
R-13	179,500	136,000	9.9	15.2	30.1	---
R-10	175,800	125,500	10.1	13.7	30.1	---
R-9	169,000	128,200	8.9	11.5	30.2	348
R-12	158,000	104,000	9.5	10.5	29.9	---

* Time at stress + 4 hour pre-heat before loading

** Net change in dimension at test temperature

Table 4

Tensile Test Data for Chromel-A Alloy

Heat Treatment	Test Temp (°F)	Ultimate Tensile Strength (psi)	0.2% Offset Yield Strength (psi)	Elongation (%)	Reduction of Area (%)	Modulus, E x 10^6 (psi)
As Hot Rolled	Room	116,000	68,000	30.4	59.5	29.7
	"	116,100	70,000	30.0	61.0	32.0
	Avg.	116,050	69,000	30.2	60.2	30.8
Annealed-1550°F-1 hr.	Room	112,800	63,400	27.8	60.3	29.7
	"	112,800	63,400	30.2	61.5	30.8
	Avg.	112,800	63,400	29.0	60.9	30.2
Annealed-1550°F-4 hr.-(coded "C1")	Room	111,200	60,200	30.8	60.2	29.6
	"	111,100	59,600	29.6	60.0	29.4
	"	113,000	57,600	36.2	61.3	33.4
	Avg.	111,767	59,133	32.2	60.5	30.8
Annealed-1550°F-24 hrs.	Room	111,000	57,100	30.6	58.9	30.3
	"	110,900	57,000	30.0	60.9	30.0
	Avg.	110,950	57,050	30.3	59.9	30.2
Annealed-2100°F--1 hr.-(coded "C2")	Room	96,900	32,400	50.0	67.7	30.6

Table 5

Rupture Test Data for Chromel A Alloy

Spec No.	Test Temp (°F)	Stress (psi)	Rupture Time (hours)	Elongation (%)	Reduction of Area (%)
Annealed 1550°F - 4 hr.					
C1-6	1000	80,000	0.5	33.6	38.0
C1-9	1000	55,000	54.3	28.0	36.5
C1-2	1200	35,000	5.4	46.5	46.0
C1-10	1200	20,000	63.4 ± 5	57.5	44.8
C1-3	1400	15,000	3.1	35.8	34.6
C1-7	1400	5,000	150.5	28.5	24.4
C1-4	1600	5,000	4.9	23.6	21.6
C1-8	1600	2,000	216.1	68.0	29.0
C1-5	1800	3,500	3.6	13.8	14.2
Annealed 2100°F - 1 hr.					
C2-13	1000	80,000	On Load	51.7	62.0
C2-3	1000	70,000	102.8	21.2	11.9
C2-2	1200	35,000	14.7	24.2	24.9
C2-6	1200	22,000	109.9	18.5	20.4
C2-4	1400	15,000	12.5	22.0	19.0
C2-7	1400	10,000	54.0	12.5	13.8
C2-5	1600	8,000	4.7	17.7	14.7
C2-10	1600	5,000	28.6	10.8	10.2
C2-12	1800	3,500	10.1	9.5	11.5

Note: C1 Series - Annealed 1550°F - 4 hrs.
C2 Series - Annealed 2100°F - 1 hr.

Table 6

Exposure Test Data for Chromel-A Alloy

Exposure Conditions

Spec. No.	Temp (°F)	Time (hrs)	Stress (psi)	Total Load Def. (%)	Plastic Load Def. (%)	Creep Def. (%)	Total Plastic Def. (%)	Total Def. (%)
				Annealed 2100°F - 1 hr.				
C2-9	1200	5.0	35,000	3.53	3.30	5.30	8.60	8.82
C2-8	1400	5.0	15,000	0.07	nil	3.85	3.85	3.92

Room Temperature Tensile Properties After Exposure

	Ultimate Tensile Strength (psi)	.2% Offset Yield Strength (psi)	Elongation (%)	Reduction of Area(%)	Modulus, E x 10^6(psi)
			Annealed 2100°F - 1 hr.		
C2-9	110,600	68,000	48.0	55.4	32.5
C2-8	101,700	46,500	40.2	52.8	30.0

