JUN 19 1975

To - C.E. Pugh
from C.E. Jaske

Conf-751106--6

MONOTONIC AND CYCLIC STRESS-STRAIN RESPONSE OF ANNEALED 2¼Cr-1Mo STEEL*

Carl E. Jaske[a]
Brian N. Leis[a]
Claud E. Pugh[b]

ABSTRACT

The stress-strain response of isothermally annealed 2¼Cr-1Mo steel under monotonic and cyclic loadings has been characterized at temperatures from 21 to 593°C (70 to 1100°F). Monotonic stress-strain curves were developed for uniaxial tensile loading of specimens at strain rates of 8.33×10^{-5} and 8.33×10^{-6} sec^{-1} (0.005 and 0.0005 min^{-1}). The cyclic stress-strain response was measured for the first 100 fully reversed strain cycles at strain ranges between 0.4 and 3.0% under uniaxial loading at a strain rate of 8.33×10^{-5} sec^{-1}. The effects of creep, stress-relaxation, and thermal-exposure hold periods on the cyclic stress-strain behavior were also investigated at 510°C (950°F).

Monotonic stress-strain curves were quantified using a power law relation between stress range and plastic-strain range. Cyclic hardening was observed at temperatures up to 427°C (800°F). A mixture of initial cyclic hardening followed by later cyclic softening was seen at temperatures from 482 to 538°C (900 to 1000°F), and cyclic softening was observed at 593°C (1100°F). For the strain ranges investigated, one measure of the cyclic stress-strain response was characterized by the ascending path of the stress-strain hysteresis loop for the tenth cycle. These cyclic stress-strain paths were approximated by a translation of the monotonic curve along the elastic modulus line. This empirical model then provides a representation of the monotonic and cyclic stress-strain response of this alloy over a wide range of temperatures and in a form consistent with the constitutive equations presently recommended for use in inelastic design analysis of stainless steel nuclear components. The reported results form part of the data base to be used by others in formulating similar general inelastic constitutive equations for analysis of 2¼Cr-1Mo steel components.

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*Research performed under Subcontract No. 4004 for the Oak Ridge National Laboratory operated by Union Carbide Corporation under contract with the U.S. Energy Research and Development ~~Agency~~ Administration.

MASTER

[a]Associate Manager and Research Scientist, respectively, Structural Materials Section, Battelle Columbus Laboratories, Columbus, Ohio 43201.

[b]~~Research Engineer~~ Section Head, Engineering ~~Solid~~ Mechanics ~~Department~~ Group, Reactor Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830.

INTRODUCTION

It is presently planned to use 2¼Cr-1Mo steel in the steam generator of a liquid metal fast breeder reactor (LMFBR). Many of the pressure vessels and piping systems in petroleum, chemical-process, and power-generation equipment have successfully used 2¼Cr-1Mo steel for a number of years. The Metal Properties Council has been involved in sponsoring four publications(1-4)* containing mechanical properties data on this material. However, these documents do not contain detailed information on monotonic and cyclic stress-strain response that is required to successfully perform reliable inelastic stress analyses in the design of an LMFBR steam generator.

The objective of this program was to experimentally develop data on the monotonic and cyclic stress-strain response of 2¼Cr-1Mo steel under uniaxial loading. These data then were used by Oak Ridge National Laboratory (ORNL) in their efforts to develop interim constitutive equations for this low-alloy steel.(5) Monotonic tensile stress-strain curves to 0.05 tensile strain were developed at temperatures from 21 to 593°C (70 to 1100°F). Stress-strain curves were developed for fully reversed strain cycling at total strain ranges between 0.004 and 0.030 over the same temperature range. The effects of creep, stress-relaxation, and thermal exposure on cyclic stress-strain behavior were investigated at 510°C (950°F) because it is anticipated that this will be the peak service temperature for the planned LMFBR steam generator. Detailed tabulations of data developed during this program are reported in Reference 6.

MATERIAL AND SPECIMEN PREPARATION

Material used for this study was furnished by ORNL in the form of a 76 by 25 cm (30 by 10-in.) section of 2.54 cm (1-in.) thick plate. (See Figure 1.) This plate was from the same heat of material (Babcock and Wilcox Heat No. 20017) used in previous programs at ORNL.(7-9) The reported(8) chemical composition of this material is listed below.

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*Numbers in parentheses indicate references listed at end of this report.

Chemical Composition, wt %

C	Mn	Si	Cr	Mo	Ni	S	P
0.135	0.57	0.37	2.2	0.92	0.16	0.016	0.012 .

Specimen blanks were taken with their longitudinal axes parallel to the rolling direction. Each specimen was first rough machined to a configuration with a test section diameter about 0.51 mm (0.20 in.) greater than the final size. (The final specimen configuration is illustrated in Figure 1.) All specimens were then subjected to an isothermal annealing heat treatment in an argon atmosphere using the following three steps.

(1) Annealed for 1/2 hour at 927°C (1700°F)

(2) Rapidly furnace cooled to 721°C (1330°F) and held at that temperature for 2 hours

(3) Air cooled to room temperature.

After heat treatment, the excess material in the test section was removed by machining away about 0.025 mm (0.001 in.) of material on each pass. The test section of each specimen was then polished with successively finer grades of silicon-carbide paper to produce a surface finish of about 0.25 μm (10 μin.) rms, with finishing marks parallel to the longitudinal axis of the specimen. Prior to installation of the experimental apparatus, each specimen was degreased with trichlorethylene, followed by reagent grade acetone.

EXPERIMENTAL APPARATUS

All of the experiments in this program were conducted using one of two similar 44.5 kN (10,000-lb.) capacity servocontrolled, electrohydraulic test systems. Specimens were loaded axially and all cyclic loading was under closed-loop strain control. Creep loading was performed under closed-loop load control.

Load was measured using a standard, strain-gaged load cell in series with the specimen. Calibration of the load cells was verified before, once during, and after the program. The load cell was equipped with a water-cooled jacket so that load-measurement errors would not be introduced by thermal gradients across the cell.

Strain was measured over a 12.7 mm (0.500-in.) gage length with a specially constructed longitudinal extensometer. Two high-purity alumina

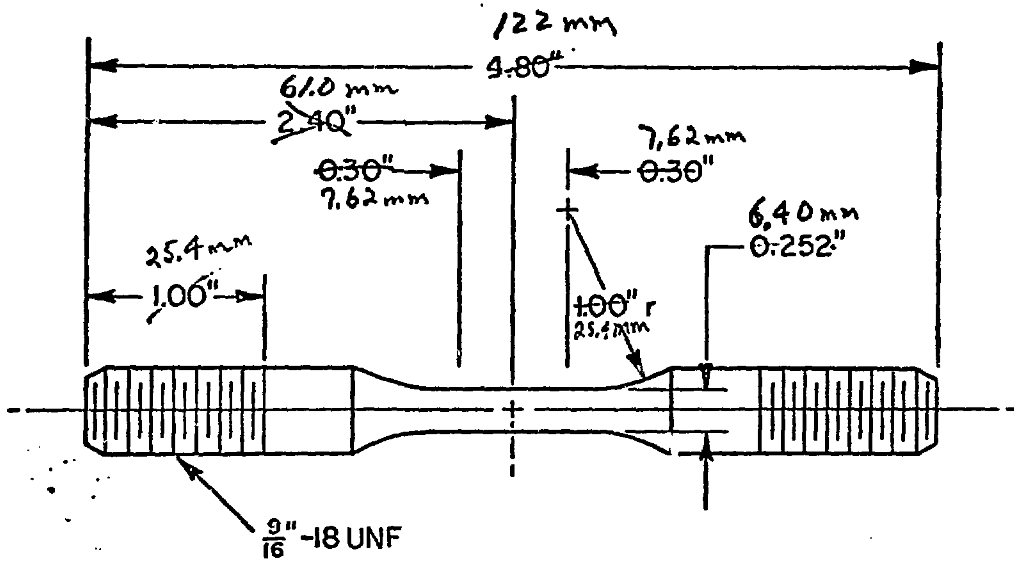


FIGURE 1. SPECIMEN CONFIGURATION

probes with knife-edge points were lightly clamped against the specimen gage section. These probes were connected to a bracket with two parallel beams joined together by a flexible elastic hinge. The transformer of a magnetically shielded linear variable differential transformer (LVDT) was attached to one beam and the core was attached to the other beam. Thus, the output signal obtained from the LVDT was directly proportional to the average deformation over the gage length of the specimen. The extensometers were calibrated before, several times during, and after the experiments, employing a mechanical micrometer capable of 2.5 m (0.0001-in.) resolution.

Specimens were heated by high-frequency induction and temperature was controlled with a standard proportional-type power controller. The geometry of the heating coil was designed to minimize temperature gradients in the test section. A specimen instrumented with five Chromel-Alumel thermocouples spot-welded along the central 12.7 mm (0.500-in.) portion was used to verify this design. With the final design, the peak temperature was within $\pm$ 1.1°C ($\pm$ 2°F) of the desired value, and the overall gradient was less than 2.8°C (5°F). In the actual test specimens, three thermocouples were spot-welded to the specimen--at the center and 6.3 mm (0.25 in.) above and below the center. Before starting each test, final precise placement of the coil was made by balancing the temperature readings at all three locations. During this adjustment and throughout the test, the central thermocouple was used to provide a feedback signal to the temperature controller.

All specimens were gripped using a fixture arrangement similar to that described by Feltner and Mitchell[10]. The upper end of the specimen was threaded into an adapter attached to the load cell which in turn was attached to the load-frame. The lower end of the specimen was attached to the hydraulic actuator through a Wood's metal-type of liquid-solid grip[11]. Both the upper and lower adapters were continuously water cooled to avoid overheating of the fixtures.

In the initial assembly of either type of fixture, alignment was checked using a carefully machined specimen that was instrumented with four strain gages. The gages were oriented longitudinally and spaced at 90-degree intervals around the diameter. Final alignment adjustments were made so as to minimize bending strains under both compressive and tensile loadings. Bending strains were 1 percent or less of the average axial strain after final adjustment and several repeated installations of the specimen. Alignment was checked both before and after the program.

Strain was programmed to follow a constant rate of either 8.33 x 10^{-5} or 8.33 x 10^{-6} sec^{-1} (0.005 or 0.0005 min^{-1}) throughout monotonic tensile loading. During strain cycling, the strain was programmed to follow a fully reversed, triangular waveform at a constant strain rate of 8.33 x 10^{-5} sec^{-1}. Initial straining was always in the tensile direction. To achieve stress relaxation, strain was simply programmed to maintain a constant value at its tensile peak.

When creep was applied before strain cycling, load was applied to give a strain rate of 8.33 x 10^{-5} sec^{-1} until the desired creep load was reached. It was held constant for the creep period and then unloaded at about the same strain rate so that the system could be switched to strain control for the remainder of the test. Intermediate creep periods and a soak period at zero load were applied in a similar manner, except that on the 20th cycle strain was programmed to a value slightly greater than zero where--upon elastic unloading--a condition of zero stress and strain was achieved.

