ROOM-TEMPERATURE CREEP PROPERTIES OF ALUMINUM EC CONDUCTOR WIRE

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ROOM-TEMPERATURE CREEP PROPERTIES OF ALUMINUM EC CONDUCTOR WIRE

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SUMMARY

In the design of overhead electrical transmission lines it is necessary to include the effects of creep. There are two aspects to the creep of these transmission lines which are of interest: one is the long time creep behavior when the cable is expected to be in service for a number of years under various weather and loading conditions; the other is the short time transient creep behavior which has significance when the lines are first constructed and the cable must be strung or "sagged in" in such a manner that equal tension is maintained throughout the line. This thesis is concerned with the short time (100 hours) room temperature transient creep behavior of a typical hard drawn EC grade aluminum conductor wire. Creep strain as a function of time and stress were determined by using a constant load test machine. Efforts were made to hold other variables such as preloading period and speed of loading constant.

The experimental data were fitted to a power function and compared to similar work. Theories of the effects of cold work on creep properties are contradictory. The experimental data of this study seem to suggest that cold work has an improving effect on short time creep properties.

of solids under constant load or stress. Historically, the study of creep can be traced back to the early nineteenth century. Unlike many other branches of applied physics, there was no satisfactory general theory developed early, indeed, this still remains the most elusive problem of all.

Creep Test

The uniaxial stress test has been the most used in creep testing. Although in actual cases there will rarely be situations where the stress applied to a part is constant in time and uniaxial, it is nevertheless true that design data can be taken most conveniently from tests made under uniaxial stresses.

Typical uniaxial tensile creep test curves show four stages of creep behavior as shown in Figure 1. The first stage, from 0 to A, called ε_o, consists of initial strain which may be either entirely elastic or partially elastic and partially plastic. During the second stage or so called primary stage, A to B, the rate of creep gradually decreases because the effects of strain hardening is greater than that of annealing. These two effects are in equilibrium during the third stage, B to C,

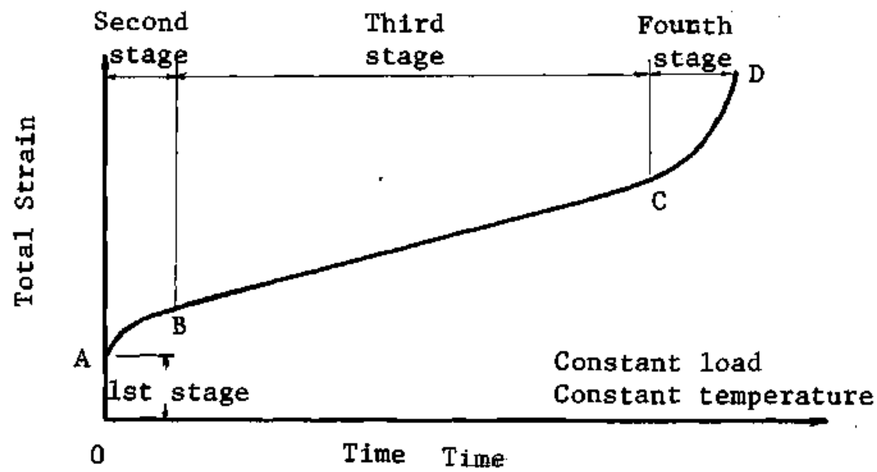

Fig. 1. Typical Uniaxial Tensile Creep Curve

giving essentially a straight line of constant minimun creep rate. The creep rate rises during the fourth stage, to fracture at D, partially because the reduced cross-sectional area causes an increase in stress. Since the testing temperature is relatively low and testing time is short, in this study, only the primary stage of creep is expected.

Tests are usually constant load rather than constant stress. When strains are small, as in the primary stage, the difference is not of importance.

<u>Temperature Effect</u>

A considerable volume of literature can be found in the creep of metals although relatively few deal with lower temperature creep. Temperature plays a very important role in creep properties. Dorn [1] and his coworker have identified that in the temperature range from 250°K to 380°K cross slip dominates the creep mechanisms of polycrystalline aluminum. The following review will be concerned with this intermediate temperature range only.

<u>Creep Measurement</u>

Creep data are usually scattered. This phenomenon is attributed to the sensitiveness of variations in specimen preparation and history as well as experimental techniques. Experimentally, measuring initial strain, ε_o, has been a difficult problem. This "instantaneous" deformation depends on speed of loading the specimen [2]. If rapid loading is attempted inertia effects in the loading member and even in the material make the readings of uncertain significance. If loading is accomplished smoothly over a period of time, then the initial deflection actually contains some creep and the slope of the subsequent curve is affected. Axiality has been another problem. Bending stress due to nonaxiality of loading the specimen can also cause error.

Analysis of Creep Curves

Numerous mathematical formulae have been proposed to represent the creep curves. Yet, it is interesting to note that even though empirical time-laws were recognized and used more than a half century ago, we are still uncertain about their physical significance.

Since this thesis is concerned with short time creep properties, only tensile test curves of primary stage creep will be reviewed.

Phillips [3], in 1905, described the creep of various metals as a logarithmic function of time.

$$\varepsilon = a + b \log t \qquad \text{Eq. 1}$$

where ε = engineering strain

t = time

a,b = material constants

Andrade [4] established his famous one-third power law as

$$1 + \varepsilon = (1 + \varepsilon_o)(1 + at^{1/3})e^{bt} \qquad \text{Eq. 2}$$

where ε_o = initial engineering strain

This equation represent a special case of what is called parabolic creep.

Other authors [5,6] have proposed a generalized power function

$$\varepsilon = \varepsilon_o + at^m \qquad \text{Eq. 3}$$

where m = material constant

This type of equation is universally recognized as a good representation for the transient creep curves of metals [e.g.28,29,30]. Russian workers e.g. Oding [27] had been able to justify this form of equation based on dislocation theory.

Crussard [7] analyzed the shape of transient creep curves of various materials and pointed out, except in a few cases, that most materials can be well represented by Eq. 3 where $0 < m < 1$, $m = 0$, or $m < 0$ these being called parabolic, logarithmic or hyperbolic, respectively. In his conclusion, for commercial aluminum without any amount of cold work, m varied from 0.19 to 0.37 in the temperature range of 100°C to 298°C increasing slightly with stress under moderate loads and no dependence on stresses under strong loads. The coefficient "a" of Eq. 3 varied as the 10th power of stress for room temperature aluminum under high loads. In general, the exponent m seems to be able to characterize the rate at which creep rate slows down. It should have a physical meaning relating to the ability of the material to strain-harden, i.e., the smaller m, the more the material is of a strain-hardening type and the more creep will be resisted. Garofalo's Survey [31] indicated that, for a variety of materials including aluminum, m might vary from 0.03 to nearly 1.0 and seemed to depend both on temperature and stress in the temperature range from 0.2 Tm to 0.7 Tm of the materials where Tm is the absolute temperature of the melting point.

Sturm and co-workers [8] tested several commercial aluminum alloys, annealed and cold worked, as well as electrical conductor wires and used an equation $\ln \varepsilon = \ln \varepsilon_1 + k \ln t$ to express the creep curves. k was found to be about 0.20 for high purity annealed aluminum alloys and from 0.26 to 0.30 for cold worked alloys. For electrical conductor wires k ranged from 0.25 to 0.26 with ultimate tensile strength in the range from 26 ksi to 27 ksi. This is about the same strength as the material used in this investigation. Once again, k was found to be independent of stress. A closer look at the values of k and m revealed that m should be slightly higher than knfor given creep data when $\varepsilon > \varepsilon_1$, where ε_1 is the engineering strain corresponding to t = 1.

Effects of Specimen Diameter and Gage Length

Usual creep specimens have a gage length lying between two to five inches with the largest cross-sectional dimension being of the order of 0.5 inch. Relatively little has been published on the effect of specimen diameter on creep properties and in some cases the results are contradictory [9,10,11]. However, Kramer [12] demonstrated that in room temperature creep tests aluminum specimens with smaller diameter had more rapid creep rates than larger ones. This was because the surface layer stress which impede dislocation motion relaxed during creep and a small diameter specimen obviously had a larger surface to volume ratio and thus a larger surface effect. Relatively little is known about the effect of gage length. A tendency to decreased rupture time and increased creep rate was noted when the length/diameter ratio of the tensile specimen was increased [2,26].

Effect of Prestrain or Cold Work

The majority of published work [13] on prestrain effects in metals and alloys has been to illustrate the influence of work hardening and substructure formation on creep properties. In general, there are two opposing effects of prestrain: namely work hardening or substructure formation giving rise to an increase in creep strength, the cavity formation at grain boundaries giving rise to decrease in creep strength.

Workers [14,15,16] using density measurement technique found that, under low or intermediate stresses, nucleation of grain boundary cracks in primary creep are negligible at room temperature. Others [17,18,31] have also shown that the effect of cold working prior to room temperature creep testing will improve creep properties such as minimum creep rate and creep life as long as no recrystallization occurs.

Burghoff and Blank [19] tested annealed and cold drawn (84%) copper wire and showed that at lower temperature the creep resistance of the drawn material was approximately three times that of the annealed material. As the test temperature increased, this difference was reduced due to progressive recrystallization of the drawn material.

However, others [20] have shown that cold work can nucleate grain boundary cracks in certain alloys and reduce subsequent creep life. The room temperature creep data obtained by Sturm, et al. [8] demonstrated that cold worked material have a greater creep slope than the annealed ones. Tapsell [22] also concluded that hard drawn aluminum and copper specimens failed earlier than annealed ones at relatively higher stresses. So the effect of prior plastic prestrain on creep is not as straight-forward as has been supposed in many papers. Williams [13] suggested that the microstructural effects of this prestrain will be the controlling factor. The initial microstructure of the system considered is of prime importance since the location of the relevant second phase particles distributed randomly or the absence of those particles (high purity metal or single phase alloy) might increase creep life due to the lack of grain boundary damage. If the structure is such that most of the second phase is present at grain boundaries then the reverse could be true. Similarly, the prestrain condition, i.e. low or high imposed strain rate, low or high temperature or stress, could affect the location of the prior damage.