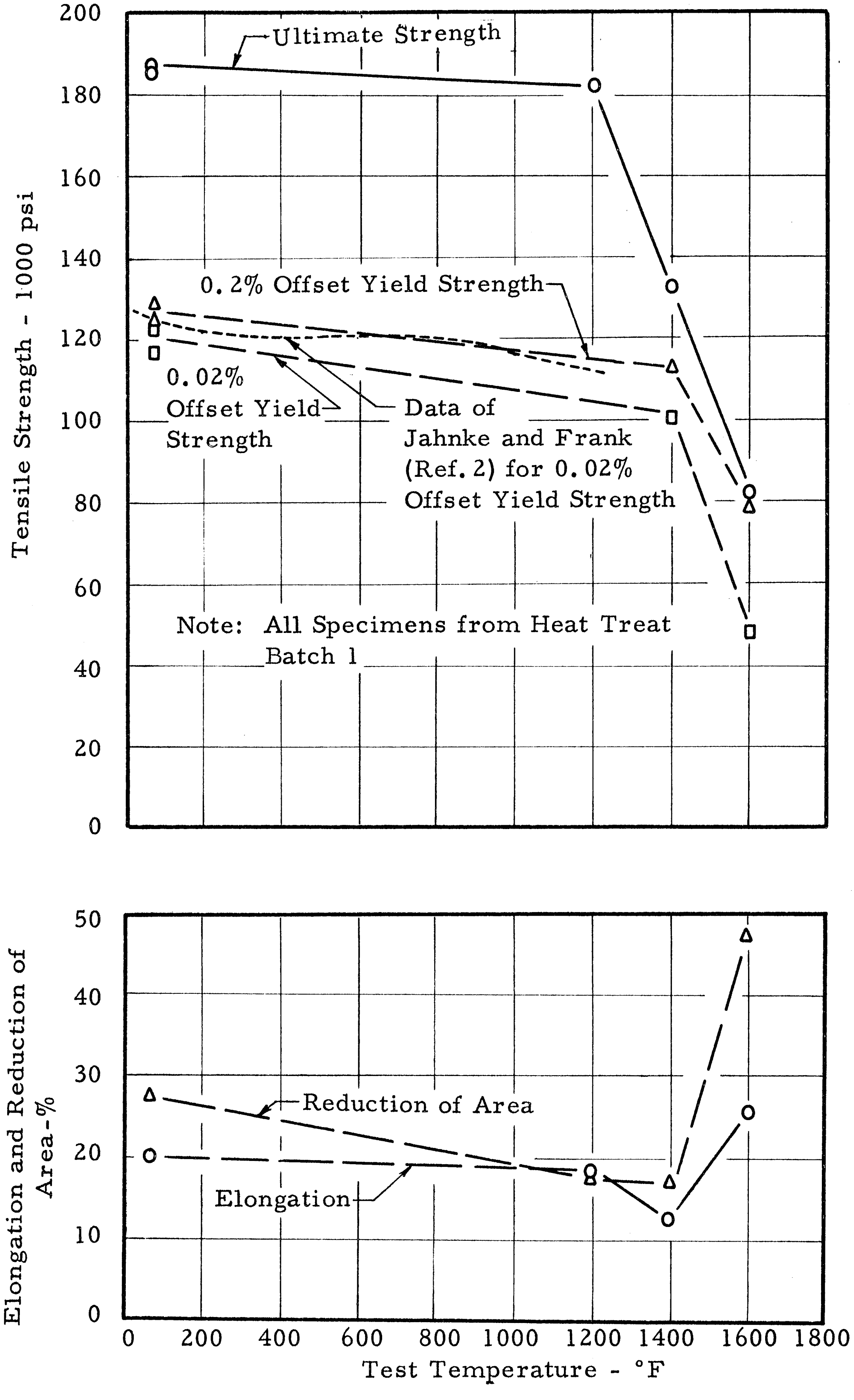

Figure 1. Effect of Test Temperature on Tensile Properties of Solution Treated and Aged Rene' 41 Alloy.

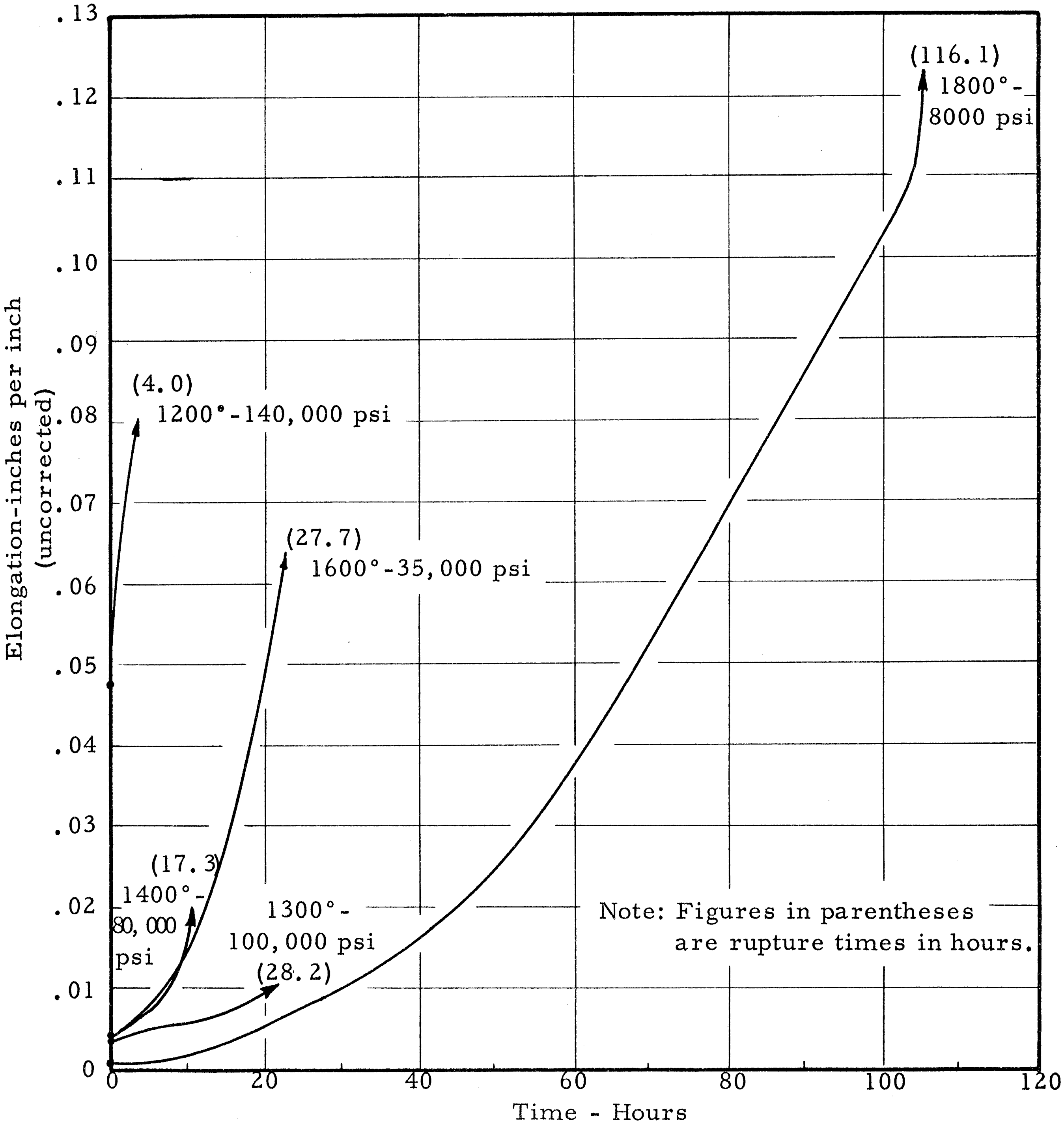

Figure 2. Time-Elongation Curves for Rupture Tests of Solution Treated and Aged Rene' 41 Alloy.