Monotonic stress-strain curves and cyclic stress-strain hysteresis loops were recorded using an X-Y recorder. Hysteresis loops were recorded continuously until approximately stable and periodically thereafter. Load was recorded continuously using a time-based strip chart recorder for all cyclic and creep-plasticity experiments. Strain was recorded in a similar manner during creep hold periods.

EXPERIMENTAL RESULTS

Control conditions and data for the 20 monotonic stress-strain experiments are listed in Table 1. Stress-strain curves were recorded up to a value of 0.05 strain. These recordings were then used to obtain the values of elastic modulus, 0.2 percent offset yield strength, and strength at 0.05 strain that are reported.

Table 2 summarizes the control conditions that were used for the 32 cyclic experiments. Nominal values of total axial strain range, $\Delta\epsilon$, and temperature are identified for each specimen. To ensure that the stress-strain response was reasonably stable, all specimens (except the four noted) were subjected to at least 100 cycles.

Seven creep-plasticity experiments were conducted as outlined in Table 3. The first three specimens (KB-42, KB-19, and KB-39) were subjected to varying amounts of creep before strain cycling. The next two specimens

TABLE 1. SUMMARY OF MONOTONIC STRESS-STRAIN RESULTS FOR ISOTHERMALLY ANNEALED $2\frac{1}{4}$Cr-1Mo PLATE

Specimen Number	Temperature		Strain Rate, sec^{-1}	Elastic Modulus		0.2 Percent Offset Yield Strength		Strength at 0.05 Strain	
	°C	°F		GPa	ksi	MPa	ksi	MPa	ksi
KB-15	21	70	8.33×10^{-5}	219	31,800	281	40.8	505	73.2
KB-53	21	70	8.33×10^{-6}	210	30,500	267	38.8	--	--
KB-44	93	200	8.33×10^{-5}	190	27,500	275	39.9	488	70.8
KB-32	204	400	8.33×10^{-5}	183	26,600	281	40.8	504	73.1
KB-20	260	500	8.33×10^{-5}	190	27,600	298	43.3	565	82.0
KB-35	316	600	8.33×10^{-5}	165	23,900	252	36.6	507	73.5
KB-21	316	600	8.33×10^{-6}		25,300	261	37.9	570	82.7
KB-43	371	700	8.33×10^{-5}	174	26,900	247	35.9	502	72.8
KB-27	427	800	8.33×10^{-5}	185	26,900	234	34.0	480	69.7
KB-11	427	800	8.33×10^{-6}	167	24,300	254	36.8	510	74.0
KB-40	482	900	8.33×10^{-5}	174	25,300	233	33.8	443	64.3
KB-68	482	900	8.33×10^{-6}	177	25,700	292	42.3	565	81.9
KB-10	510	950	8.33×10^{-5}	175	25,400	235	34.1	439	63.7
KB-4	510	950	8.33×10^{-6}	175	25,400	257	37.3	443	64.3
KB-59	510	950	8.33×10^{-6}	156	22,600	232	33.7	386	56.0
KB-16	538	1000	8.33×10^{-5}	150	21,800	225	32.6	379	55.0
KB-29	538	1000	8.33×10^{-6}	158	22,900	236	34.3	309	44.9
KB-66	566	1050	8.33×10^{-5}	147	21,400	214	31.1	314	45.6
KB-58	593	1100	8.33×10^{-5}	153	22,200	186	27.0	222	32.2
KB-64	593	1100	8.33×10^{-6}	147	21,300	172	24.9	170	24.7

TABLE 2. CYCLIC STRESS-STRAIN EXPERIMENTS FOR ISOTHERMALLY ANNEALED 2¼Cr-1Mo PLATE AT A STRAIN RATE OF 8.33 x 10^{-3} SEC^{-1} FOR 100 CYCLES OR MORE

Temperature		Specimen Numbers				
°C	°F	$\Delta\varepsilon$ = 0.004	$\Delta\varepsilon$ = 0.006	$\Delta\varepsilon$ = 0.010	$\Delta\varepsilon$ = 0.020	$\Delta\varepsilon$ = 0.030
21	70	KB-18	—	KB-65 and KB-54	KB-7	—
93	200	KB-63	—	KB-14	—	—
204	400	KB-47	—	KB-22	—	—
316	600	KB-60	—	KB-36	KB-52	—
427	800	KB-34	—	KB-56[a]	KB-9	KB-70[b]
482	900	KB-33	—	KB-48	KB-26	KB-24[c]
510	950	KB-30	KB-62	KB-51	KB-3	KB-41
538	1000	KB-13	—	KB-61	KB-45[d]	KB-12
593	1100	KB-6	—	KB-37	KB-55	KB-8

(a) Induction heater failed after only 50 cycles
(b) Specimen buckled after only 3 cycles
(c) Specimen buckled after only 6 cycles
(d) Extensometer slipped and specimen buckled after only 10 cycles

TABLE 3. CREEP-PLASTICITY INTERACTION EXPERIMENTS FOR ISOTHERMALLY ANNEALED $2\frac{1}{4}$Cr-1Mo PLATE AT 510°C (950°F) WITH A CYCLIC STRAIN RATE OF 8.33×10^{-5} SEC^{-1}

Specimen Number		Type of Loading	Total Axial Strain Range, $\Delta\epsilon$	Strain Cycle Number	Creep Stress MPa	Creep Stress ksi	Hold Time, hr
KB-42	a.	Creep to 0.00048 strain					23
	b.	Strain cycling	0.0041	1 to 20	172	25	
KB-19	a.	Creep to 0.00100 strain			172	25	80
	b.	Strain cycling	0.0041	1 to 77			
KB-39	a.	Creep to 0.00204 strain			172	25	105
	b.	Strain cycling	0.0040	1 to 20			
KB-23	a.	Strain cycling	0.0042	1 to 20			
	b.	Creep to 0.00058 strain			172	25	80
	c.	Strain cycling	0.0042	21 to 40			
KB-5	a.	Strain cycling	0.0101	1 to 20			
	b.	Creep to 0.00040 strain			172	25	80
	c.	Strain cycling	0.0101	21 to 683			
KB-31	a.	Strain cycling	0.0040	1 to 20			
	b.	Soak at 510 C (950 F)			0	0	80
	c.	Strain cycling	0.0040	21 to 40			
KB-17	a.	Strain cycling	0.0041	1 to 20			
	b.	Strain hold at +0.0020 strain			Relaxation		80
	c.	Strain cycling	0.0041	21 to 40			

(KB-23 and KB-5) had a period of creep between two periods of strain cycling. Specimens KB-31 and KB-17 were subjected to a thermal exposure and a tensile strain hold, respectively, between two intervals of strain cycling. At least 20 cycles were applied during each period of strain cycling to assure that a relatively stable stress-strain response was developed.

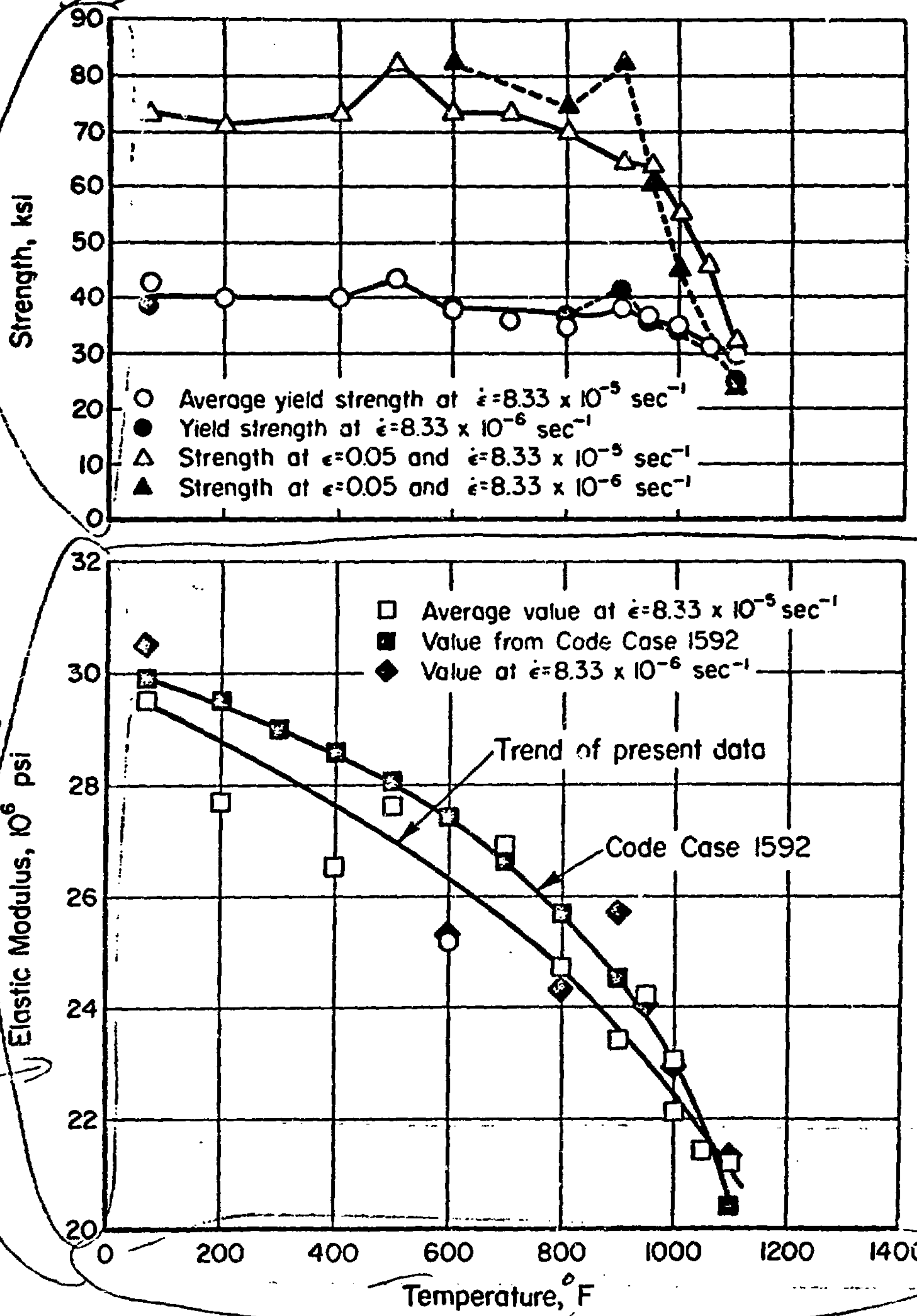
Monotonic Stress-Strain

The influence of temperature on monotonic tensile properties and stress-strain curves is illustrated in Figures 2 and 3, respectively. Since all of the cyclic tests were initiated by tensile straining, it was possible to obtain monotonic values of elastic modulus and 0.2 percent offset yield strength (except where $\Delta\epsilon/2 = 0.002$) for each test. By combining these data with appropriate data from Table 1, the average values of yield strength and elastic modulus at 8.33×10^{-5} sec^{-1} were determined and included in Figure 2.