Purposes of This Investigation

This investigation is an experimental study of the primary stage creep characteristics of hard drawn high purity aluminum wires which are used in overhead power transmission lines. A creep machine was designed and constructed for use in this investigation. Heavily cold worked wire specimens were tested on the creep machine and subjected to different weights hanging on them. Data taken were strain as a function of time. These data were analyzed and fitted into the power function Eq. 3

$$\varepsilon = \varepsilon_o + at^m$$

Values of "a" and m were calculated and compared to those previously obtained in the literature cited.

It is also the purpose of this investigation to evaluate the performance of this machine.

Efforts are made to minimize the influence of speed of loading on the creep measurements.

CHAPTER II

EXPERIMENTAL APPARATUS, MATERIAL, AND PROCEDURE

General Description of the Test Machine

A nine foot tall tensile test machine was designed and constructed as shown in the photograph of Fig. 2 and in the diagram of Fig. 3. Test wire was hung through a long tube and subjected to a constant load. The amount of elongation of the wire as a function of time was recorded.

The machine consists of a 2-in ID × 3-in OD × 80-in long aluminum tube mounted on the plate of a 24-in × 24-in × 28-in all welded steel frame which rests on its four legs. The upper end of the machine is a Jacobs chuck screw fastened to a hollow stud which in turn is fixed from its side by a smaller screw through the tube wall. The test wire is gripped by the chuck and passes through the middle of the stud.

The lower grip is shown in Fig. 4. By turning the screw inward, one of the two clamps is caused to advance and thus grip the wire by the grooved surfaces of the two clamps. A circular plate is employed to seal the bottom so that the clamps do not have any vertical motion relative to the wire. The grip can be slid into the tube from the lower end and secured by sliding a pin which limits its travel 9/16 inch before it reaches its lowest position. This 9/16 inch is the maximum range the machine can be used to measure the vertical displacement of the wire.

Extending downward from the grip are two threaded rods. These rods are used to carry the mainload assembly. Also, a micrometer is installed ...eam extended from the left rod.

Fig. 2. Photograph of the Creep Test Machine

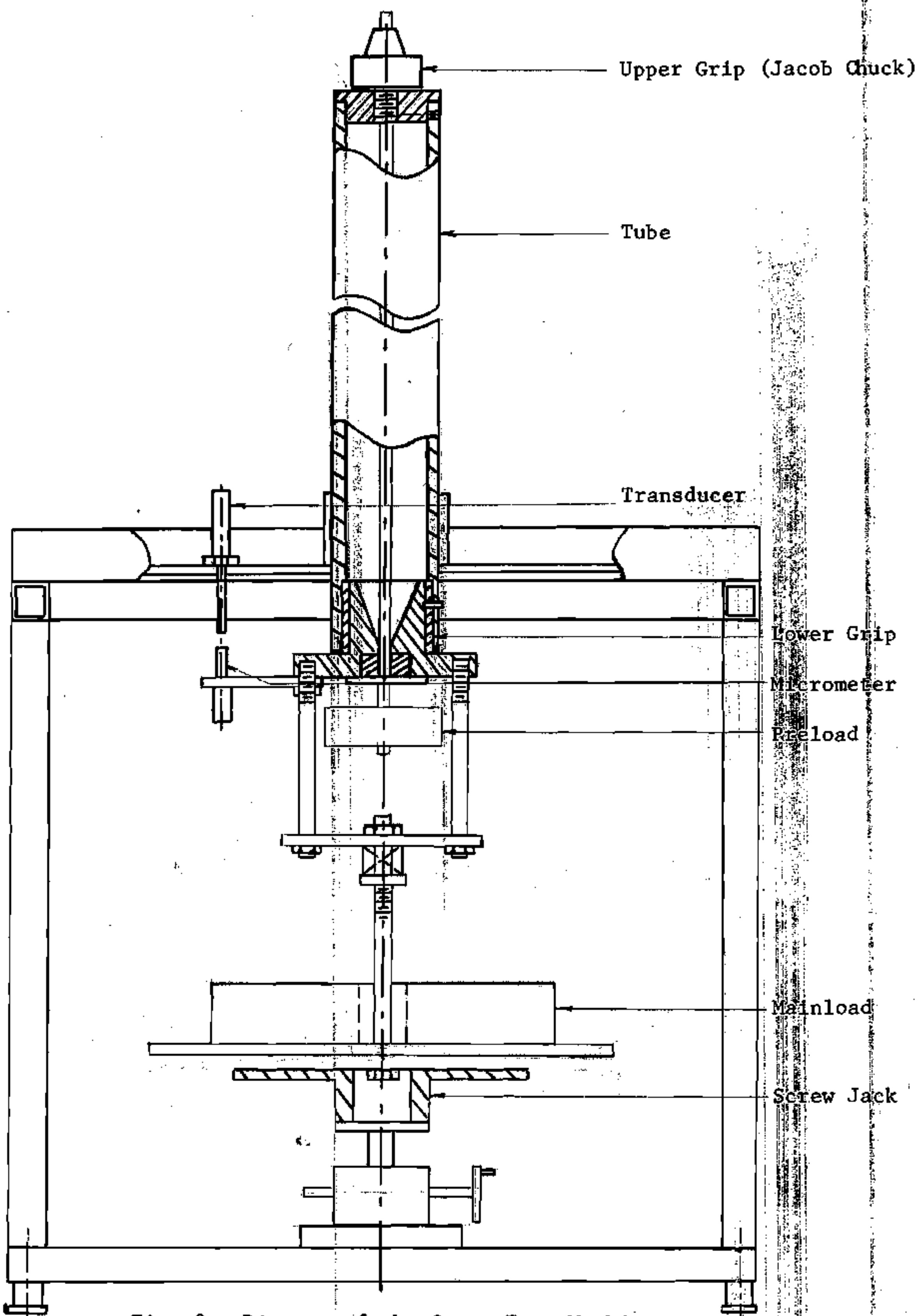

Fig. 3. Diagram of the Creep Test Machine

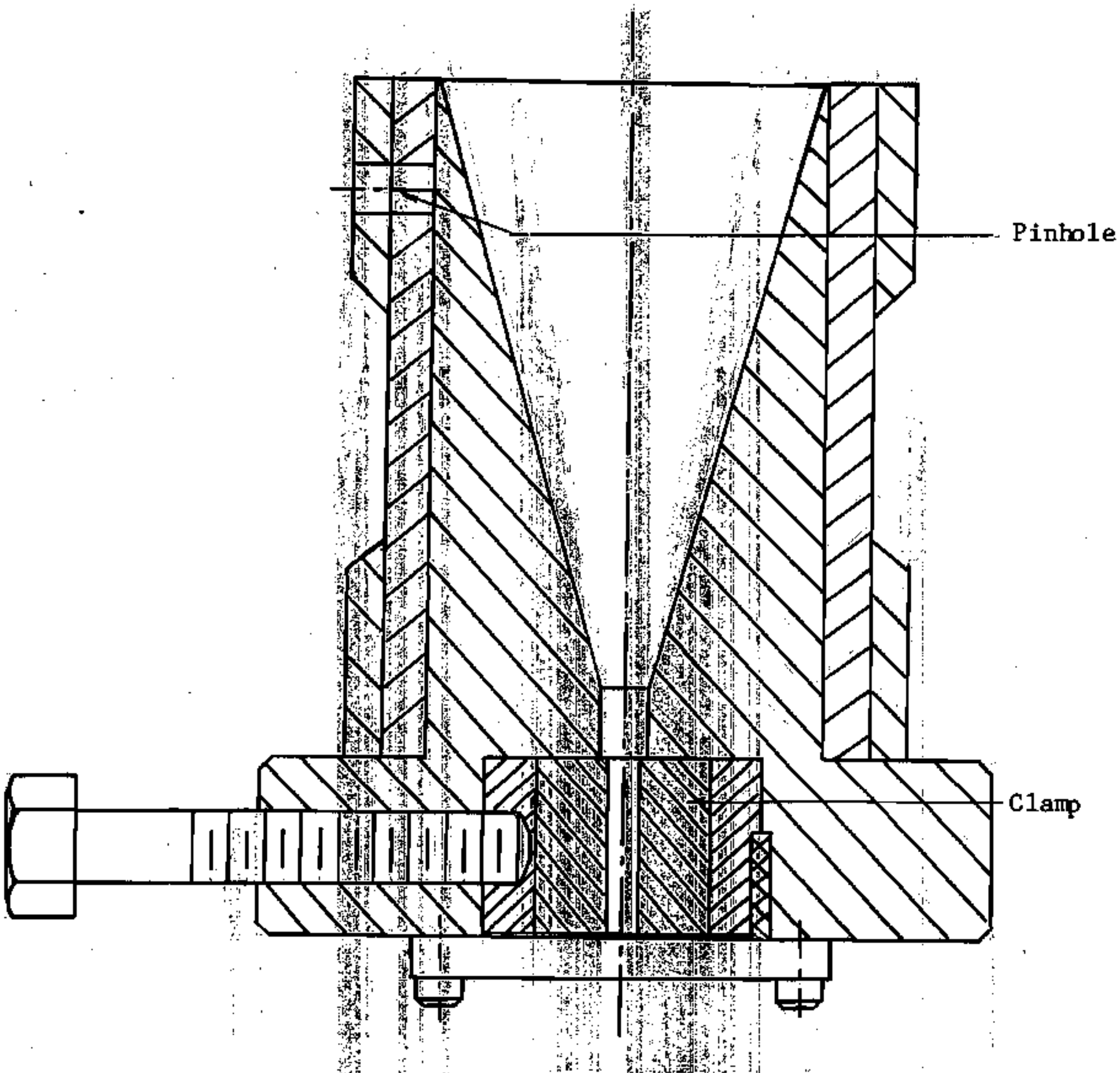

Fig. 4. Diagram of the Lower Grip

on a beam extended from the left rod. The micrometer works either as a calibrator when the grip is stationary or as a indicator of the displacement of the lower grip when the test is in progress.