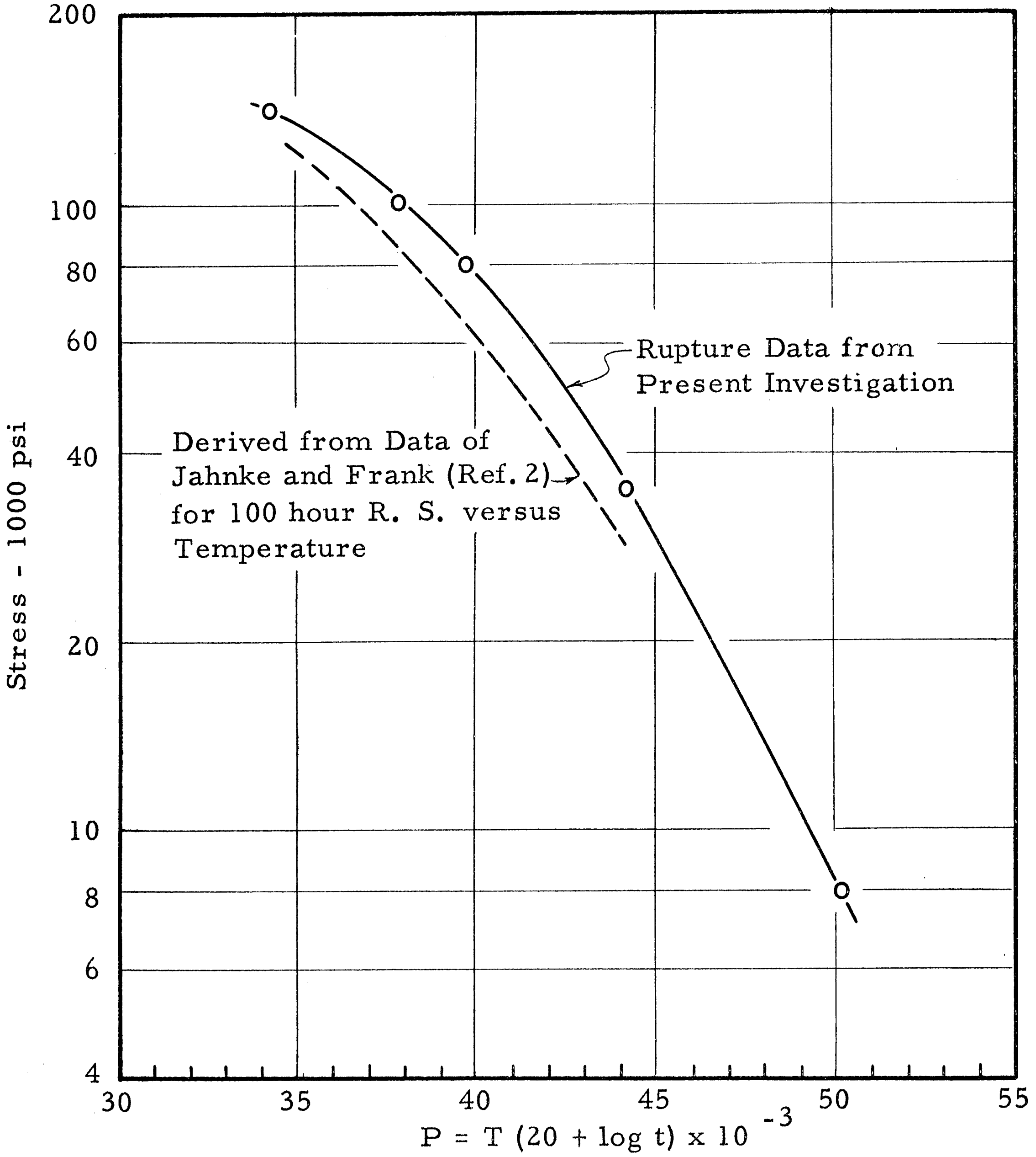

Figure 3. Master Rupture Curve for Solution Treated and Aged Rene' 41 Alloy.

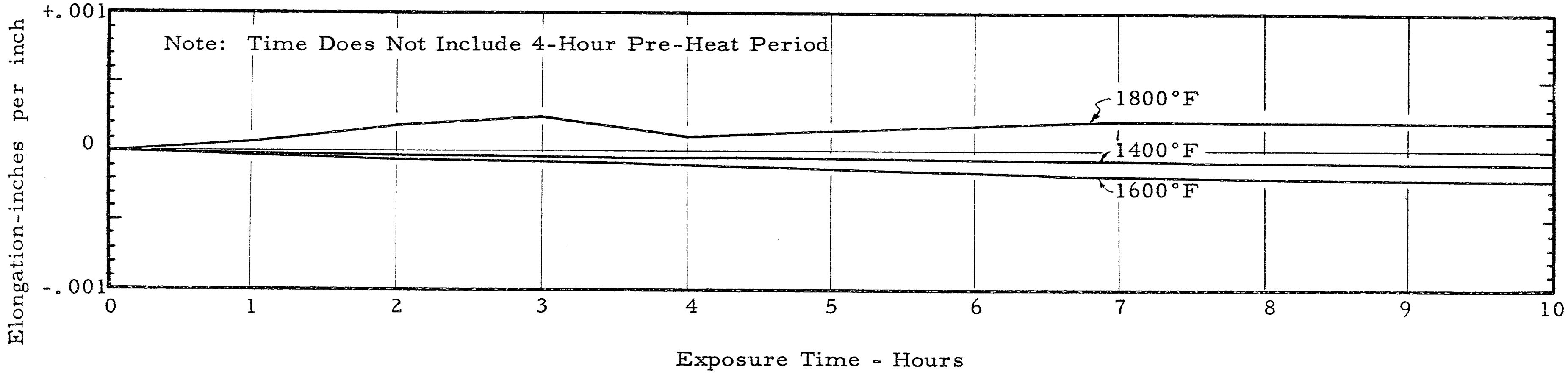

Figure 4. Dimensional Change with Time for Unstressed Exposure Tests of Solution Treated and Aged Rene' 41 Alloy.