Except for an intermediate peak at 260°C (500°F), the strength decreased gradually up to 427°C (800°F). Strength showed another peak at 480°C (900°F), and then decreased more rapidly above that temperature. Average yield strength values from the present work were about 21 to 35 MPa (3 to 5 ksi) above those reported by ORNL[9] for this same plate in the solution-annealed condition and close to the mean trend of data reported by Smith[4]. The strength at 0.05 strain became closer to the yield strength as temperature increased above 427°C (800°F), and both strengths were about the same at 593°C (1100°F). This means that the stress-strain curve past yield had a shallower slope in this temperature regime. (See Figure 3.)

The slower strain rate had little effect on yield strength except at 593°C (1100°F), where the yield strength dropped. This was probably caused by more creep taking place at the slower strain rate than at the faster one. Below 510°C (950°F), the strengths at 0.05 strain for the slower strain rate were greater than those for the faster rate, indicating a strengthening effect that may be due to dynamic strain aging. However, the opposite trend was observed above 510°C (950°F), where creep appeared to weaken the material at the slower rate.

Add Strength, MPa scale



Add "Elastic Modulus, GPa" scale

FIGURE ~~6~~ 2. INFLUENCE OF TEMPERATURE ON THE MONOTONIC TENSILE PROPERTIES OF ISOTHERMALLY ANNEALED $2\frac{1}{4}$Cr-1Mo PLATE (additional data taken from ASME Code Case 1592[12])

Add "Temperature, °C" scale

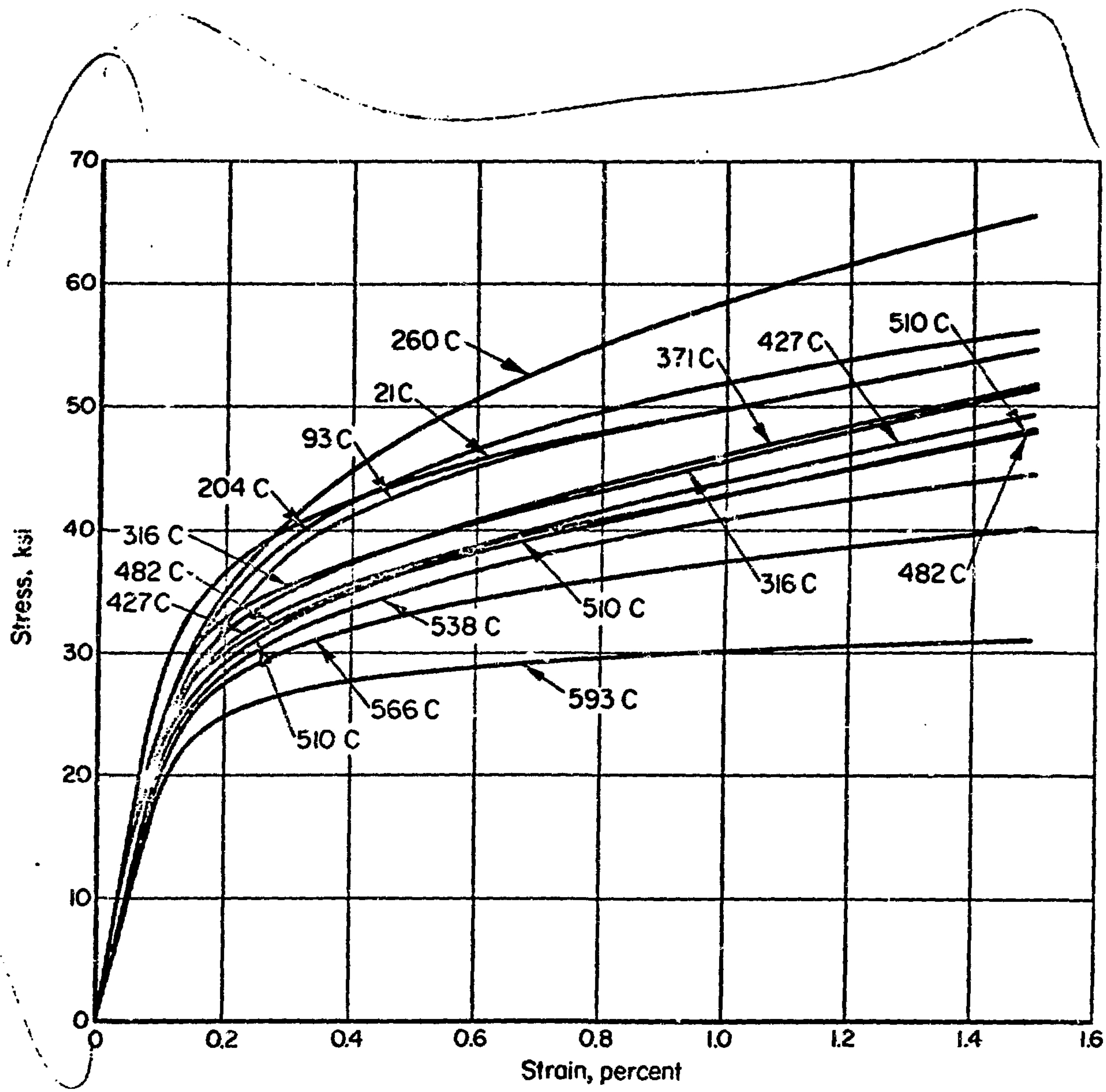


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FIGURE 7. INFLUENCE OF TEMPERATURE ON THE MONOTONIC STRESS-STRAIN BEHAVIOR OF ISOTHERMALLY ANNEALED 2¼Cr-1Mo PLATE AT A STRAIN RATE OF 8.33 x 10^{-5} SEC^{-1} ~~(0.005 MIN^{-1})~~

Elastic modulus gradually decreased with increasing temperature. Although values from this study fell slightly below those given in ASME Code Case 1592[12], the overall trend of the data was about the same as that from the Code Case. The slower strain rate had no significant effect on elastic modulus.

Cyclic Stress-Strain

Examination of the data showed that the cyclic tensile stress amplitude response was approximately the same as the compressive response. Thus, only the tensile stress amplitudes or stress ranges are discussed in the remainder of this paper.

At 21, 93 and 204°C (70, 200 and 400°F), the peak stress values indicated rapid cyclic hardening to a stable value within the first 10 strain cycles, as illustrated by the data at 21°C (70°F) in Figure 4a. This trend in cyclic hardening was also observed for the higher strain ranges (1, 2 and 3 percent) at 316 and 427°C (600 and 800°F), as illustrated for 427°C (800°F) in Figure 4b. For the 0.4 percent strain range at these latter two temperatures, stress response was not close to a stable condition until 100 cycles. The stress amplitude at 10 cycles, however, was about 90 percent of the stable value.

A peak in the hardening response, followed by cyclic softening thereafter, was noted for all tests above 0.4 percent strain range at 482, 510, and 538°C (900, 950 and 1000°F), as illustrated for 510°C (950°F) in Figure 4c. This type of unstable behavior was probably related to overaging and the development of microscopic cracks for these conditions. It was also observed that several of the intermediate strain level tests [e.g., Specimens KB-51, KB-3 and KB-62 at 510°C (950°F)] had more cyclic hardening than those at higher strain levels. A significant difference in cyclic hardening behavior was noted between the two specimens at 1.0 percent strain range at 510°C (950°F). (Compare solid diamonds with solid triangles in Figure 4c.) In contrast, the cyclic hardening behavior was very repeatable at the 0.4 percent strain range at this temperature. Stable stress values were reached after 15 to 20 cycles at the 0.4 percent strain level at 510 and 538°C (950 and 1000°F), and the stress amplitudes at 10 cycles were about 98 percent of the stable values.