The transducer used in this investigation is a Daytronic model DS-200 and has a linear range of ±0.1-in. It is a linear variable differential transformer transducer with a movable core which rest against the micrometer head. The original head of the transducer was not long enough to reach the micrometer head and hence replaced by a longer brass rod. With this arrangement, as the test wire extends, the displacement of the lower grip is detected by the transducer through the displacement of the micrometer. This motion is translated into an electrical signal which is amplified by a Daytronic model 300 D transducer amplifier indicator with a type 73 Differential Transformer Plug-in unit. This transducer-amplifier system is capable of measuring a displacement of 0.00001 inch.

A Heath model EUW20A servo-recorder was employed in order to establish a permanent record of the creep test. The output of the Daytronic amplifier is input to the recorder. The chart of the recorder can operate over a range of speeds from 0.5-in/hr. to 120-in/min. This higher chart speed allow the creep test to be investigated more closely at the beginning of the test.

A total of 230 lbs of lead was used as dead weights in this investigation. The lead was recast as preload and main loads as shown in Fig. 1. The preload weight was 33.5 lbs.

Material

The specimens were provided in the form of coils of wire by the Southwire Co., Carrolton, GA. These 0.133-inch diameter aluminum wires were hard-drawn electric conductor grade aluminum wires with a purity up to 99.45%. The wires were cold drawn from a 0.318-inch in diameter rod and thus had been cold worked 81%. The physical dimensions and properties of the wires were all the same except that they came from different drawing drums during their manufacturing processes and were designated as No. 7, 8, 13, 16 and 18. Tensile properties were obtained with a standard Instron Tensile Tester. The resulting ultimate tensile strength was about 28,400 psi with a yield strength of 24,400 psi. The elongation was only 2% as shown in Figure 5. Creep specimens were cut from these wires to a length 90-inchs of each and used in its natural form, i.e. no straightening was done before being tested.

Experimental Procedure

The wire was put through the tube and gripped in the upper chuck. The lower grip was then slid into the tube from the lower end and temporarily secured by the pin. Clamps were inserted into the slot of the lower grip with the circular plate screw-tightened to seal the bottom of the grip. A preload was then put on by passing the wire through the center hole of the preload weight and bending into a hook. At this stage, with the lower grip resting on the pin in the pinhole of the tube wall and its clamps in the open position, calibration of the transducer-amplifier-recorder system was done. The micrometer attached to the lower grip was used to mechanically simulate a displacement from which the transducer-

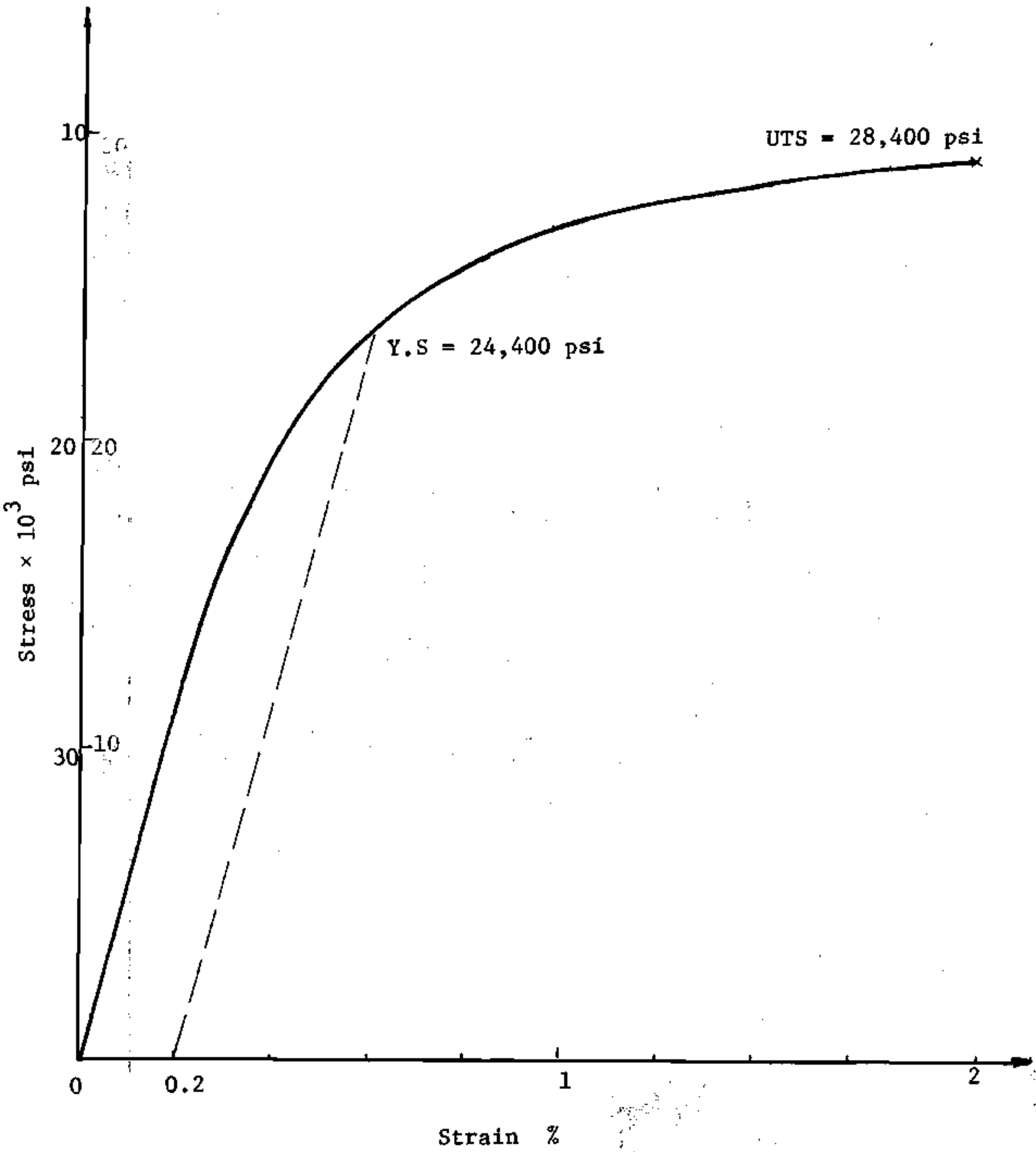

Fig. 5. General Tensile Characteristics of the Specimen

amplifier-recorder system was calibrated. This calibration test showed that the displacement measuring system had a sensitivity of 0.00001 inch. Recalibration of the system was performed each time a new test was performed to assure proper function of the system.

After calibration, the main-load carrying pan was assembled with the screw jack handwheeled to its upper position to support the load of the pan. Then, the main loads were put on the pan. Of special importance was to make sure that the lower grip was free of the load of the main load carrying system, otherwise partial load would be added to the wire before the test started. The grip was tightened to the wire at its uppermost position by turning the screw inward. The amplifier and recorder were quickly set to a desired reading. Then the handwheel screw jack was lowered slowly and gradually the main load was hung on the wire and the test started. Each test was conducted over a time period of 100 hours. Constant checks of the recording systems were made to inspect any malfunctioning of the system.

All test were conducted at a room temperature of about 70°F. The prestraining period was about ten minutes for each test.

Three sets of constant-load creep tests were conducted on each of the five different numbered specimens. The first set of tests, designated Test A, used a mainload of 72.5 lbs. The weights of the lower grip and the mainload carrying assembly, together weighing seven and a half pounds, were also carried by the specimen during testing. Adding up these weights along with the preload and the mainload, Test A was run at a total of 114 lbs, equivalent to a stress level of 8,200 psi, about one-third the yield strength of this particular wire. Test B, similarly, with a total of 173 pounds, was run at a stress level of 12,500 psi, which is about one-half of its yield strength. Test C, with 210 pounds total, was conducted at 15,100 psi, about two-third of its yield strength.

CHAPTER III

RESULTS

Creep Test Data

The results of Test A are given in Table 1 and the graph of Figure 6. Average values and standard deviations* of the strain data are calculated and also listed in the table. The strains, in Figure 7, tend to level off only after a short period of time because of the relatively low creep stress. Three of the five data sets fall close together while the other two spread widely above and below.

Table 2 and Figure 7 are the results of Test B. The same phenomenon of data scatter is observed in this test except the scatter is somewhat wider than that of Test A.

Similarly, Table 3 and Figure 8 are results of Test C. The strain data seems symmetric about their average values and stress effects are more pronounced.

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* Standard Deviation s

$$s = \left(\frac{\sum_{n=1}^{N} (\varepsilon - \bar{\varepsilon})^2}{N - 1} \right)^{\frac{1}{2}}$$

where N = number of observations

ε = 5 in our case

$\bar{\varepsilon}$ = Average strain Value

Table 1. Results of Test A

Gage length = 80.82 inch Weight = 114 lbs Specimen dia. = 0.133 inch

Time (min)	Strain × 10^{-4} Specimen No. 7	8	13	16	18	Average	Std. Dev
1	8.72	8.21	8.72	10.98	8.78	9.08	1.09
2	8.83	8.28	8.80	11.04	8.88	9.17	1.08
3	8.93	8.33	8.86	11.10	8.95	9.23	1.07
4	9.04	8.37	8.91	11.15	9.02	9.30	1.07
5	9.09	8.41	8.95	11.19	9.09	9.35	1.07
6	9.11	8.45	9.00	11.22	9.14	9.38	1.06
7	9.14	8.48	9.02	11.25	9.16	9.41	1.07
8	9.19	8.51	9.04	11.27	9.24	9.45	1.06
9	9.22	8.55	9.07	11.28	9.27	9.48	1.05
10	9.24	8.56	9.09	11.30	9.29	9.50	1.05
12	9.28	8.61	9.13	11.33	9.32	9.53	1.04
14	9.33	8.65	9.16	11.36	9.38	9.58	1.04
16	9.35	8.71	9.18	11.40	9.42	9.61	1.04
18	9.38	8.72	9.21	11.43	9.47	9.64	1.04
20	9.43	8.74	9.26	11.45	9.49	9.67	1.04
24	9.44	8.65	9.30	11.49	9.54	9.68	1.07
28	9.50	8.84	9.33	11.53	9.57	9.75	1.03
34	9.56	8.90	9.39	11.60	9.65	9.82	1.04
40	9.63	8.91	9.45	11.64	9.72	9.87	1.04
50	9.69	9.00	9.50	11.71	9.82	9.94	1.04
60	9.75	9.06	9.56	11.77	9.89	10.00	1.03
75	9.82	9.13	9.60	11.93	10.00	10.09	1.08
90	9.90	9.18	9.69	12.03	10.03	10.17	1.09
120	10.00	9.29	9.77	12.13	10.15	10.27	1.09
150	10.07	9.40	9.84	12.18	10.23	10.34	1.07
180	10.08	9.48	9.94	12.21	10.24	10.39	1.06