Table 5

Rupture Test Data for Chromel A Alloy

Spec No.	Test Temp (°F)	Stress (psi)	Rupture Time (hours)	Elongation (%)	Reduction of Area (%)
Annealed 1550°F - 4 hr.					
C1-6	1000	80,000	0.5	33.6	38.0
C1-9	1000	55,000	54.3	28.0	36.5
C1-2	1200	35,000	5.4	46.5	46.0
C1-10	1200	20,000	63.4 ± 5	57.5	44.8
C1-3	1400	15,000	3.1	35.8	34.6
C1-7	1400	5,000	150.5	28.5	24.4
C1-4	1600	5,000	4.9	23.6	21.6
C1-8	1600	2,000	216.1	68.0	29.0
C1-5	1800	3,500	3.6	13.8	14.2
Annealed 2100°F - 1 hr.					
C2-13	1000	80,000	On Load	51.7	62.0
C2-3	1000	70,000	102.8	21.2	11.9
C2-2	1200	35,000	14.7	24.2	24.9
C2-6	1200	22,000	109.9	18.5	20.4
C2-4	1400	15,000	12.5	22.0	19.0
C2-7	1400	10,000	54.0	12.5	13.8
C2-5	1600	8,000	4.7	17.7	14.7
C2-10	1600	5,000	28.6	10.8	10.2
C2-12	1800	3,500	10.1	9.5	11.5

Note: C1 Series - Annealed 1550°F - 4 hrs.
C2 Series - Annealed 2100°F - 1 hr.

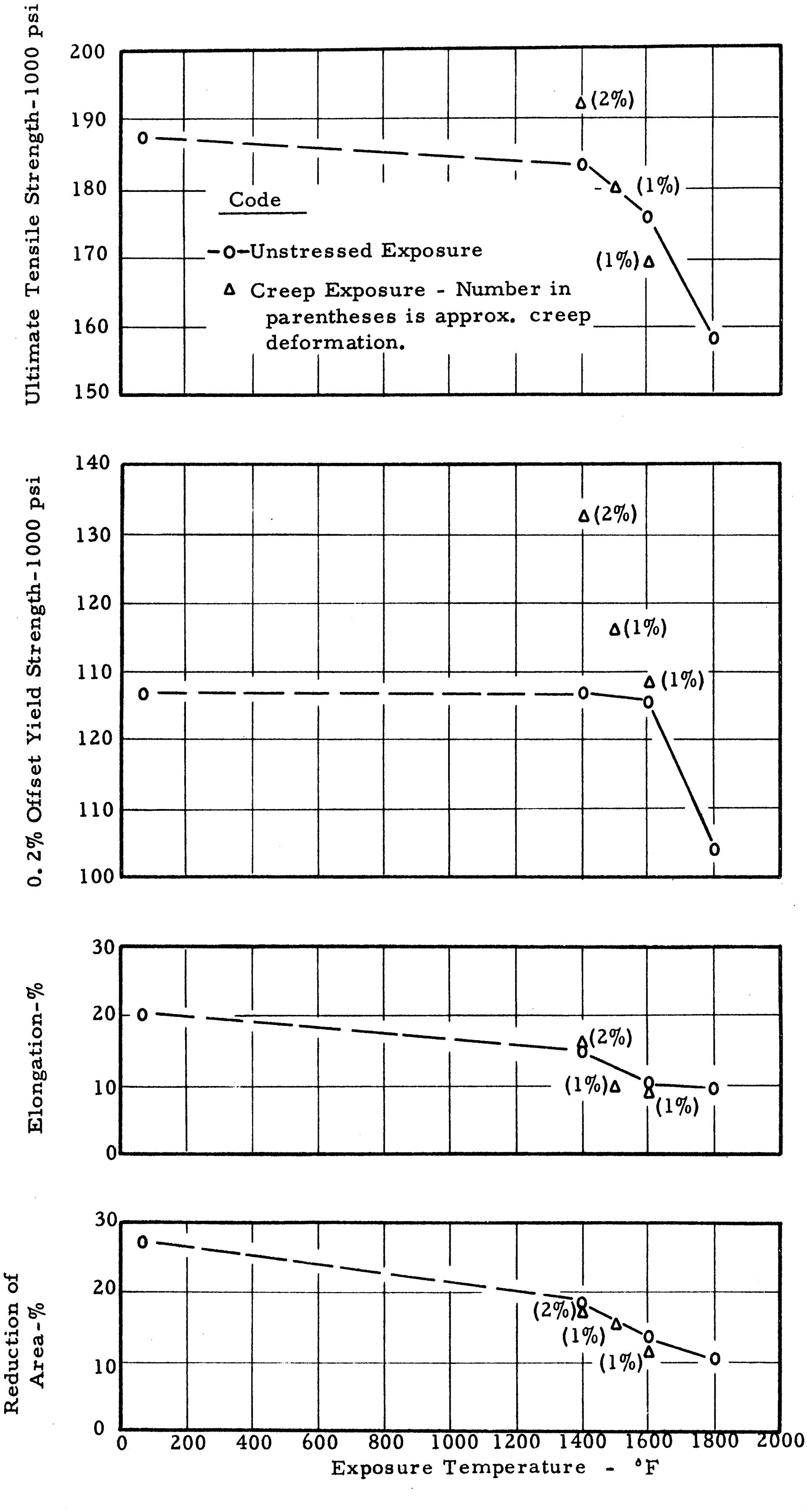

Figure 6. Effect of 10 Hours Exposure with or without Stress on Room Temperature Tensile Properties of Solution Treated and Aged Rene' 41 Alloy.