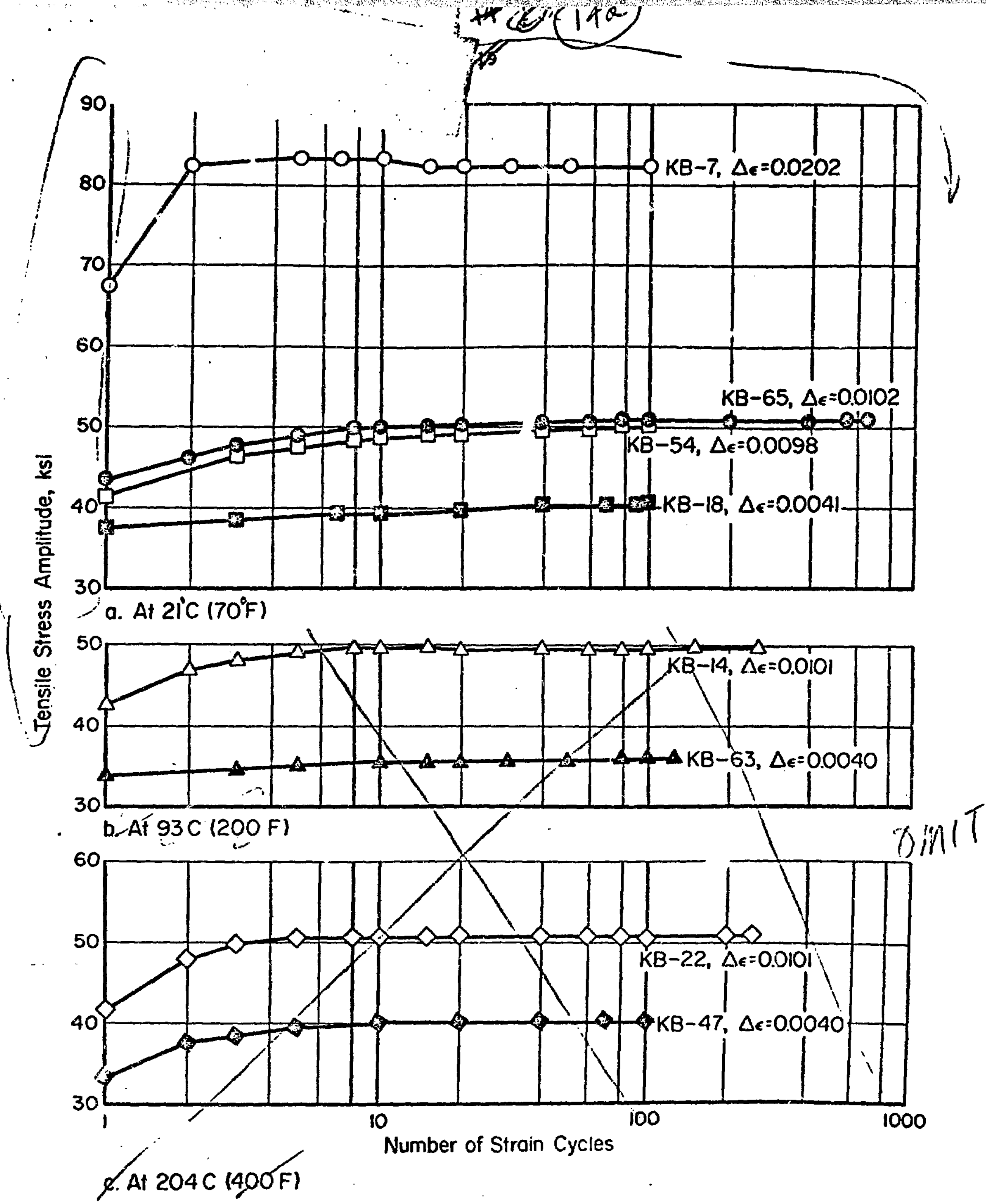

FIGURE 4. CYCLIC STRESS AMPLITUDE RESPONSE OF ISOTHERMALLY ANNEALED $2\frac{1}{4}$Cr-1Mo PLATE

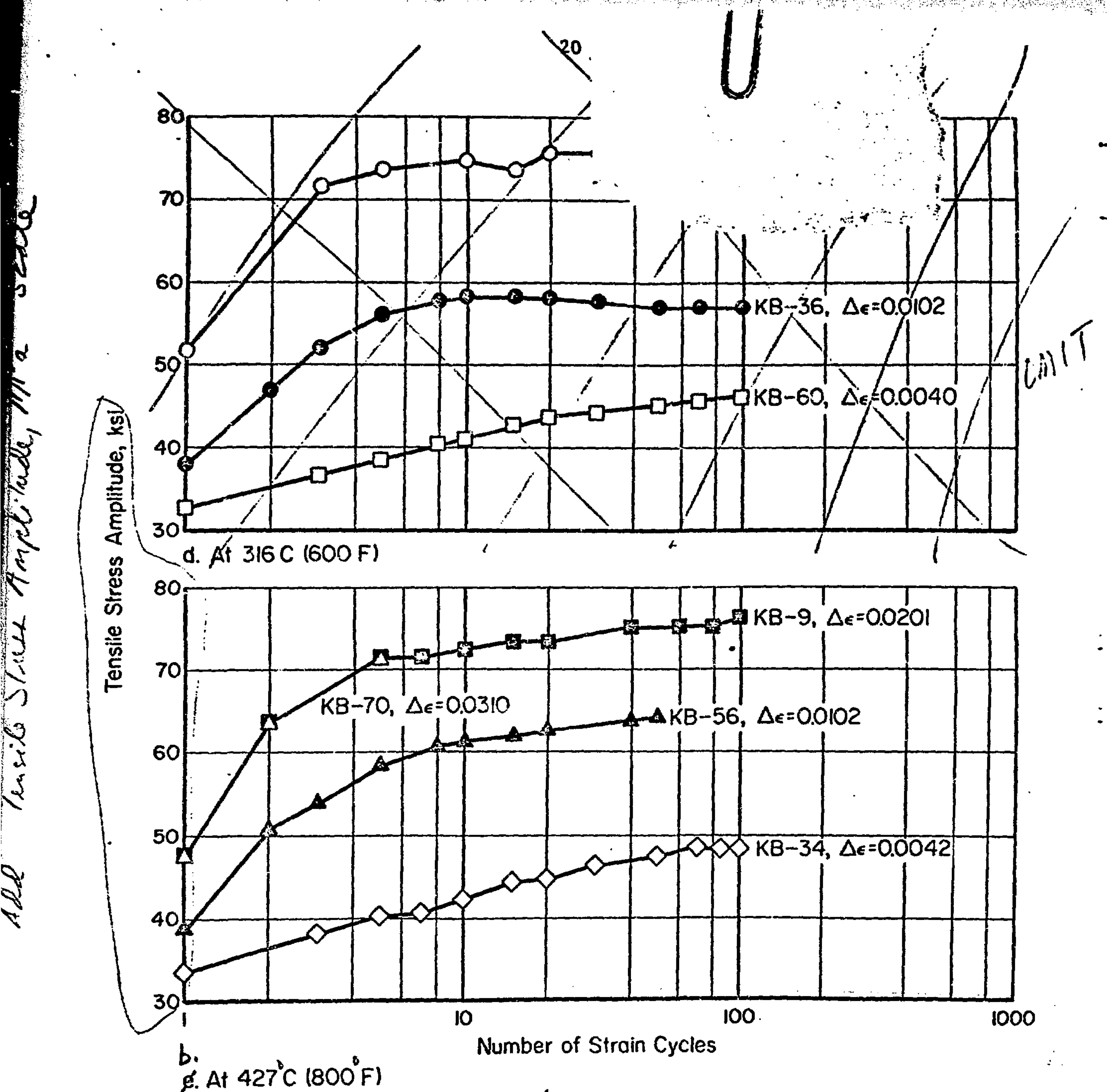

FIGURE ~~8~~ 4. Continued

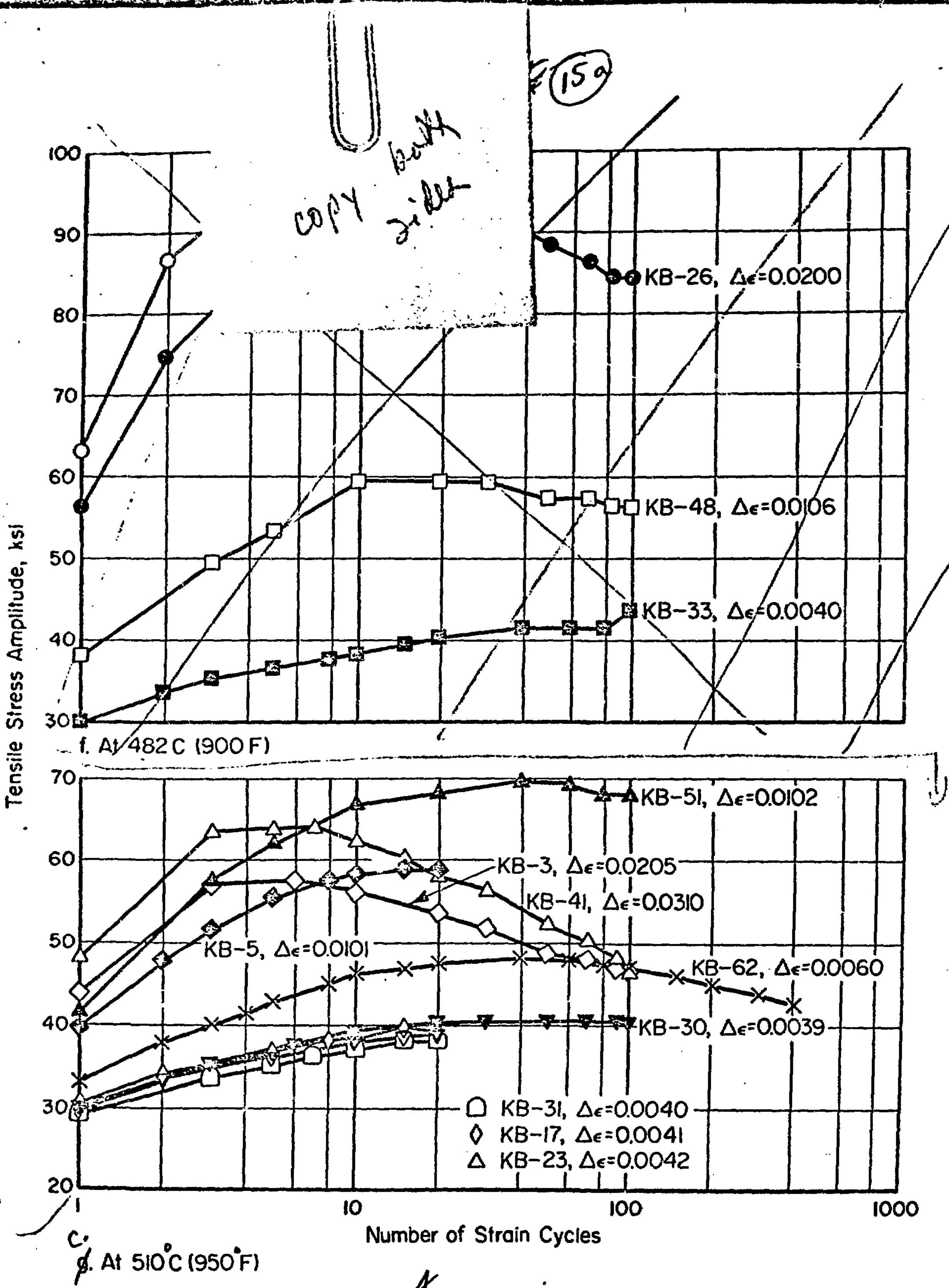

FIGURE 4. Continued

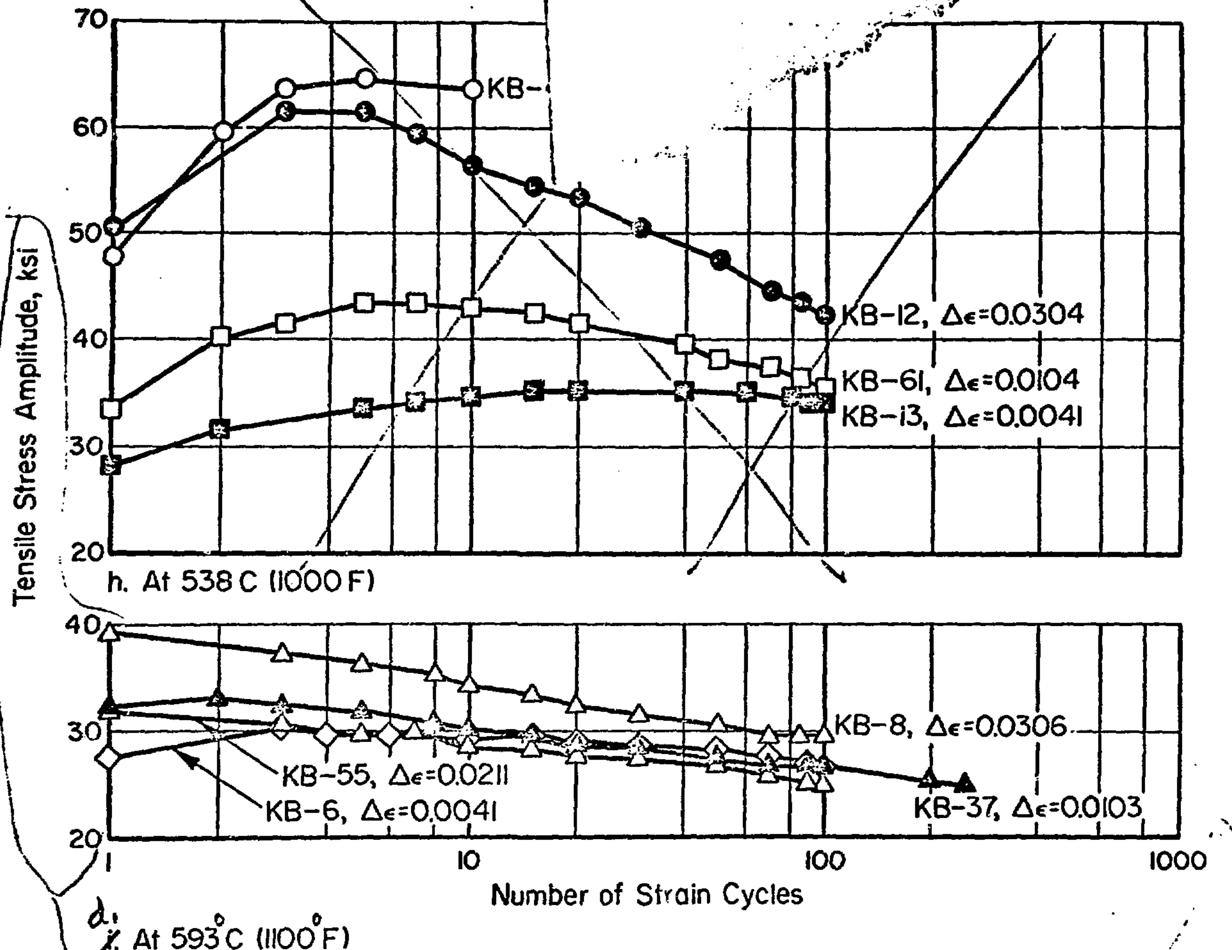

FIGURE 4. Continued

For the two lower strain ranges at 593°C (1100°F), initial cyclic hardening was followed by gradual softening. At the two higher strain ranges, only gradual cyclic softening was observed. The overall cyclic stress response was very similar for strain ranges between 0.4 and 2.0 percent at this temperature. (See Figure 4d.)