(Cont'd)

Table 1. Results of Test A (Cont'd)

Gage length = 80.82 inch Weight = 114 lbs Specimen dia. = 0.133 inch

Time (min)	Strain × 10^{-4} Specimen No. 7	8	13	16	18	Average	Std. Dev.
240	10.17	9.48	10.06	12.26	10.35	10.46	1.06
300	10.18	9.60	10.07	12.35	10.43	10.52	1.06
360	10.18	9.70	10.11	12.42	10.50	10.58	1.07
420	10.29	9.70	10.18	12.48	10.55	10.64	1.07
480	10.29	9.70	10.25	12.51	10.60	10.67	1.08
600	10.42	9.94	10.29	12.61	10.62	10.77	1.05
750	10.42	10.08	10.38	12.70	10.72	10.86	1.05
900	10.73	10.15	10.43	12.77	10.80	10.98	1.04
1200	10.75	10.22	10.58	12.96	10.95	11.09	1.08
1500	10.79	10.28	10.70	13.14	11.00	11.18	1.13
1800	10.98	10.28	10.78	13.21	11.07	11.26	1.13
2100	11.07	10.33	10.83	13.26	11.17	11.33	1.13
2400	11.15	10.36	10.86	13.30	11.25	11.38	1.13
3000	11.35	10.42	11.00	13.50	11.40	11.53	1.15
3600	11.37	10.45	11.12	13.57	11.41	11.58	1.17
4200	11.37	10.48	11.12	13.61	11.48	11.61	1.16
4800	11.37	10.51	11.28	13.66	11.53	11.67	1.18
5400	11.41	10.53	11.29	13.70	11.56	11.70	1.19
6000	11.44	10.55	11.47	13.73	*	11.80	1.36

* recorder failure

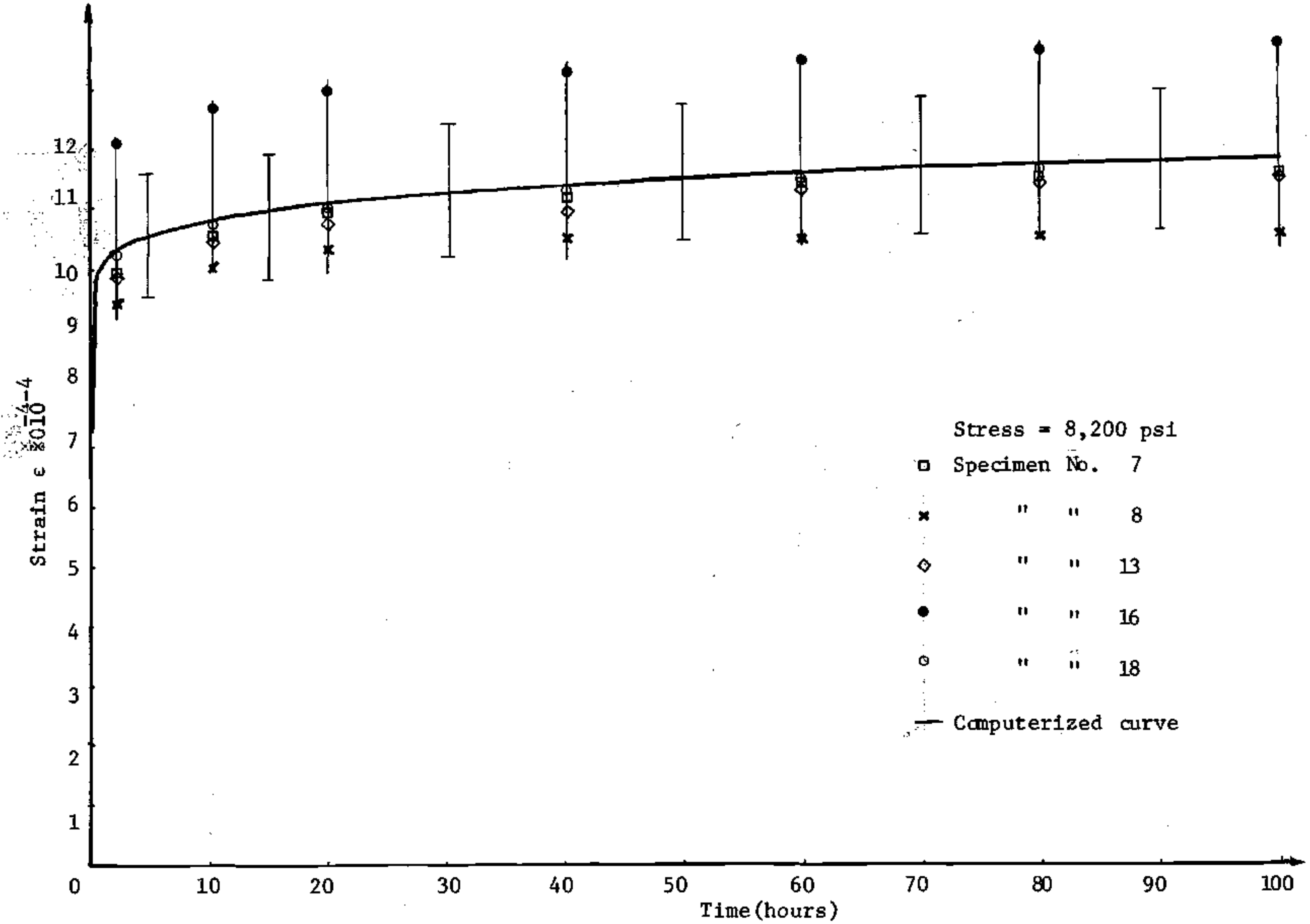

Fig. 6. Results of Test A

Table 2. Results of Test B

Gage length = 80.82 inch   Weight = 173 lbs   Specimen dia. = 0.133 inch

Time (min)	Strain $\times 10^{-4}$ Specimen No. 7	8	13	16	18	Average	Std. Dev.
1	15.08	16.32	11.60	15.95	14.64	14.72	1.87
2	15.27	16.57	11.76	15.99	14.75	14.87	1.87
3	15.40	16.77	11.89	16.02	14.85	14.93	1.87
4	15.48	16.88	12.00	16.05	14.93	15.07	1.86
5	15.57	16.98	12.09	16.07	15.02	15.15	1.85
6	15.63	17.06	12.16	16.09	15.10	15.21	1.85
7	15.75	17.12	12.24	16.12	15.16	15.28	1.84
8	15.76	17.17	12.31	16.18	15.21	15.33	1.83
9	15.82	17.26	12.37	16.21	15.26	15.37	1.84
10	15.85	17.30	12.41	16.25	15.29	15.42	1.84
12	15.94	17.38	12.51	16.30	15.34	15.49	1.83
14	15.99	17.44	12.62	16.36	15.42	15.57	1.81
16	16.07	17.52	12.66	16.39	15.48	15.62	1.82
18	16.12	17.54	12.72	16.44	15.52	15.67	1.80
20	16.17	17.62	12.74	16.47	15.57	15.71	1.82
24	16.25	17.70	12.84	16.52	15.61	15.78	1.81
28	16.33	17.78	12.97	16.58	15.70	15.87	1.79
34	16.43	17.89	13.05	16.69	15.79	15.97	1.80
40	16.48	17.98	13.13	16.74	15.89	16.04	1.80
50	16.58	18.05	13.23	16.82	15.96	16.13	1.79
60	16.65	18.15	13.35	16.95	16.05	16.23	1.78
75	16.74	18.28	13.46	17.06	16.21	16.35	1.79
90	16.85	18.38	13.57	17.16	16.30	16.45	1.78
120	16.98	18.49	13.73	17.25	16.43	16.58	1.76
150	17.07	18.63	13.88	17.35	16.58	16.70	1.75

(Continued)

Table 2. Results of Test B (Cont'd)

Gage length = 80.82 inch Weight = 173 lbs Specimen dia. = 0.133 inch

Time (min)	Strain × 10^{-4} Specimen No. 7	8	13	16	18	Average	Std. Dev.
180	17.25	18.77	14.00	17.44	16.68	16.83	1.76
240	17.33	18.89	14.14	17.63	16.89	16.98	1.75
300	17.45	19.02	14.23	17.90	17.05	17.10	1.78
360	17.52	19.14	14.31	17.92	17.19	17.26	1.78
420	17.62	19.25	14.39	18.00	17.19	17.29	1.79
480	17.62	19.35	14.48	18.07	17.32	17.37	1.79
600	17.69	19.53	14.64	18.19	17.47	17.50	1.79
750	17.85	19.69	14.81	18.31	17.63	17.65	1.78
900	18.00	19.82	15.03	18.45	17.71	17.80	1.75
1200	18.18	20.04	15.18	18.56	17.94	17.98	1.76
1500	18.47	20.25	15.26	18.71	18.06	18.17	1.81
1800	18.56	20.37	15.35	19.13	18.19	18.32	1.85
2400	18.65	20.58	15.64	19.15	18.47	18.50	1.80
3000	18.68	20.74	15.80	19.33	18.77	18.66	1.80
3600	18.88	20.86	15.94	19.45	18.93	18.81	1.79
4200	19.13	20.97	16.07	19.45	19.03	18.93	1.78
4800	19.15	21.13	16.12	19.56	19.15	19.02	1.82
5400	19.29	21.23	16.23	19.70	19.25	19.14	1.82
6000	19.40	21.30	16.39	19.77	19.36	19.24	1.78