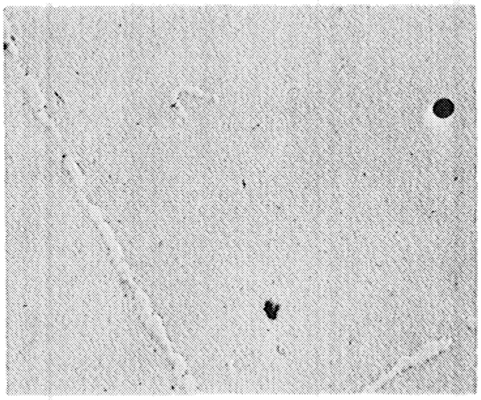

Figure 7 x8200

As Treated

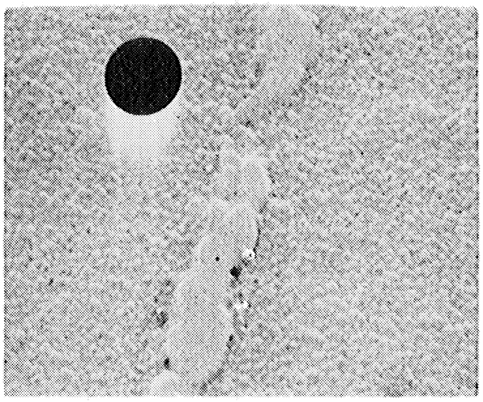

Figure 8 x31,000

As Treated

(Solution Treated: 1950°F-1/2 hr + Air Cool
Aged: 1400°F-16 hr + Air Cool)

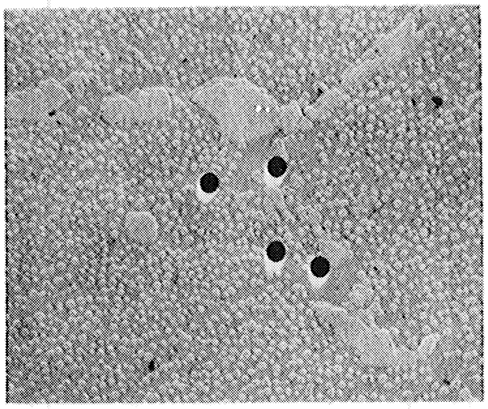

Figure 9 x8200

Rupture Test: 1600°-35,000 psi. Failed at 27.7 hr.

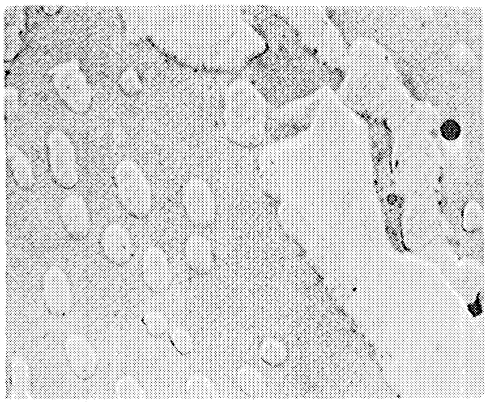

Figure 10 x8200

Rupture Test: 1800°-8,000 psi. Failed at 116.1 hr.

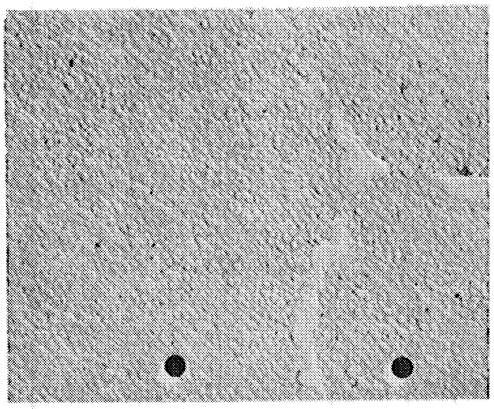

Figure 11 x8200

Exposed 10 hrs. at 1600°F at no stress.

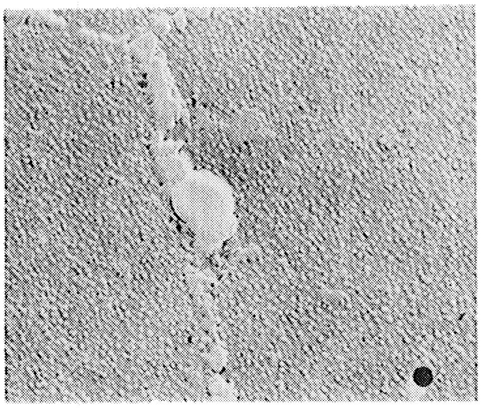

Figure 12 x8200

Creep Tested 10 hrs. at 1600°-35,000 psi to 0.96% deformation.

Notes: Etchant: Electrolytic "G" Etch.
Black spots are 3400 A diameter polystyrene latex balls to indicate direction of shadowing.

Figures 7-12. Electron Micrographs of René 41 Alloy.