Cyclic stress response was practically the same after all three levels of prior creep strain at 172 MPa (25 ksi) and 510°C (950°F), as shown in Figure 5. Instead of cyclically hardening from 207 to 276 MPa (30 to 40 ksi) at 0.4 percent strain range, the material only hardened from 207 to 227 MPa (30 to 33 ksi) after being subjected to creep. Figure 6 shows an example of hysteresis loops after creep exposure. When an 80-hour-hold period of creep, stress relaxation, or thermal exposure was introduced after 20 cycles at a strain range of 0.4 percent at 510°C (950°F), the subsequent stress response was about the same as the stable response after prior creep, as illustrated in Figure 7. Hysteresis loops from the strain hold test are shown in Figure 8. Similar stable loops were obtained after the two other types of hold periods. This result indicates that the thermal exposure was primarily responsible for the reduced amount of cyclic hardening under these conditions. An 80-hour intermediate creep period at a 1.0 percent strain range and at 510°C (950°F) caused significant subsequent cyclic softening back to approximately the monotonic level of stress response. Hysteresis loops for this test are shown in Figure 9.

Based upon the foregoing examination of cyclic stress-strain behavior, it was concluded that the stress-strain hysteresis loop for the 10th cycle was one measure of the stable stress-strain response. This conclusion is valid for the following conditions combined:

- Isothermally annealed 2-1/4Cr-1Mo plate
- Temperatures from 21 to 593°C (70 to 1100°F)
- Strain ranges between 0.4 and 3.0 percent.

Stress-strain curves for the ascending half of the hysteresis loops were, for practical purposes, about the same as those for the descending half (i.e., the loops were symmetrical). Representative ascending curves for 10th cycle loops are compared with monotonic stress-strain curves in Figure 10. Both monotonic stress and strain values have been doubled for this comparison. The monotonic curves were taken from the tensile tests at 8.33×10^{-5} sec^{-1}, and average yield strength points are indicated for comparison.

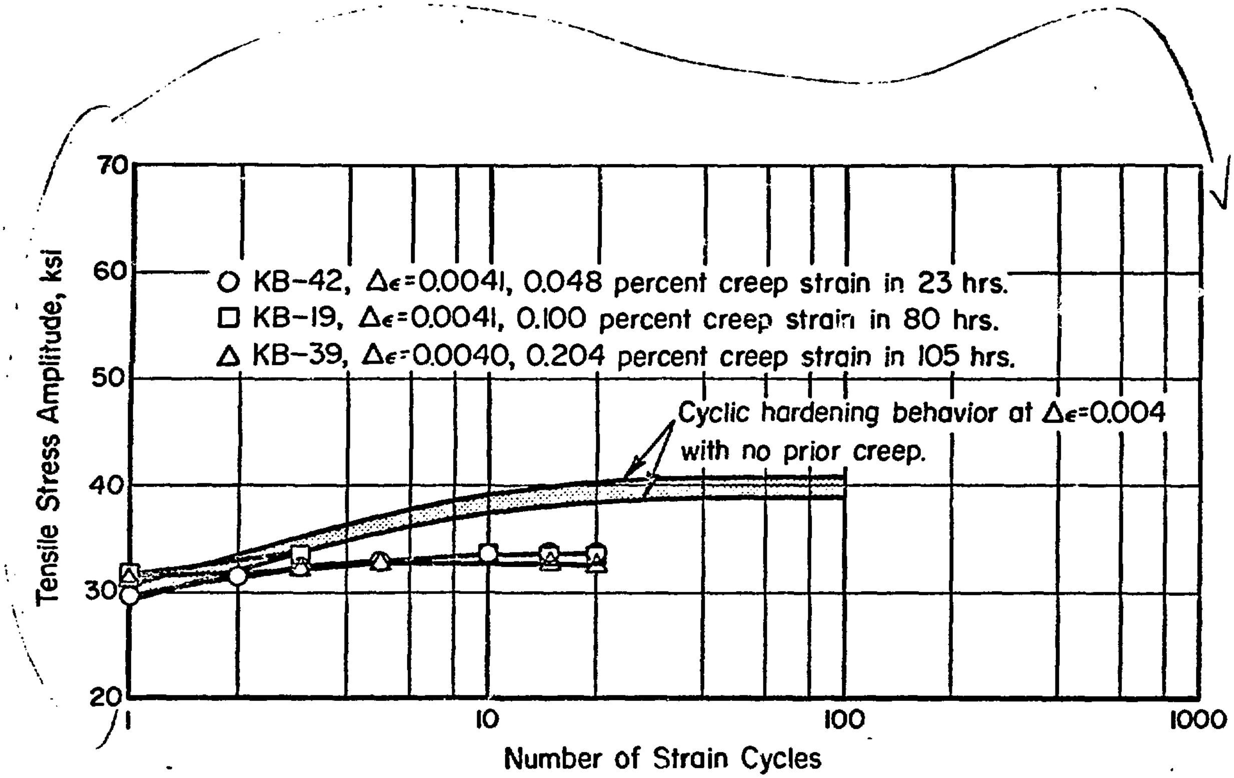

FIGURE 5. EFFECT OF PRIOR CREEP ON CYCLIC STRESS AMPLITUDE OF ISOTHERMALLY ANNEALED 2¼-Cr-1Mo PLATE AT 510°C (950°F)

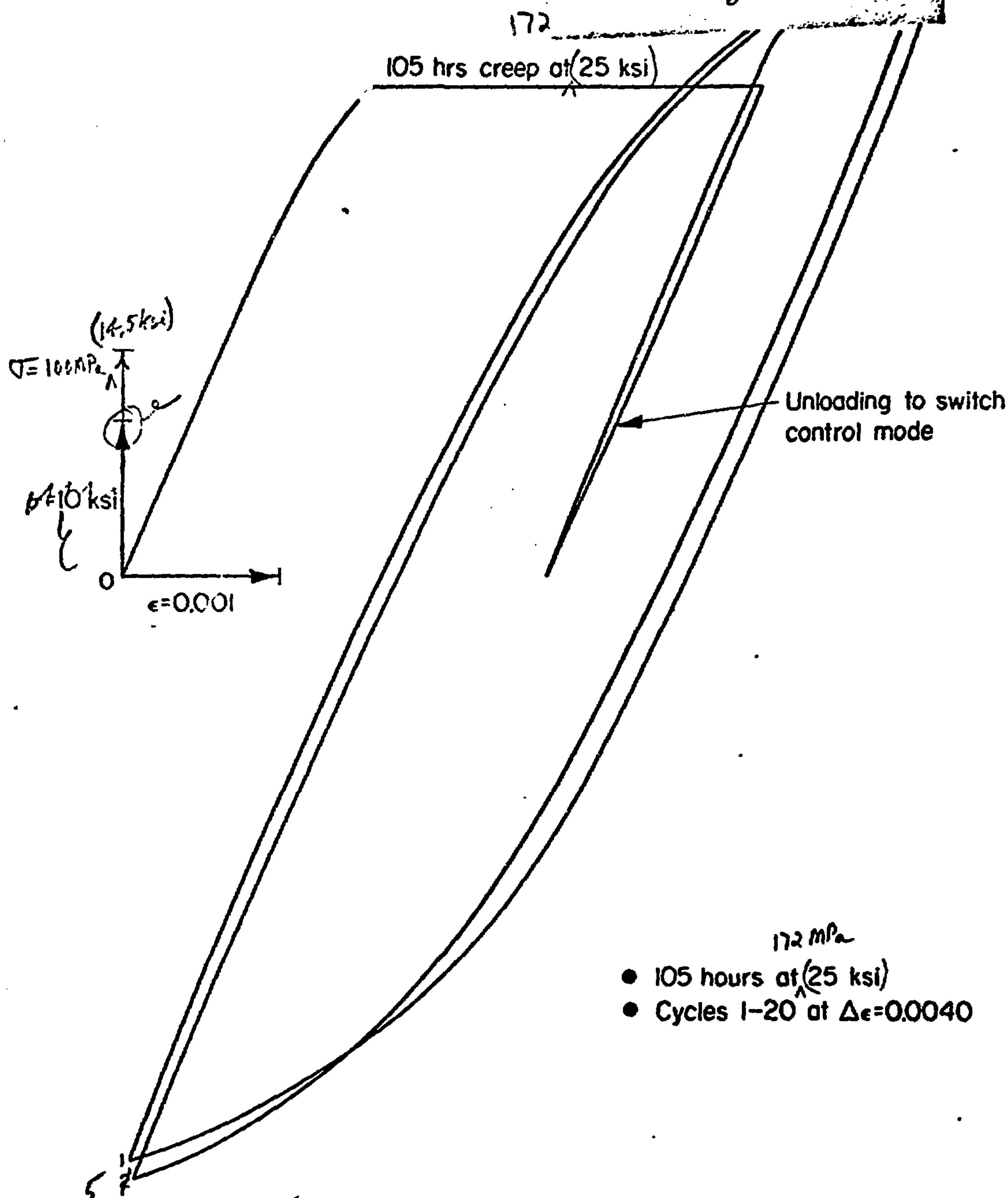

FIGURE 16. EFFECT OF PRIOR CREEP ON STRAIN CYCLING DEFORMATION RESPONSE OF ISOTHERMALLY ANNEALED 2¼Cr-1Mo PLATE AT 510°C (950°F), SPECIMEN KB-39

Add "Tensile Stress Amplitude, MPa" scale.