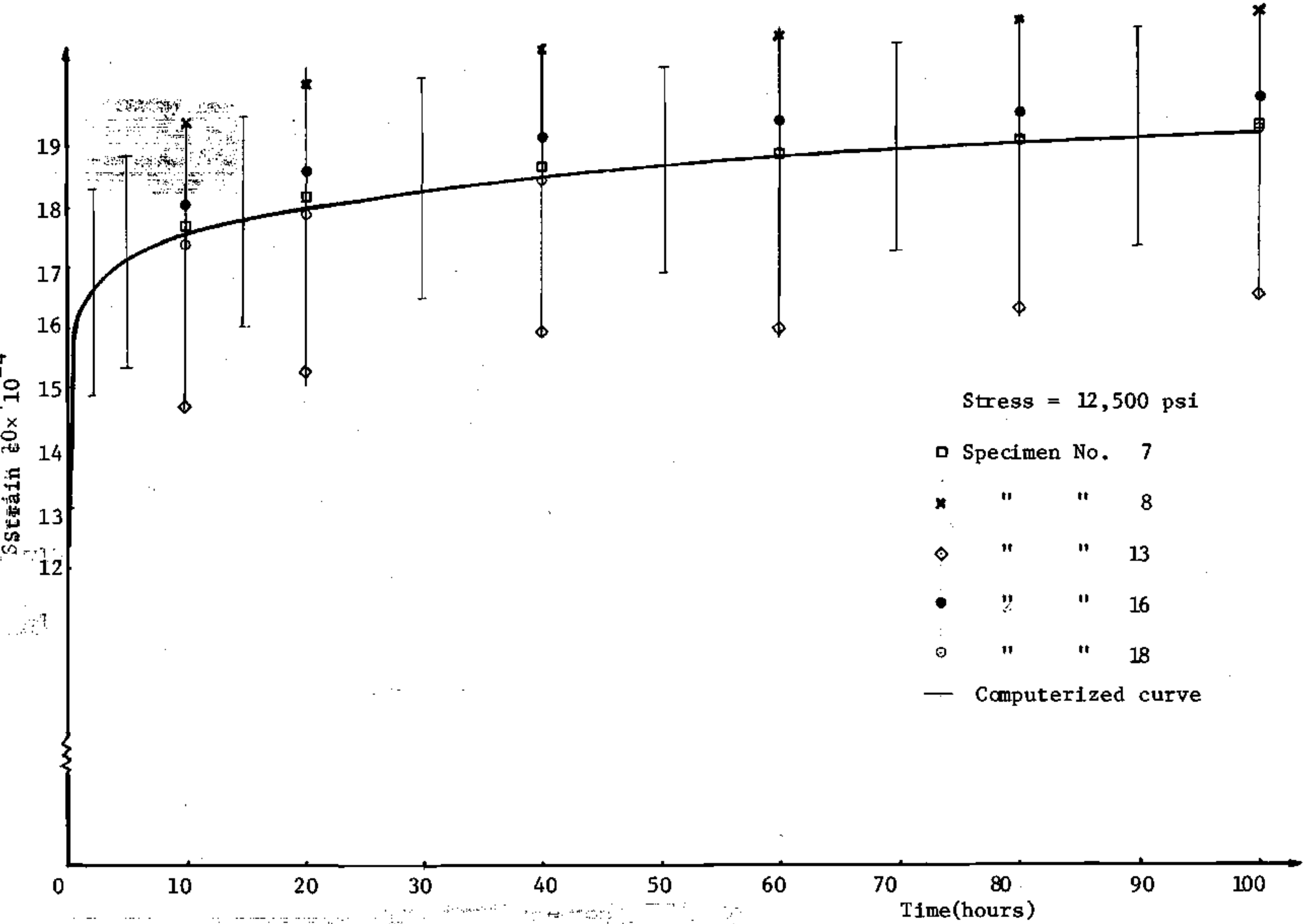

Fig. 7 Results of Test B

Table 3. Results of Test C

Gage length = 80.82 inch   Weight = 210 lbs   Specimen dia. = 0.133 inch

Time (min)	Strain × 10^{-4} Specimen No. 7	8	9	13	16	Aver-age	Std. Dev.
1	24.38	23.15	19.58	22.70	20.32	22.03	2.01
2	24.60	23.46	19.80	22.87	20.54	22.25	1.98
3	24.76	23.67	19.94	22.99	20.69	22.41	2.03
4	24.88	23.82	20.06	23.10	20.83	22.54	2.03
5	24.98	23.97	20.17	23.21	20.94	22.65	2.04
6	25.03	24.07	20.25	23.27	21.03	22.73	2.03
7	25.09	24.15	20.29	23.39	21.10	22.80	2.04
8	25.13	24.25	20.38	23.45	21.18	22.88	2.03
9	25.17	24.31	20.42	23.51	21.23	22.93	2.03
10	25.23	24.38	20.48	23.52	21.31	22.98	2.02
12	25.34	24.47	20.59	23.65	21.43	23.10	2.02
14	25.39	24.60	20.72	23.74	21.54	23.20	2.00
16	25.46	24.66	20.76	23.79	21.60	23.25	2.00
18	25.53	24.75	20.81	23.87	21.68	23.33	2.01
20	25.61	24.76	20.98	23.92	21.76	23.41	1.97
24	25.67	24.89	21.07	24.05	21.89	23.51	1.96
28	25.80	24.99	21.08	24.13	21.96	23.59	2.01
34	25.90	25.13	21.28	24.20	22.10	23.72	1.97
40	26.06	25.24	21.48	24.33	22.21	23.86	1.96
50	26.22	25.40	21.65	24.50	22.37	24.03	1.96
60	26.27	25.72	21.65	24.62	22.51	24.15	2.01
75	26.42	25.75	21.90	24.73	22.69	2[illegible].30	1.95
90	26.64	25.85	22.11	24.87	22.80	24.45	1.94
120	26.76	26.08	22.23	25.07	23.03	24.63	1.95
150	27.02	26.23	22.33	25.10	23.17	24.77	1.99

(continued)

Table 3. Results of Test C (Cont'd)

Gage length = 80.82 inch Weight = 210 lbs Specimen dia. = 0.133 inch

Time (min)	Strain × 10^{-4} Specimen No. 7	8	13	16	18	Aver-age	Std. Dev.
180	27.11	26.35	22.42	25.13	23.29	24.86	1.99
240	27.37	26.58	22.77	55.26	23.51	25.10	1.96
300	27.54	26.74	22.89	25.38	23.63	25.24	1.98
360	27.54	26.89	22.89	25.46	23.74	25.30	1.99
420	27.77	27.01	23.08	25.58	23.82	25.45	2.01
480	27.80	27.13	23.12	25.71	23.92	25.54	2.01
600	28.01	27.30	23.26	25.86	24.09	25.70	2.03
750	28.27	27.52	23.65	26.02	24.23	25.92	2.03
900	28.27	27.72	23.71	26.14	24.37	26.04	2.00
1200	28.82	28.32	23.89	26.40	24.60	26.40	2.18
1500	28.82	28.45	24.13	26.61	24.75	26.55	2.11
1800	29.32	28.58	24.35	26.75	24.90	26.78	2.19
2100	29.39	2866	24.52	26.89	25.01	26.89	2.15
2400	29.45	28.73	24.65	27.00	25.13	26.99	2.12
3000	29.72	29.03	24.87	27.21	25.38	27.24	2.15
3600	29.72	29.30	25.06	27.33	25.58	27.40	2.11
4200	30.31	29.42	25.20	27.49	25.76	27.64	2.23
4800	30.31	29.53	25.37	27.58	25.90	27.74	2.17
5400	30.44	29.67	25.37	27.83	26.10	27.88	2.19
6000	30.46	29.96	25.45	27.93	26.19	27.99	2.22
	30		25				