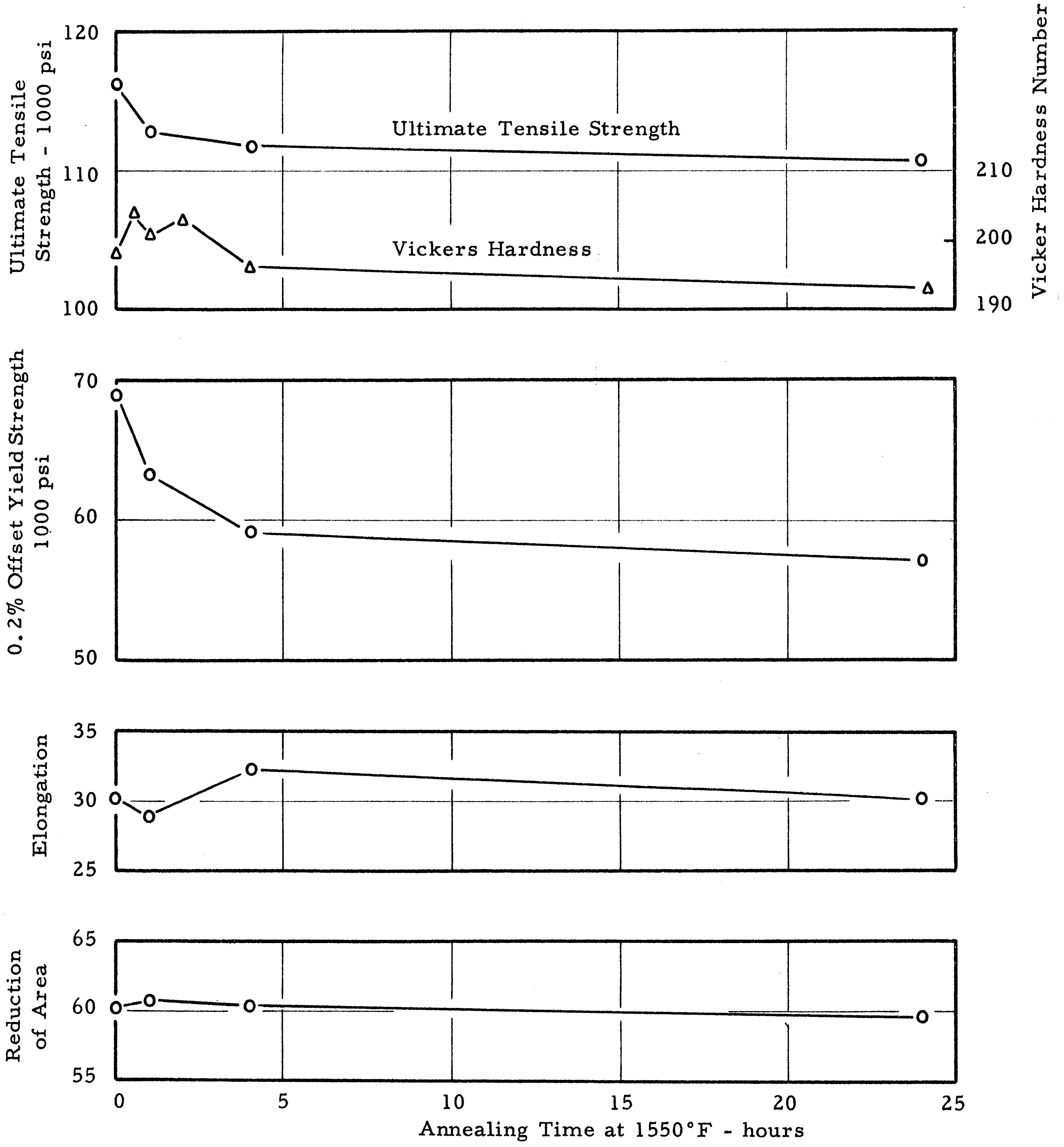

Figure 13. Effect of Annealing Time at 1550°F on Room Temperature Tensile Properties and Hardness of Chromel - A.

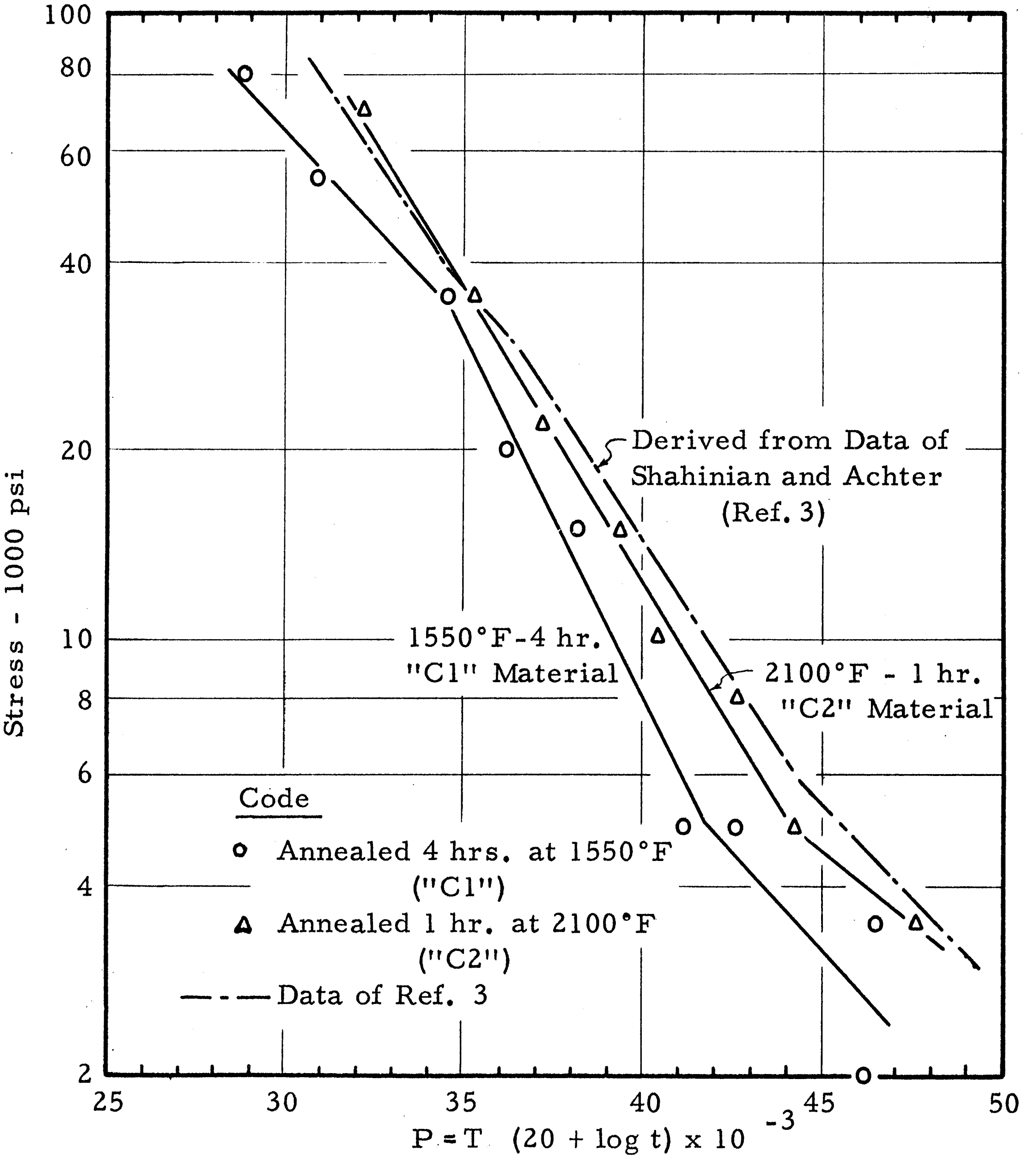

Figure 14. Master Rupture Curves for Chromel A Alloy.