U 26 21 19

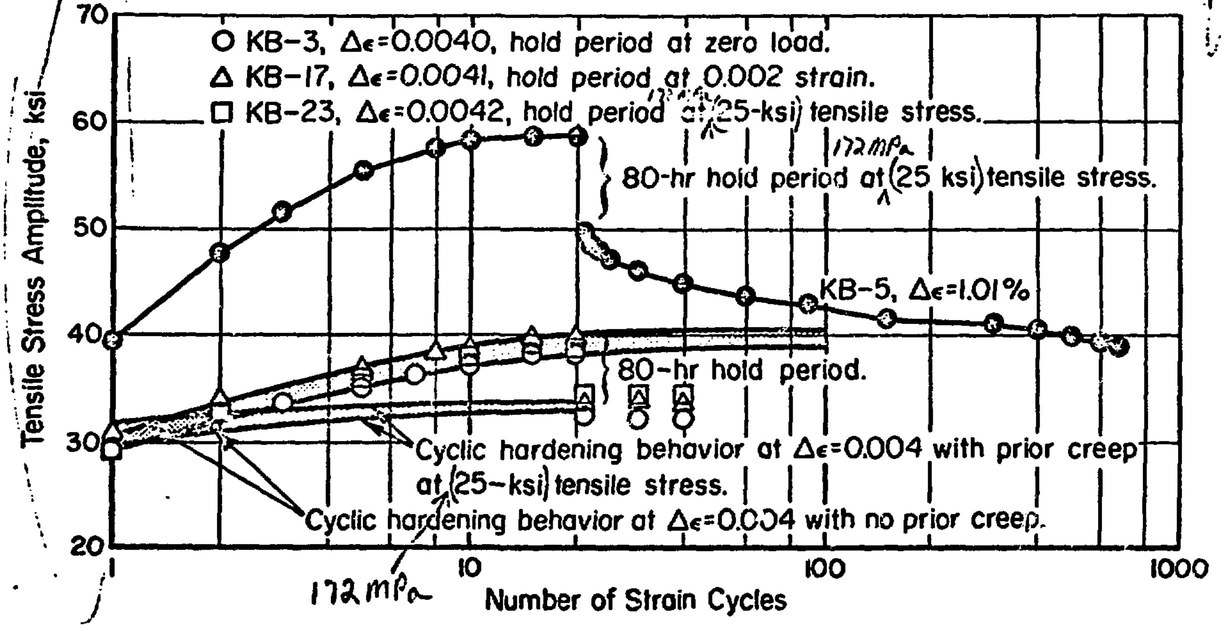

FIGURE 7. EFFECT OF INTERMEDIATE HOLD PERIOD ON CYCLIC STRESS AMPLITUDE OF ISOTHERMALLY ANNEALED 2½Cr-1Mo PLATE AT 510°C (950°F)

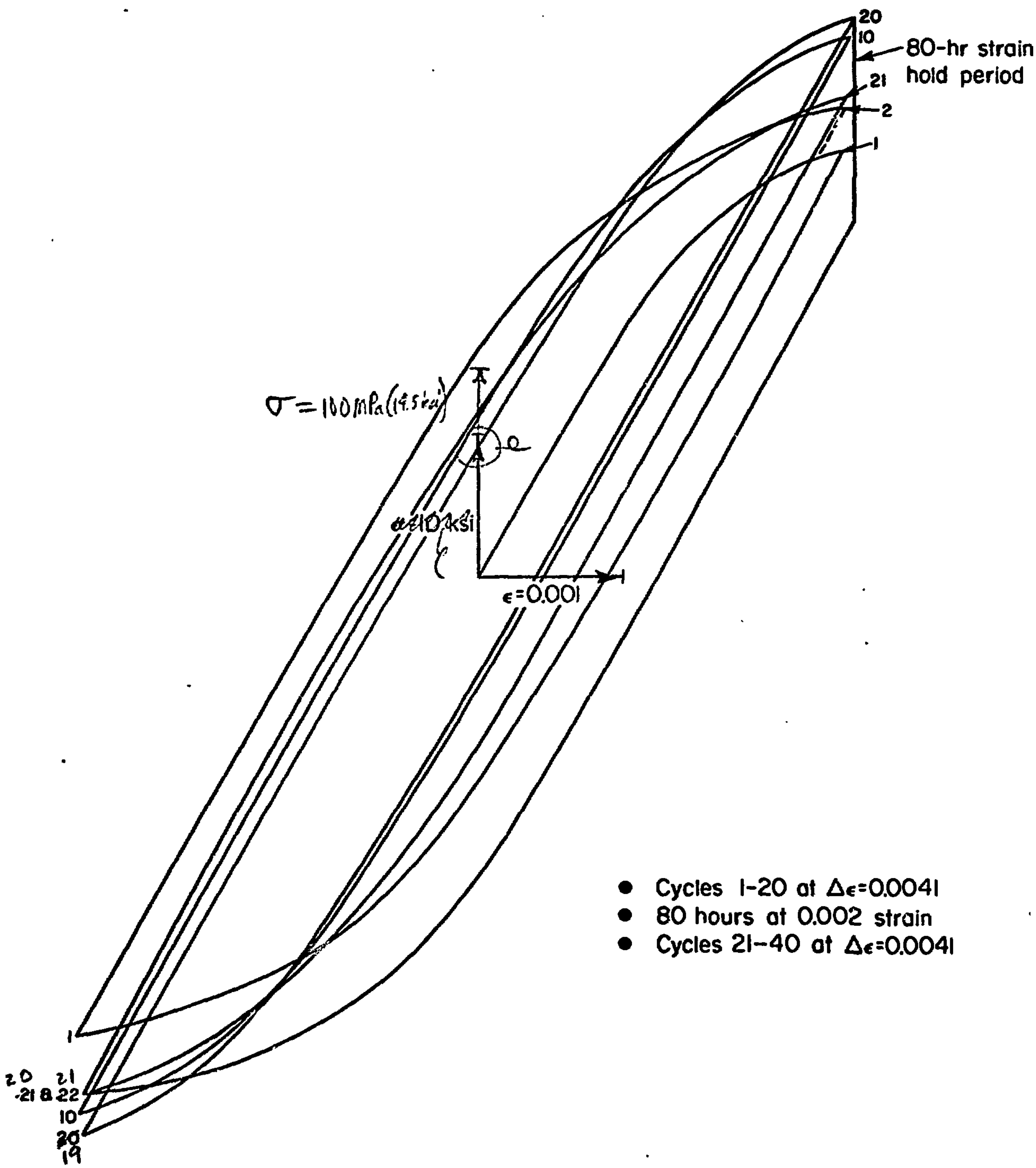

FIGURE 8. EFFECT OF STRAIN HOLD PERIOD ON STRAIN CYCLING DEFORMATION RESPONSE OF ISOTHERMALLY ANNEALED 2¼Cr-1Mo PLATE AT 510°C (950°F), SPECIMEN KB-17

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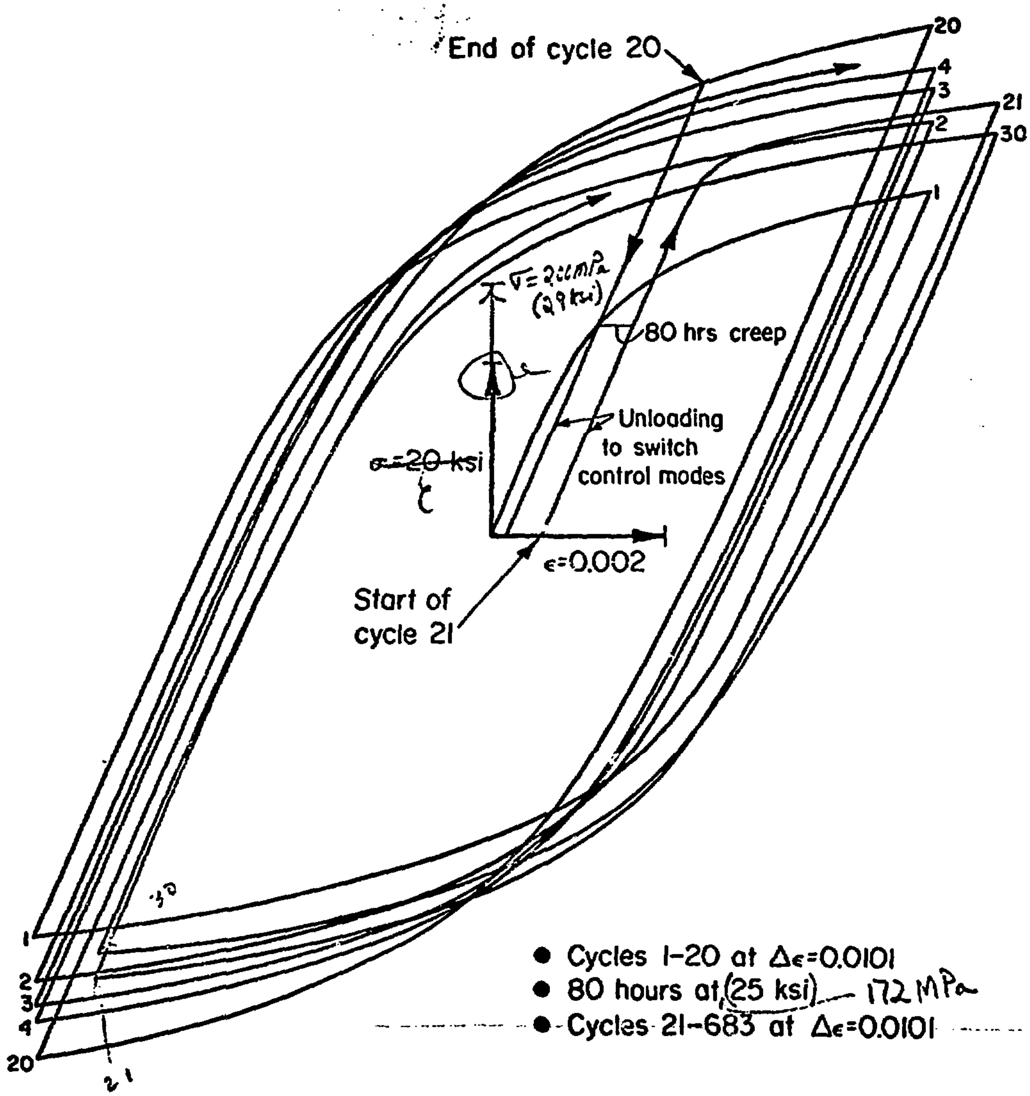

FIGURE 9. EFFECT OF CREEP HOLD PERIOD ON STRAIN CYCLING DEFORMATION RESPONSE OF ISOTHERMALLY ANNEALED $2\frac{1}{4}Cr-1Mo$ PLATE AT 510°C (950°F), SPECIMEN KB-5