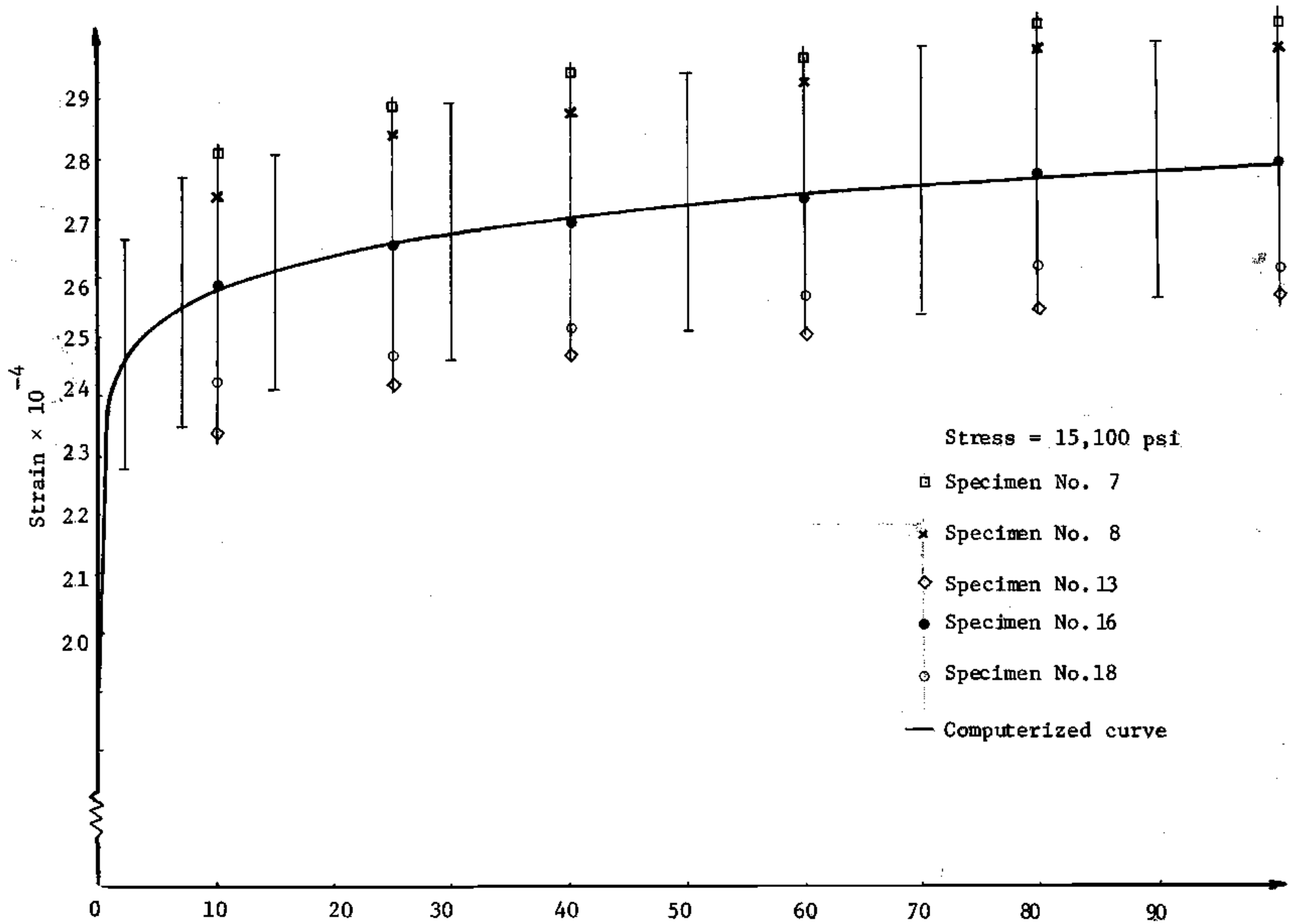

Fig. 8. Result of Test C

Data Analysis

As discussed in Chapter 1, most strain versus time data of transient creep can be expressed by a power function of the form

$$\varepsilon = \varepsilon_o + at^m \qquad \text{Eq. 3}$$

Here ε_o is an instantaneous deformation which is quite difficult to observe experimentally since the exact zero starting time is hard to determine. Thus, the identification of ε_o, "a" and m are made by employing the basic mathematical relations characteristic of this type of equation. Procedure for calculating power creep equation constants involve both graphical and analytical analysis. A so-called non-linear regression method based on an iterative approach [25] was used in this investigation. The calculations involved using a computer program which is shown in the Appendix. The equation was fitted to the mean value of the data points for each of the three tests A, B and C. Results are listed in Table 4 and represented graphically in Figures 6, 7 and 8 for Tests A, B and C, respectively.

The values of "a" as a function of stress are presented in Figure 9. 9. A finite difference method [7] was employed to determine the value of m, thereby avoiding any experimental error in ε_o, in order to check and assess the m values previously obtained by the non-linear regression method. Briefly, this method consists in taking time steps in geometrical progression

$$t_1, \quad t_2=ct_1, \quad t_3=c^2t_1, \quad \ldots \quad t_n=c^{n-1}t_1, \quad t_{n+1}=c^nt_1 \ldots,$$

where c is an arbitrary positive constant.

The corresponding strains,

$$\varepsilon_1, \varepsilon_2, \varepsilon_3, \ldots \varepsilon_n, \varepsilon_{n+1}, \ldots,$$

are determined and the differences

$$\Delta\varepsilon_1=\varepsilon_2-\varepsilon_1, \qquad \Delta\varepsilon_2=\varepsilon_3-\varepsilon_2, \qquad \ldots \qquad \Delta\varepsilon_n=\varepsilon_{n+1}-\varepsilon_n \ldots,$$

are calculated. Then on a log-log scale all the $\Delta\varepsilon_n$ versus the corresponding t_n are plotted and, if $\varepsilon(t)$ is a power function of time, the points should lie on a straight line of slope m.

The data in the results of applying this analysis are shown in Tables 5, 6 and 7 and plotted in Figures 10, 11 and 12 for Tests A, B and C, respectively. A regression method was used to compute the linear relationship between $\Delta\varepsilon$ and t with the help of a programmed Wang's calculator. The values of the intersection and slope of the regression line were immediately obtained after the data had been fed into the calculator.

Table 4. Results of Data Analysis

Test	$\varepsilon_o \times 10^{-4}$	$a \times 10^{-4}$	m	m*
A	7.29	1.72	0.111	0.126
B	12.09	2.54	0.119	0.140
C	18.15	3.79	0.109	0.129

*m obtained in the Finite Difference Analysis.

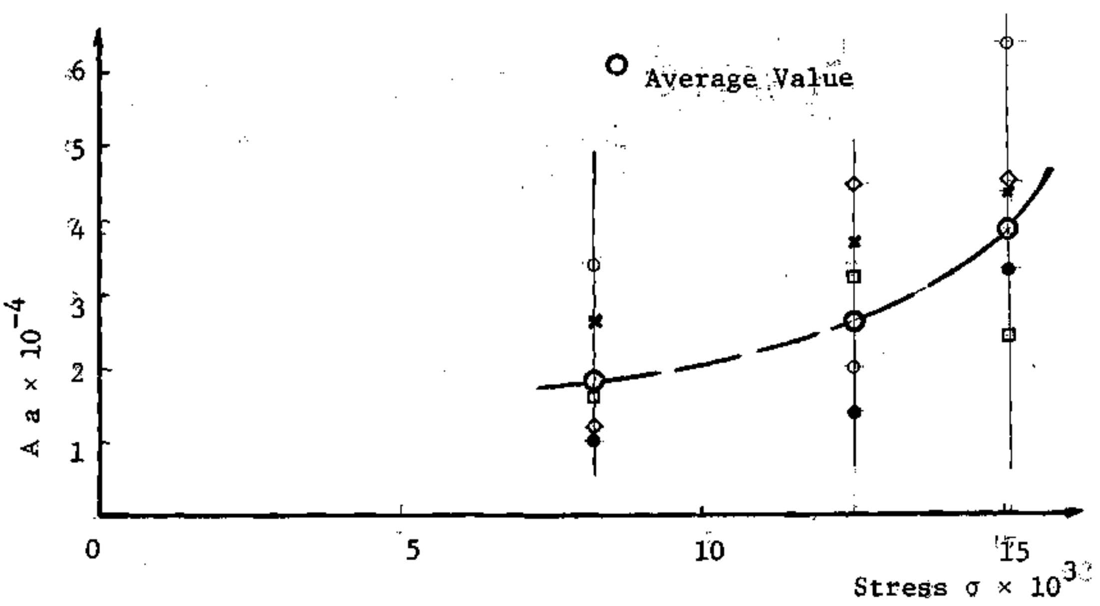

Fig. 9. Variation of "a" with Stress

Table 5. Data Used in the Finite Difference Analysis of Test A

Time (min)	Strain × 10^{-4} Specimen No. 7	8	13	16	18 $t_1 = 1$, $C = 2$	Average	$\Delta\varepsilon$
1	8.72	8.21	8.72	10.98	8.78	9.08	0.09
2	8.83	8.28	8.80	11.04	8.88	9.17	0.13
4	9.04	8.37	8.91	11.15	9.02	9.30	0.15
8	9.19	8.51	9.04	11.27	9.24	9.45	0.16
16	9.35	8.71	9.18	11.40	9.42	9.61	0.19
32	9.54	8.88	9.37	11.58	9.62	9.80	0.24
64	9.77	9.08	9.59	11.81	9.93	10.04	0.26
128	10.02	9.36	9.79	12.15	10.17	10.30	0.18
256	10.17	9.51	10.07	12.29	10.37	10.48	0.23
512	10.35	9.78	10.26	12.54	10.61	10.71	0.31
1024	10.74	10.18	10.49	12.84	10.86	11.02	0.30
2048	11.06	10.32	10.84	13.25	11.16	11.32	0.28
4096	11.37	10.44	11.12	13.69	11.46	11.60	