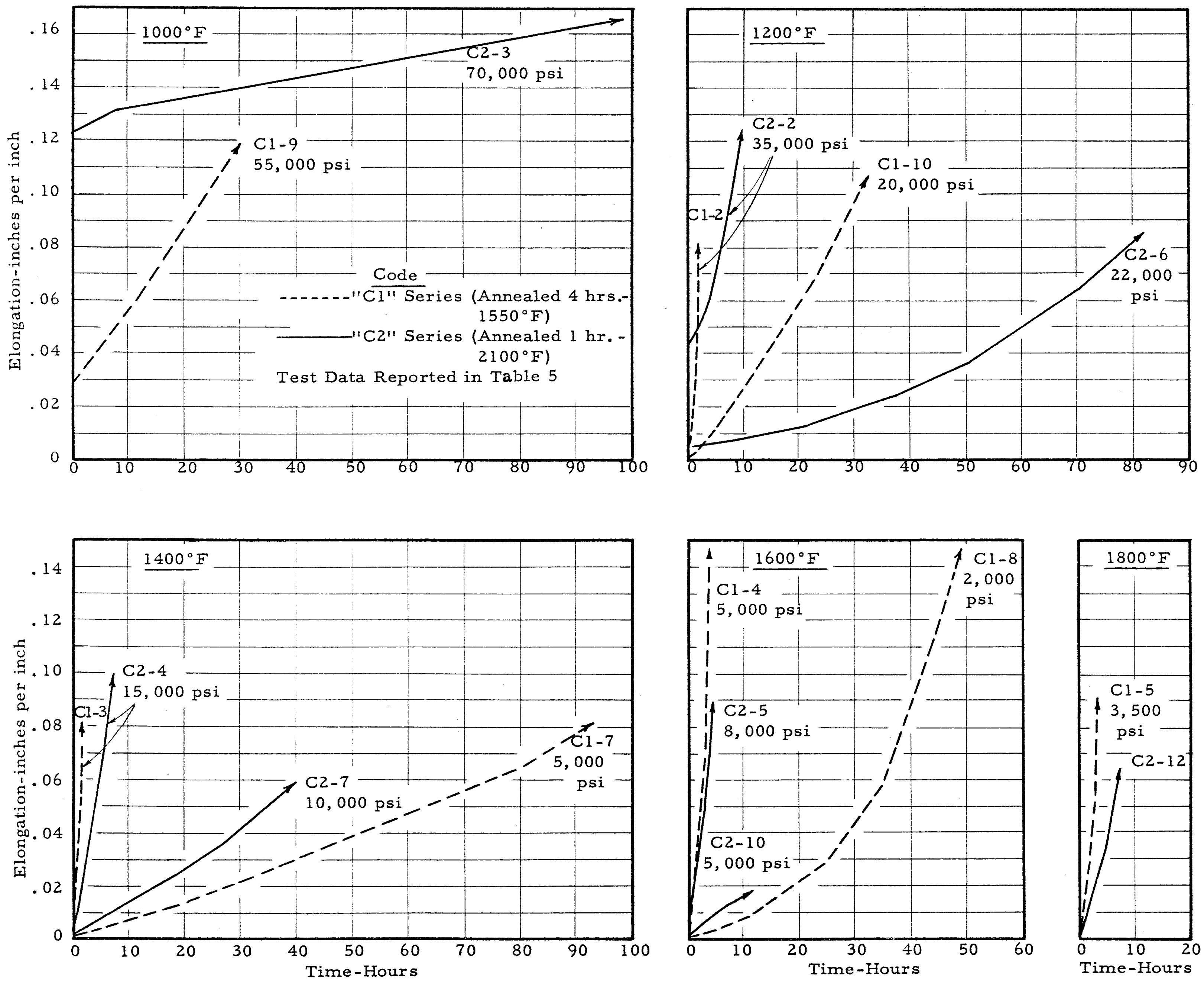

Figure 15. Time-Elongation Curves for Rupture Tests of Chromel A Alloy.

Annealed 1550°F-4 hr.

Annealed 2100°F-1 hr.

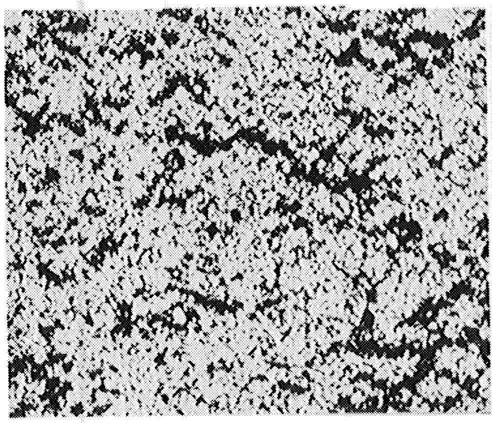

Figure 16 x100
Spec. No. C1-10: 1200°F-20,000 psi. Failed at 63±5 hrs.

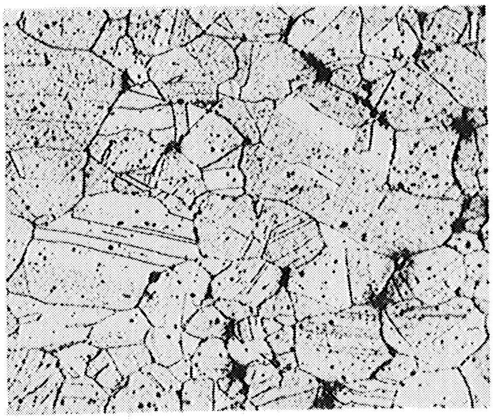

Figure 17 x100
Spec. No. C2-6: 22,000 psi. Failed at 109.9 hrs.