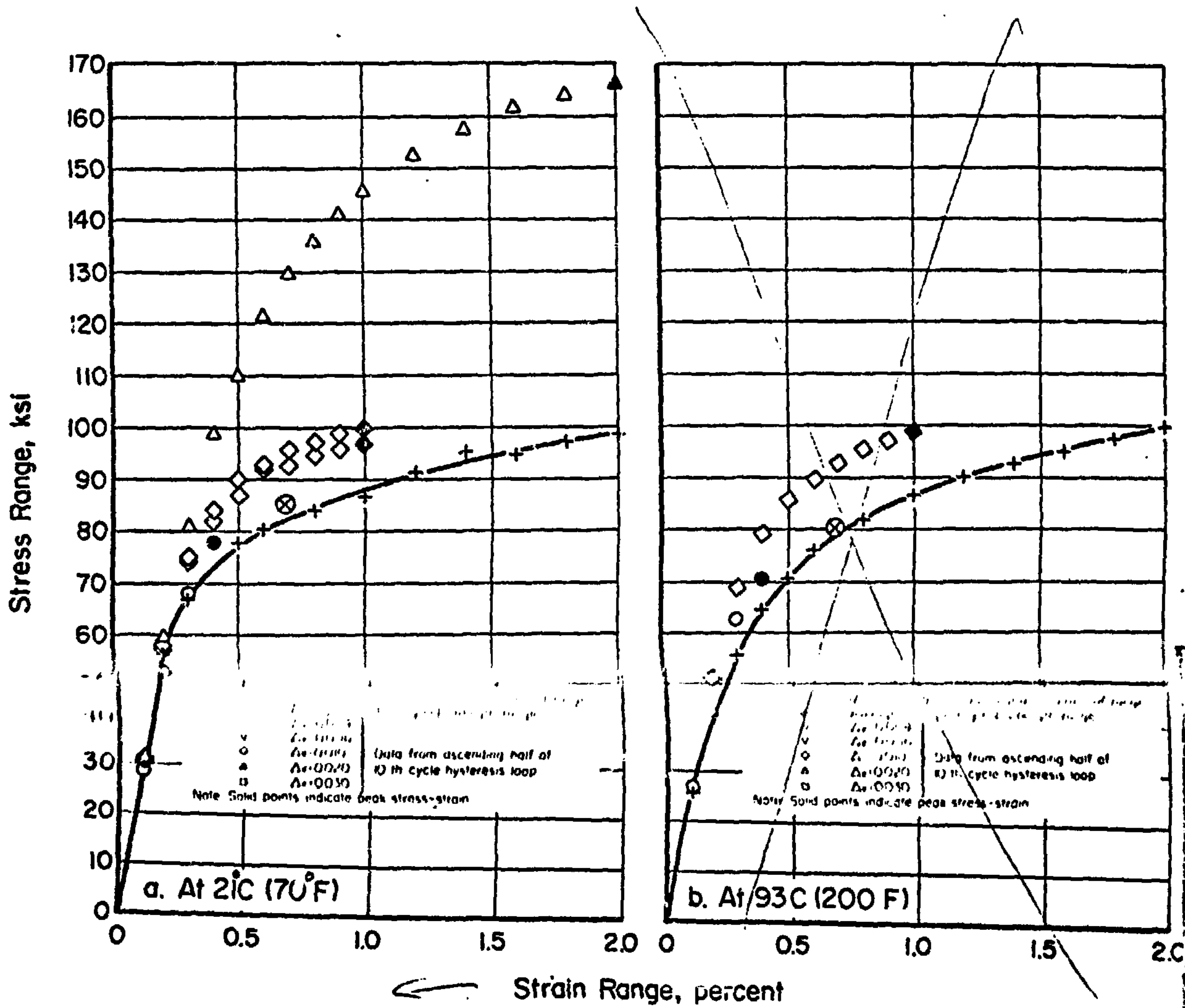

FIGURE 10. COMPARISON OF MONOTONIC AND CYCLIC STRESS-STRAIN RESPONSE OF ISOTHERMALLY ANNEALED 2¼Cr-1Mo PLATE AT A STRAIN RATE OF 8.33 x 10^{-5} SEC^{-1} ~~(0.005 MIN^{-1})~~

22b

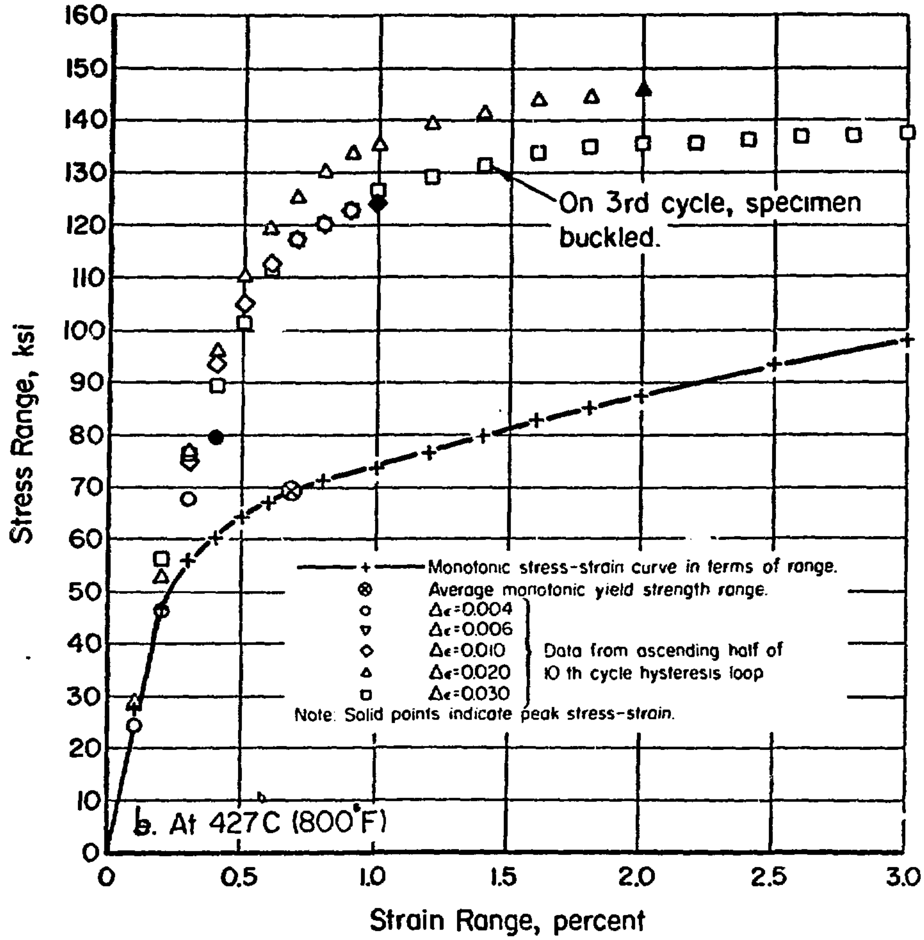

FIGURE 10. (Continued)

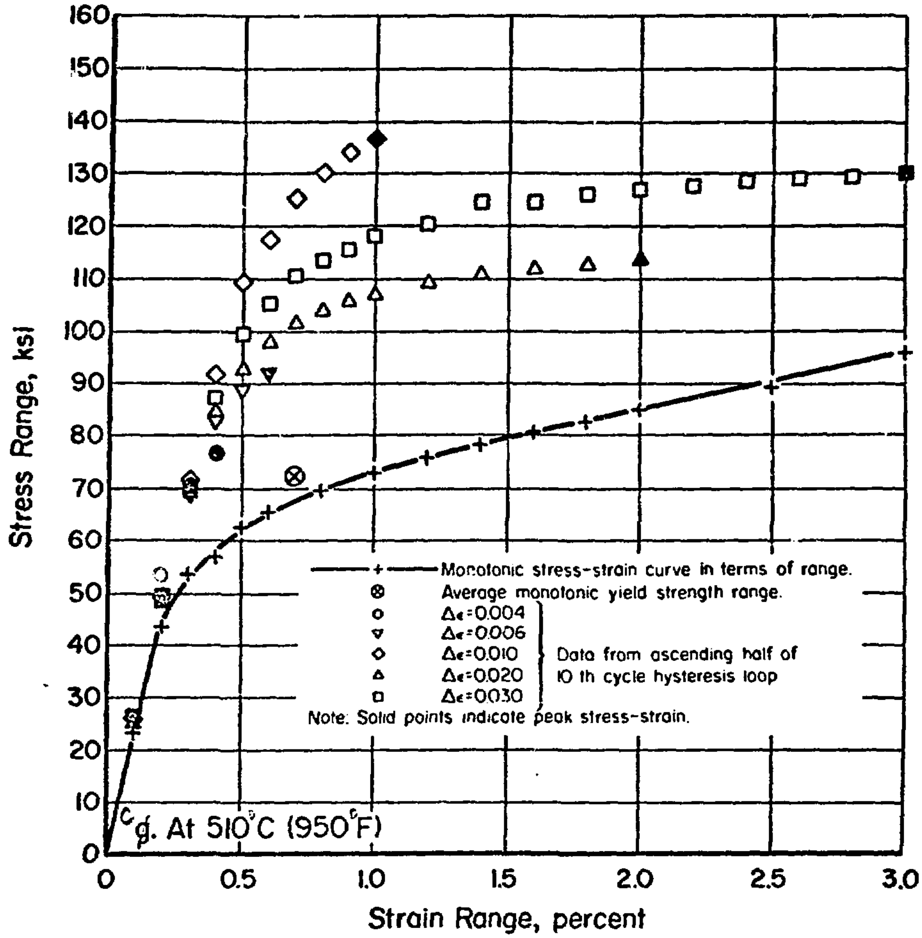

FIGURE 10. (Continued)

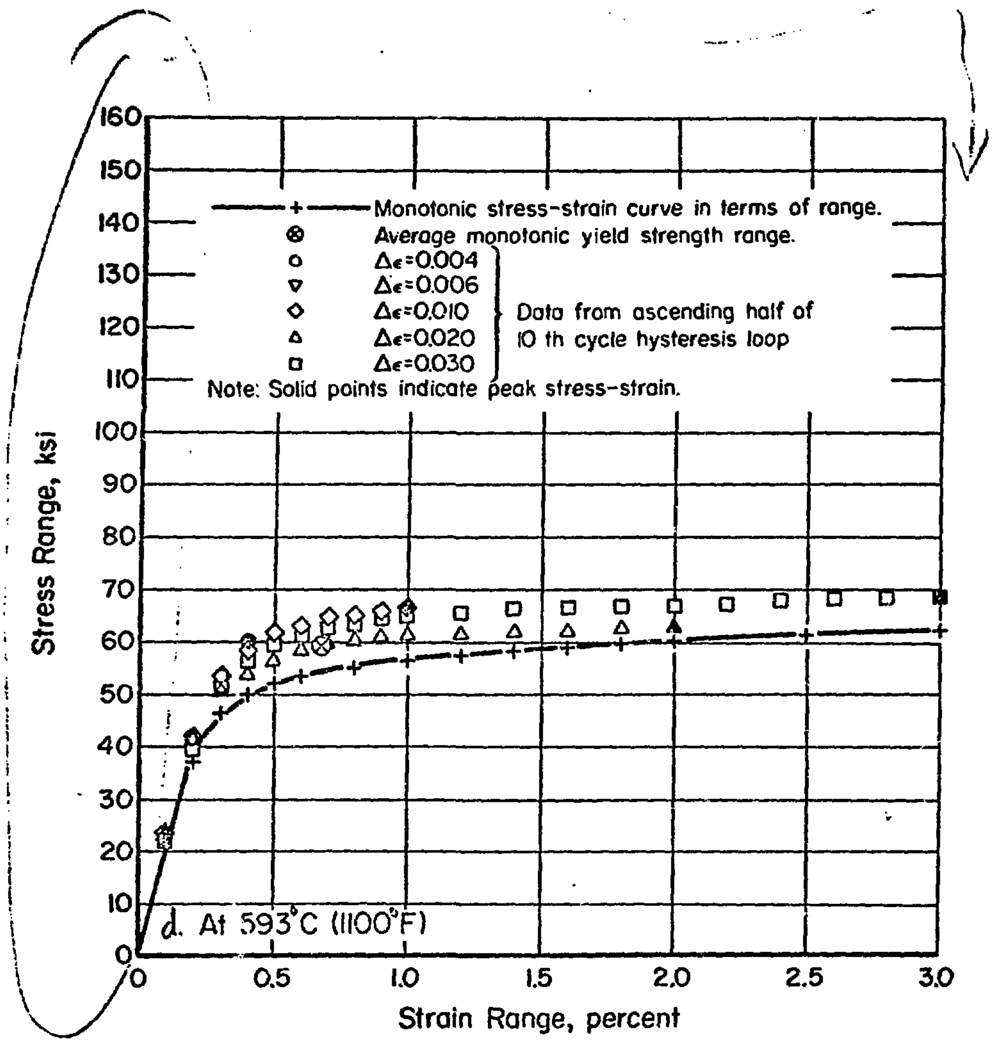

FIGURE ~~14.~~ 10 (Continued)