m = 0.126

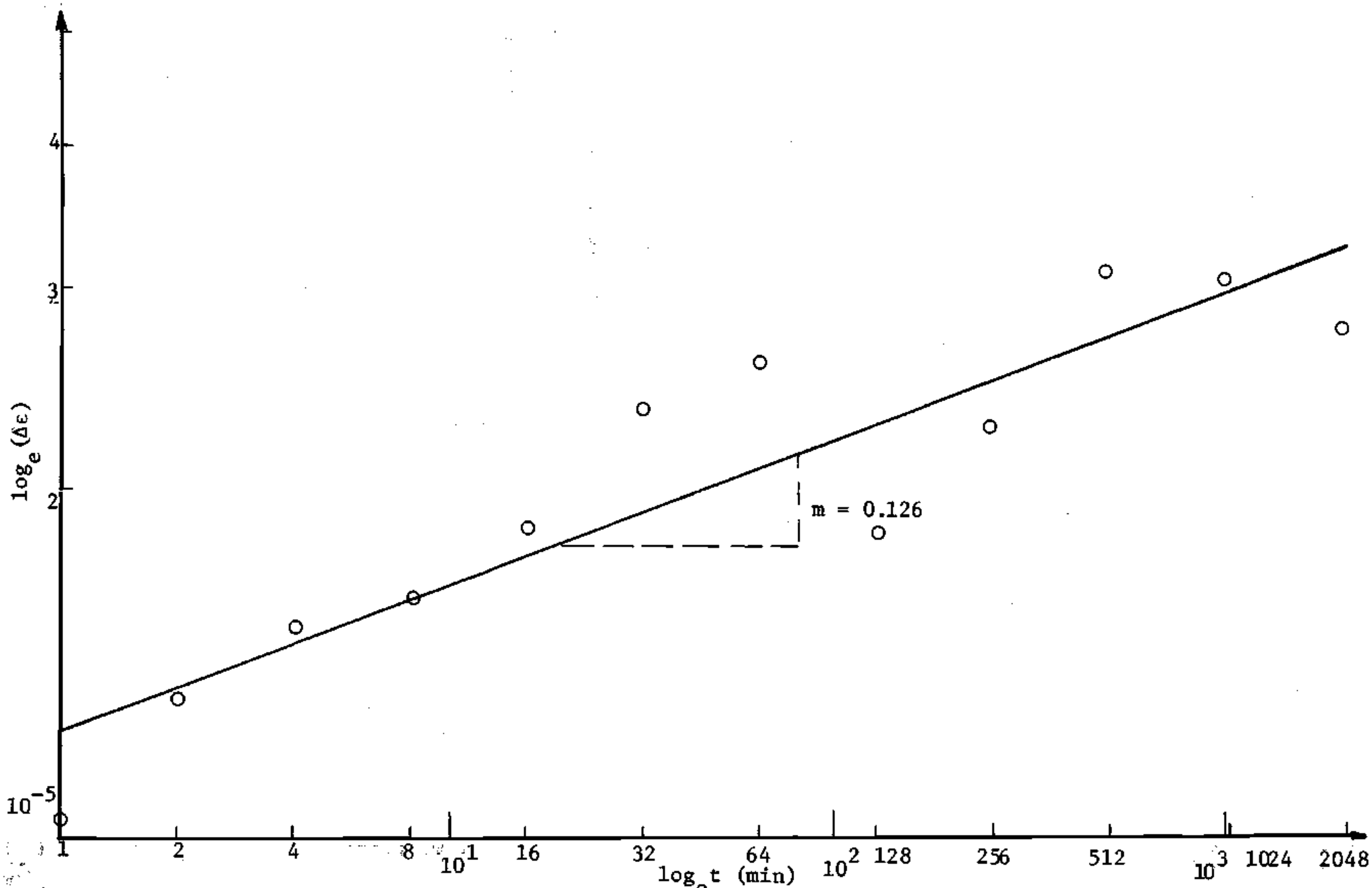

Fig. 10. Determination of m by the Finite Difference Method of Test A

Table 6. Data Used in the Finite Difference Analysis of Test B

Time (min)	Strain × 10^{-4} Specimen No. 7	8	13	16	18	$t_1 = 1$, C = 2 Average	$\Delta\varepsilon$
1	15.08	16.32	11.60	15.95	14.64	14.72	0.15
2	15.27	16.57	11.76	15.99	14.75	14.87	0.20
4	15.48	16.88	12.00	16.05	14.93	15.07	0.26
8	15.76	17.17	12.31	16.18	15.21	15.33	0.29
16	16.07	17.52	12.66	16.39	15.48	15.62	0.32
32	16.40	17.85	13.02	16.66	15.76	15.94	0.32
64	16.67	18.18	13.38	16.98	16.09	16.26	0.35
128	17.00	18.53	13.77	17.28	16.47	16.61	0.41
256	17.37	18.93	14.17	17.71	16.94	17.02	0.40
512	17.64	19.40	14.52	18.10	17.36	17.42	0.52
1024	18.07	19.90	15.08	18.61	18.02	17.94	0.47
2048	18.60	20.47	15.50	19.14	18.33	18.41	0.48
4096	19.05	20.94	16.03	19.45	19.00	18.89	

m = 0.140

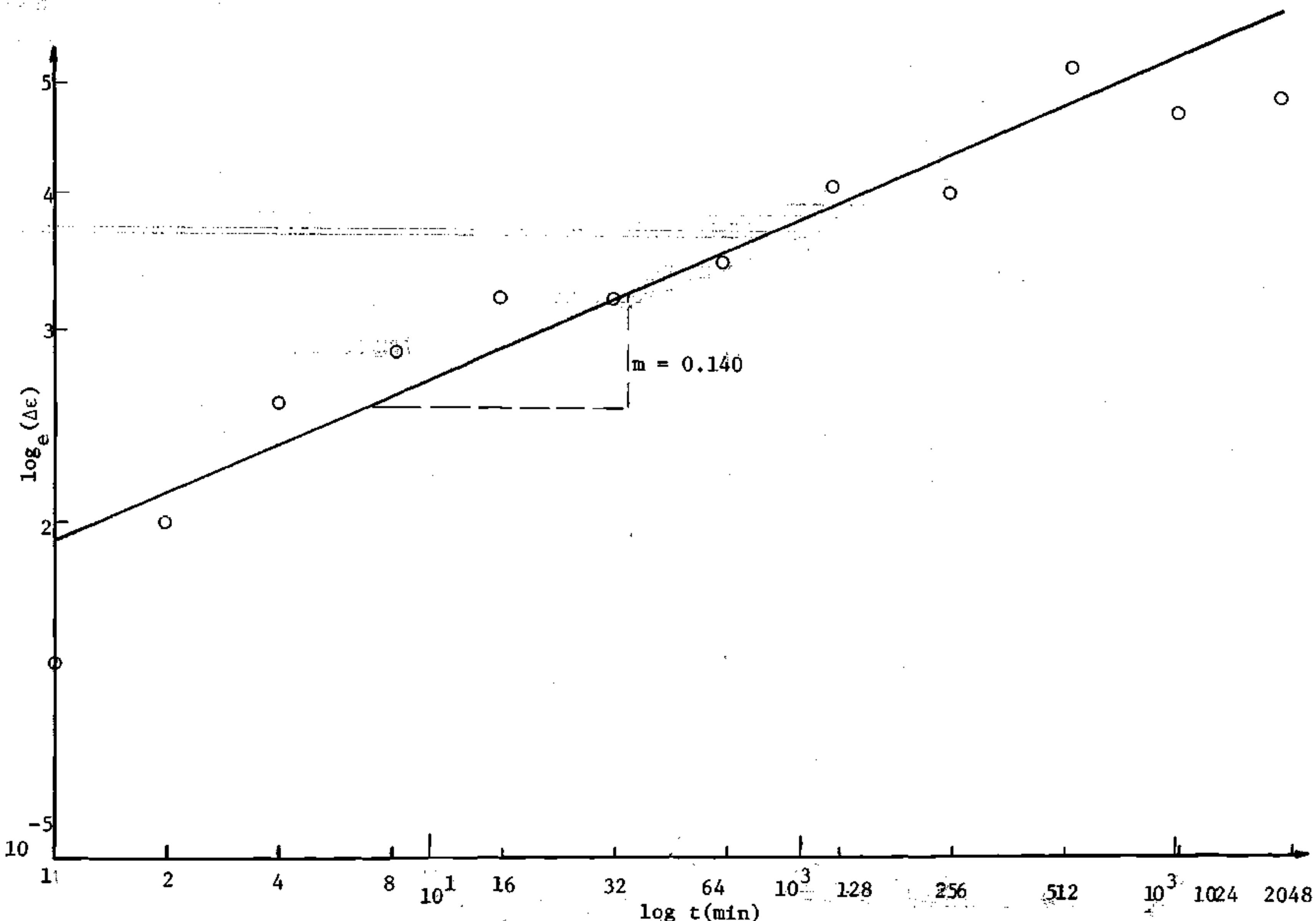

Fig. 11. Determination of m by the Finite Difference Method of Test B

Table 7. Data Used in the Finite Difference Analysis of Test C

Time (min)	Strain × 10^{-4} Specimen No. 7	8	13	16	18	$t_1 = 1$, $C = 2$ Average	$\Delta\varepsilon$
1	24.38	23.15	19.58	22.70	20.32	22.03	0.22
2	24.60	23.46	19.80	22,87	20.54	22.25	0.29
4	24.88	23.82	20.06	23.10	20.83	22.54	0.34
8	25.13	24.25	20.38	23.45	21.18	22.88	0.37
16	25.46	24.66	20.76	23.79	21.60	23.25	0.43
32	25.87	25.09	21.22	24.18	22.06	23.68	0.52
64	26.31	25.73	21.75	24.65	22.55	24.20	0.48
128	26.84	26.13	22.26	25.08	23.07	24.68	0.46
256	27.42	26.62	22,81	25.30	23.55	25.14	0.52
512	27.96	27.25	23.22	25.81	24.04	25.66	0.51
1024	28.44	28.03	23.78	26.23	24.45	26.17	0.70
2048	29.37	28.65	24.49	26.87	24.99	26.87	0.72
4096	30.21	29.40	25.17	27.46	25.73	27.59	
			2				