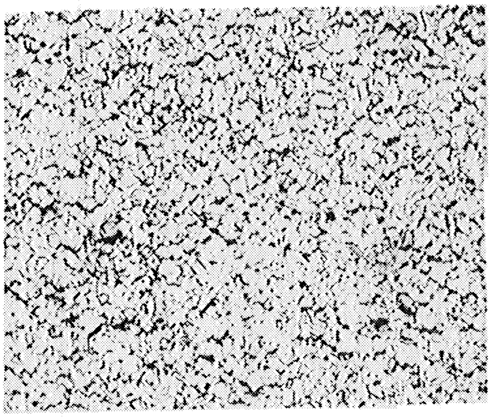

Figure 18 x100
Spec. No. C1-4: 1600°F-5,000 psi. Failed at 4.9 hrs.

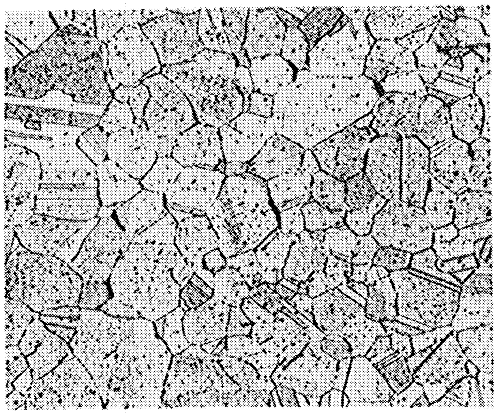

Figure 19 x100
Spec. No. C2-5: 1600°F-8,000 psi. Failed at 4.7 hrs.

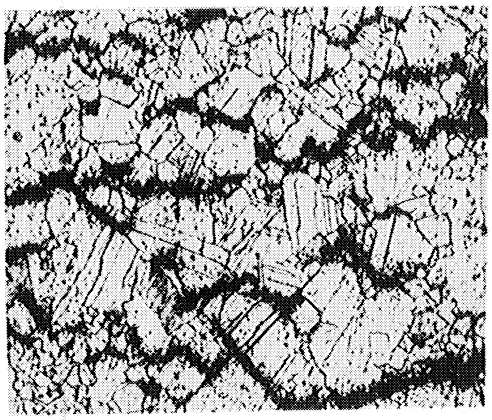

Figure 20 x100
Spec. No. C1-5: 1800°F-3,500 psi. Failed at 3.6 hrs.

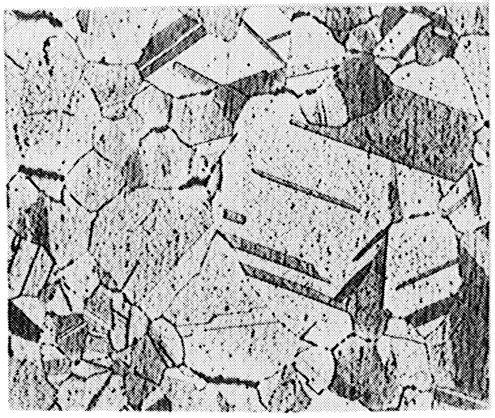

Figure 21 x100
Spec. No. C2-12: 1800°F-3,500 psi. Failed at 10.1 hrs.

Etchant: Marble's Reagent

Figures 16-21. Optical Micrographs of Chromel A Alloy After Rupture.

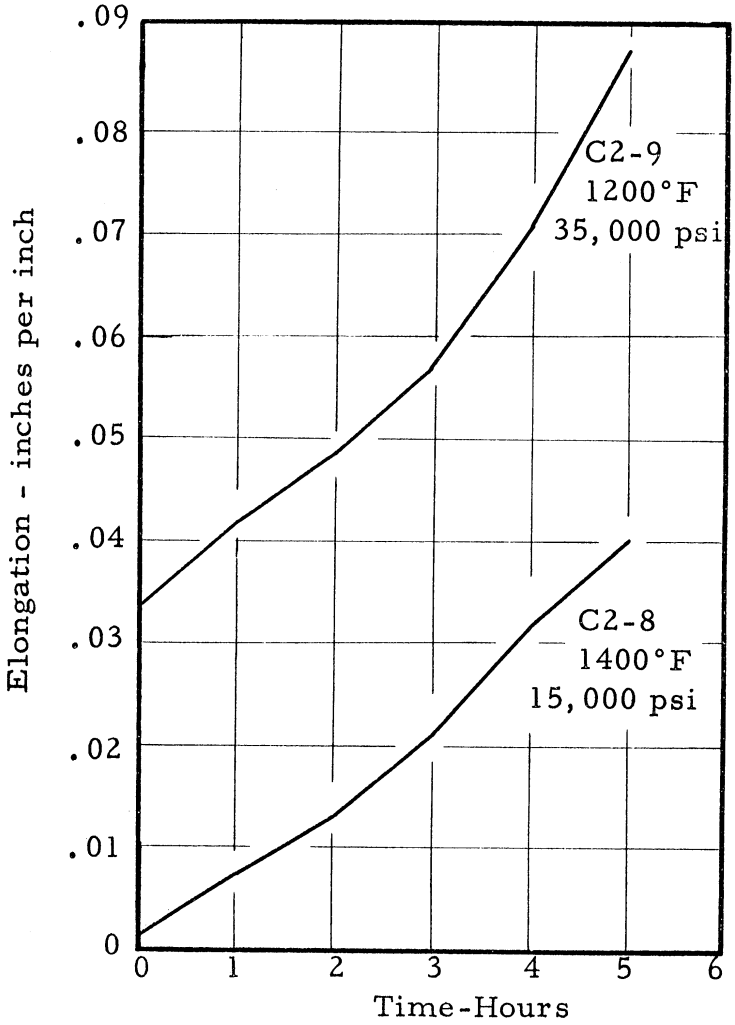

Figure 22. Time-Elongation Curves for Stress-Exposure Tests of Chromel A Alloy.