The solid points in Figure 10 indicate the peak stress range values for the ascending branch of the 10th cycle. As hypothesized by Masing[13] and much later observed by Morrow[14], the cyclic stress-strain curve, defined by the locus of the stable peak stress values, is often geometrically similar to the hysteresis curve but scaled by a factor of 0.5. However, such behavior obviously was not observed in the present study. With the exception of the 2.0 percent strain range at 21°C (70°F), it was noted that the cyclic curves in Figure 10 could be better approximated by translating the corresponding monotonic stress-strain curve along the elastic modulus. The extent of this shift was arbitrarily quantified in terms of an increment in the proportional stress defined by the following ratio:

$$\Delta\sigma_s/\Delta\sigma_o \quad ,$$

where $\Delta\sigma_s$ is the stable stress range at a strain range equal to twice the proportional limit strain range, and $\Delta\sigma_o$ is the corresponding monotonic stress range. Values of this ratio are presented in Table 4. It was found that the monotonic stress-strain range curves could be represented by a power function,

$$\Delta\sigma = K(\Delta\epsilon_p)^n \quad ,$$

where $\Delta\sigma$ is stress range, $\Delta\epsilon_p$ is inelastic strain range, K is a strength coefficient, and n is a strain hardening exponent. Appropriate values of K and n are also given in Table 4. Adopting the above approach to characterizing material stress-strain response, tabulated values of the strain hardening exponent describe both the monotonic and cyclic material strain hardening, whereas tabulated values of the strength coefficient are valid only for describing monotonic stress-strain response. Values of the strength coefficient useful in describing metal cyclic stress-strain behavior are equal to $(\Delta\sigma_s/\Delta\sigma_o) \cdot K$. Note that only one variable, the ratio $\Delta\sigma_s/\Delta\sigma_o$, is required to mathematically describe the cyclic stress-strain behavior of a metal using this approach. Thus, each cyclic stress-strain path can be calculated using the appropriate parameters from Table 4. Values for intermediate strain ranges should be determined by interpolation.

Creep Strain

The influence of strain cycling on subsequent creep behavior at 172 MPa (25 ksi) and 510°C (950°F) is shown in Figure 11. For the three specimens with no

TABLE 4. PARAMETERS FOR DEFINING CYCLIC STRESS-STRAIN RESPONSE OF ISOTHERMALLY ANNEALED $2\frac{1}{4}$Cr-1Mo PLATE

Temperature		Elastic Modulus		Strength Coefficient, K		Strain Hardening Exponent,	Cyclic Hardening Ratio, $\Delta\sigma_s/\Delta\sigma_o$				
°C	MPa	GPa	ksi	MPa	ksi	n	$\Delta\varepsilon = 0.004$	$\Delta\varepsilon = 0.006$	$\Delta\varepsilon = 0.01$	$\Delta\varepsilon = 0.02$	$\Delta\varepsilon = 0.03$
21	70	203	29,500	1,240	180	0.11	1.07	--	1.14	1.35 [a]	--
93	200	191	27,700	1,450	210	0.18	1.15	--	1.19	--	--
204	400	183	26,500	1,660	241	0.26	1.14	--	1.19	--	--
316	600	174	25,200	1,240	180	0.17	1.23	--	1.36	1.41	--
427	800	170	24,700	1,430	207	0.20	1.29	--	1.51	1.55	1.45
482	900	161	23,400	1,850	269	0.22	1.33	--	1.36	1.60	1.71
510	950	167	24,200	1,440	209	0.21	1.31	1.35	1.37	1.42	1.39
538	1000	152	22,100	1,160	168	0.17	1.21	--	1.29	1.39	1.32
593	1100	146	21,200	579	84	0.08	1.16	--	1.16	1.10	1.12

(a) Branch of hysteresis loop does not adequately model metal cyclic stress-strain curve.

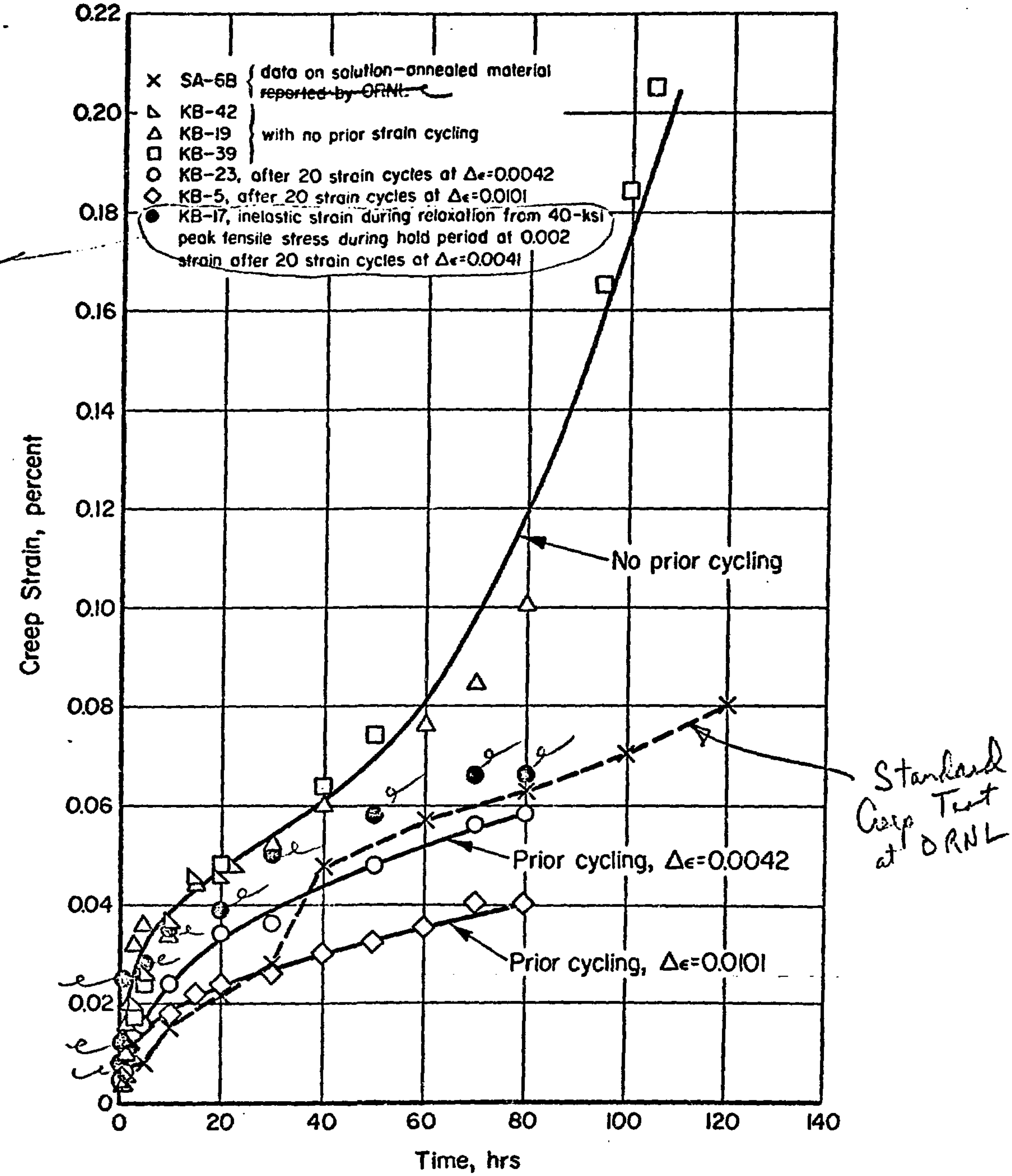

FIGURE 15. CREEP BEHAVIOR OF ISOTHERMALLY ANNEALED 2¼Cr-1Mo PLATE AT 172MPa (25 ksi) AND 510°C (950°F)

prior cycling, an average curve is shown. This curve fell above that from a standard creep test for solution-annealed specimen from the same plate that was conducted at ORNL. (See dashed curve in Figure 11.) The creep rate also increased after about 50 to 60 hours.

Prior strain cycling increased the creep resistance or decreased the creep rate. The creep resistance was greater at $\Delta\epsilon = 0.01$ than at $\Delta\epsilon = 0.004$ because of greater cyclic hardening at the higher strain range.

CONCLUSIONS

Based upon the experimental work of this study, nine significant conclusions were reached regarding stress-strain behavior of isothermally annealed 2½Cr-1Mo steel at a strain rate of 8.33×10^{-5} sec^{-1} (0.005 min^{-1}).

(1) Monotonic yield-strength values were similar to those usually reported for this alloy.

(2) Monotonic strength decreased with increasing temperature from 21 to 593°C (70 to 1100°F), but showed intermediate peaks in strength at 260 and 482 C (500 and 900°F).

(3) Decreasing the strain rate to 8.33×10^{-6} sec^{-1} decreased the yield strength at 593°C (1100°F), but had little effect at lower temperatures.

(4) Cyclic strain hardening was observed at temperatures between 21 and 538°C (70 and 1000°F), and gradual cyclic softening was observed at 593°C (1100°F).

(5) For strain ranges near 0.6 percent and greater at 482, 510, and 538°C (900, 950, and 1000°F), initial cyclic hardening was followed by subsequent cyclic softening.

(6) Monotonic stress-strain range response was quantitatively described by a power function

$$\Delta\sigma = K(\Delta\epsilon_p)^n$$

at temperatures from 21 to 593°C (70 to 1100°F).

(7) The ascending portion of the stress-strain path for the 10th cycle provided one measure of stable cyclic stress-strain behavior at temperatures between 21 to 593°C (70 to

1100°F), and it was quantified through a translation of the monotonic stress-strain curve along the elastic slope.

(8) Creep, stress relaxation, and thermal exposure hold periods significantly reduced the amount of cyclic hardening at 510°C (950°F).

(9) Strain cycling increased the subsequent creep resistance at 510°C (950°F).

ACKNOWLEDGEMENTS

The experimental work described in this report was conducted in the Structural Materials Laboratory at Battelle's Columbus Laboratories (BCL) and was sponsored by Oak Ridge National Laboratory (ORNL), operated by Union Carbide Corporation for the U.S. Energy Research and Development Administration (formerly the U. S. Atomic Energy Commission) under Subcontract No. 4004. Messrs. N. D. Frey and H. J. Malik of BCL were responsible for actual performance of the experiments.

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