$m = 0.129$

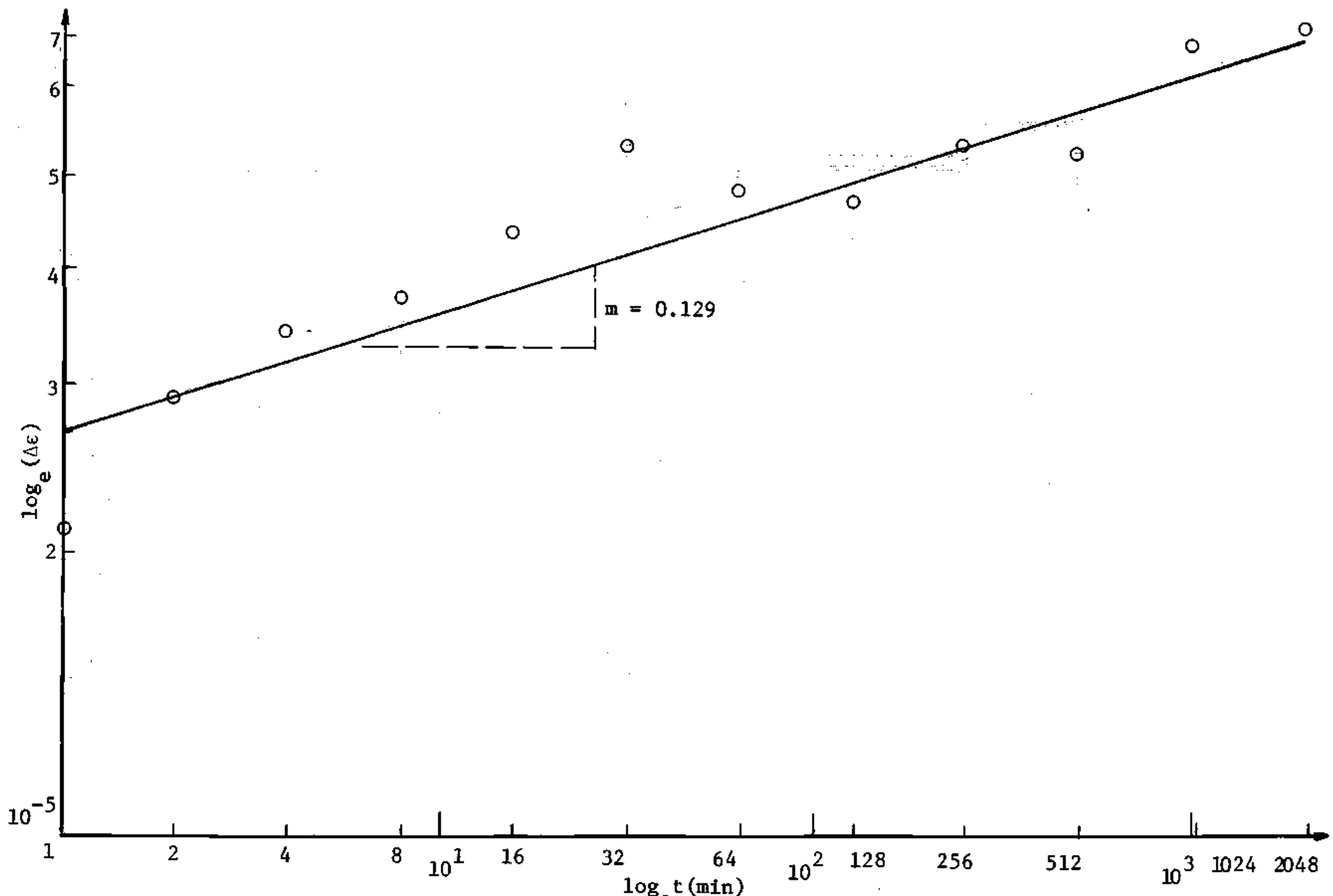

Fig. 12. Determination of m by the Finite Difference Method of Test C

CHAPTER IV

DISCUSSION

The data shown in Tables 1-3 are creep strains due to the weights of the main load and accessories. The straining effect of the preload is not included. Their effects should be discussed in two aspects. First, the preload certainly produces an amount of elastic strain which is expected to be approximately 0.024% according to its modulus of elasticity and should be added to the initial strain, ε_o. However, it will not affect the values of "a" and m which we are most interested in. Second, the preload could induce creep strain. Since the stress on the wire was 2,400 psi and preload time is short (only about ten minutes compared to 100 hours of total testing time) the creep strain is expected to be negligible according to McVetty [23] and Sturm, et al. who found that under a limiting stress, about 15% of the ultimate tensile strength of either aluminum or copper, the creep rate was extremely low. In our case, the ultimate tensile strength of this particular wire is about 28,400 psi. Beyond that, there might be bending stresses left in the wire due to the fact that the wire is not entirely straight even after the preloading period. There is no way to evaluate the magnitude of these stresses.

Let us consider the results in Chapter III. The data seem a little scattered which is expected in every creep test. The material constant "a" in the power function varies merely from 1.72×10^{-4} to

3.79×10^{-4} in the stress range investigated. The variation of "a" as a function of stress apparently does not agree well with what Crussard observed, probably because the stress range studied here is not wide enough to make comparison relevant. However, the average value of "a" does tend to "take off" at higher stresses as shown in Figure 7. The values of m were determined by the two different methods as previously shown in Chapter III. There two methods are in good agreement. The constant shows very little variation and in fact does not vary with stress in a consistent manner. Apparently m is not a function of stress. This conforms very well with the observations by previous workers. However, m is significantly lower than the values they have shown. The difference could be attributed to such factors as speed of loading, residual bending stresses and size of diameter etc. Unfortunately, neither of their testing details are available nor is there any way to evaluate the quantitative differences due to these factors in the present case. An estimate of the initial elastic strains of this material yields values of 0.000848, 0.001288 and 0.001556 for stresses of 8.2 ksi, 12.5 ksi and 15.1 ksi respectively. Compared to the results of this investigation, the initial strain ε_o obtained in the test is higher than these elastic strain of a conventional tension test by an average of about 15%. Since the room temperature tensile properties are not greatly influenced by changes in the rate of straining in the ordinary tension test [24], this seems to suggest that the residual bending stresses may be the dominating factor preventing us from getting a more accurate initial strain reading and subsequently lowers the m value.

Diameter should not be an important factor in this case because the diameter of the wires used here are about the same as those in the literature cited.

It seems fair to conclude that this particular wire does have good creep resistance, at least in the transient creep range investigated, due to the low values of m obtained in this experiment.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this investigation into the creep of aluminum conductor, the following conclusions can be made.

(1) The results suggested that this particular aluminum wire had a very good creep resistance perhaps because of the cold worked effect although there are some uncertainties involved in determining the data.

(2) The material constant m or so called susceptibility of the power function is not a function of stress.

(3) The other material constant "a" does not vary with σ^{10} as observed by Crussard [7] and no relationship with stress is suggested in this investigation.

In view of gaining more understanding of the creep behavior of materials. The following are suggested.

(1) Wire straightener, which will inevitably induce some uncertain amount of cold work, could be used before testing the wire specimens. The result should be interesting in comparing the effects of bending stresses left in the unstraightened wires.

(2) Different degree cold-worked specimens can be used in order to get a through understanding of the effect of cold work upon creep at least for high purity aluminum.

(3) Mathematical representation of creep curves and experimental variables such as loading speed perhaps should be standardized in order to make comparisons possible.

APPENDIX

The non-linear regression analysis applied to Eq. 3 in Chapter I follows from a rearrangement of the equation in the form:

$$\varepsilon = \varepsilon_o + aF \qquad \text{Eq. (A.1)}$$

where $F = t^m$. If a value of m is selected at random, an improved value of F is given by

$$F + \left(\frac{dF}{dm}\right)dm = F + F'dm \qquad \text{Eq. (A.2)}$$

where

$$F' = t^m \ln t$$

Hence Eq. (A.1) can be rewritten

$$\varepsilon = \varepsilon_o + a(F + F'dm) \qquad \text{Eq. (A.3)}$$

or

$$\varepsilon = \varepsilon_o + aF + aF'dm \qquad \text{Eq. (A.4)}$$

Let $b = dm$, $G = aF'$

$$\varepsilon = \varepsilon_o + aF + bG \qquad \text{Eq. (A.5)}$$

Then the sum of the squares of the residuals becomes:

$$\sum(R)^2 = \sum(\varepsilon - \varepsilon_o - aF - bG)^2 \qquad \text{Eq. (A.6)}$$

Differentiating (A.6) with respect to ε_o, a and b for N experimental points:

$$\sum_{i=1}^{N} \varepsilon = N\varepsilon_o + a \sum_{i=1}^{N} F + b \sum_{i=1}^{N} G \qquad \text{Eq. (A.7)}$$

$$\sum_{i=1}^{N} \varepsilon F = \varepsilon_o \sum_{i=1}^{N} F + a \sum_{i=1}^{N} (F)^2 + b \sum_{i=1}^{N} FG \qquad \text{Eq. (A.8)}$$

$$\sum_{i=1}^{N} \varepsilon G = \varepsilon_o \sum_{i=1}^{N} G + a \sum_{i=1}^{N} FG + b \sum_{i=1}^{N} (G)^2 \qquad \text{Eq. (A.9)}$$

Tentative values for both a and m are first selected and used to evaluate the summation terms in equations (A.7), (A.8) and (A.9). These three equations can be solved simultaneously for ε_o, b and an improved values of a. Then an improved value of m is obtained by adding the value of b to the previously employed value of m. Using this improved m value and the calculated value of a, the simultaneous solution of (A.7), (A.8) and (A.9) is repeated. Convergence is obtained after several iterations as indicated by the value of b being close to zero. Proper values of m is obtained along with ε_o and a.

The following is the computer program used in this investigation.

```
DIMENSION EP(60),T(60),F(60),G(60),B(3,4),IR(3),JC(3),X(3)
INTEGER N
READGMR N
FORMAT ( )
DO 100 j=1.15
READ(5,1) A,M
WRITE(6,1) A,M
READ(5,1)N
DO 20 I = 1,N
READ(5,1) T(I),EP(I)
WRITE(6,1) T(T),EP(I)
```

```
20    CONTINUE
21    DO 30 I = 1,N
      F(I) = T(I) ** M
      G(I) = A*(T(I)**M)*ALOG(T(I))
30    CONTINUE
      SEP = 0.0
      SFG = 0.0
      SG2 = 0.0
       SG = 0.0
       SF = 0.0
      SEPF = 0.0
      SEPG = 0.0
      SF2 = 0.0
      DO 40 I = 1,N
      SEP = SFP + EP(I)
       SF = SG + G(I)
      SEPF = SEPF + (EP(I)*F(I))
      SF2 = SF2 + (F(I)**2)
      SFG = SFG + (F(I)*G(I))
      SG2 = SG2 + (G(I)**2)
      SEPG = SEPG + (EP(I)*G(I))
40    CONTINUE
      B(1,1) = N
      B(1,2) = SF
      B(1,3) = SG
      B(1,4) = SEP
      B(2,1) = SF
      B(2,2) = SF2
      B(2,3) = SEGF
      B(2,4) = SEPF
      B(3,1) = SGG
      B(3,2) = SFG
      B(3,3) = SG2
      B(3,4) = SEPG
      CALL LSIMEQ(B,3,IR,JC,3,1.0E-07,X,IERR1)
      WRITE(6,1) IERR1
50    DO 50 I = 1,3
50    WRITE(6,1) X(T)
      A = X(2)
      M = M+X(3)
      IF (ABS(X(3)). LT. 1.0E-06) GO TO 100
      GO TO 21
100   WRITE(6,2) A,M
2     FORMAT ('A = ''F10.4'6X, 'M = 'F8.5)
      STOP
      END
```

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