Design of Apparatus for Constant-Stress or Constant-Load Creep Tests

F. GAROFALO
O. RICHMOND
W. F. DOMIS
Edgar C. Bain Laboratory for Fundamental Research, United States Steel Corporation Research Center, Monroeville, Pa.

Apparatus has been designed and built for conducting creep tests under constant-stress or constant-load conditions. An exact mathematical solution describing the shape of the cam lever for constant stress is given. This solution applies for the large strains usually found for ductile metals and alloys, as long as the strain is uniform.

The initial specimen length employed in a constant-stress creep test ordinarily is fixed by the dimensions of the cam system used. It is shown by the present analysis that the initial specimen length may be changed if an approximate adjustment is made in the initial setting of a properly designed cam lever.

The direction of the load axis remains fixed and therefore the apparatus has the advantage of a more complex level-beam machine. The results of a number of creep tests under constant-stress conditions are reported.

Introduction

Engineering design of equipment subjected to creep conditions is usually based on creep and creep-rupture results obtained from constant-load tests. Therefore, a great deal of creep information is continually being obtained on commercial alloys under constant-load conditions. It is important, however, in studying basic aspects of creep to obtain results also under conditions of constant stress [1–6].[1] During a creep test the cross-sectional area of the specimen decreases with increasing strain, and under a constant load the stress increases. Since creep rate is a function of the stress, it becomes difficult to analyze constant-load results in terms of basic mechanisms of creep.

In the present paper, a compact, cam-lever type device for application of either constant stress or constant load in simple tension for large uniform deformations is described. The profile of the constant-stress cam lever is similar to that of the Andrade-Chalmers beam [2], which was defined from a graphical design. In the present case, exact parametric equations for the cam profile have been determined. For constant load, the device reduces to two rigidly attached wheels, one with a larger radius for load application and one with a smaller radius to transmit the load to the specimen.

Using this apparatus, a series of creep tests on a Type 316 austenitic stainless steel have been made under constant-stress conditions and the results of these tests are reported.

Design of Test Apparatus

Although this presentation deals primarily with constant-stress testing, a constant-load assembly is also described because it forms an integral part of the apparatus that was constructed.

The constant-load system is shown schematically in Fig. 1. The load to the specimen is transmitted through the smaller wheel of radius R, whereas the applied load W is transmitted through the large wheel of radius ρ. The mechanical advantage, therefore, is ρ/R.

To maintain a constant stress, a cam lever with a profile similar to the Andrade-Chalmers beam [2] has been designed by an analytical method and is shown schematically in Fig. 2. Transmittal of forces is essentially the same as for the constant-load assembly. In the actual apparatus to be described later the constant-load wheel is rigidly attached to one side of the small wheel and the constant-stress cam is rigidly attached to the opposite side. Thus, for either constant load or constant stress, the load to the specimen is applied through the same wheel of radius R. For the constant-stress case the initial mechanical advantage is r_0/R, but diminishes as the specimen elongates.

In order to maintain a constant stress, the load P on the specimen must be reduced as the specimen elongates to compensate for the reduction in area A. Thus the instantaneous stress P/A must remain constant. By assuming constancy of volume and uniform strain[2] LA, where L is the specimen length, must remain

[1] Numbers in brackets designate References at end of paper.

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[2] If intercrystalline cracks or necking occur in the early stages of creep these conditions are not satisfied and the creep will not remain constant.

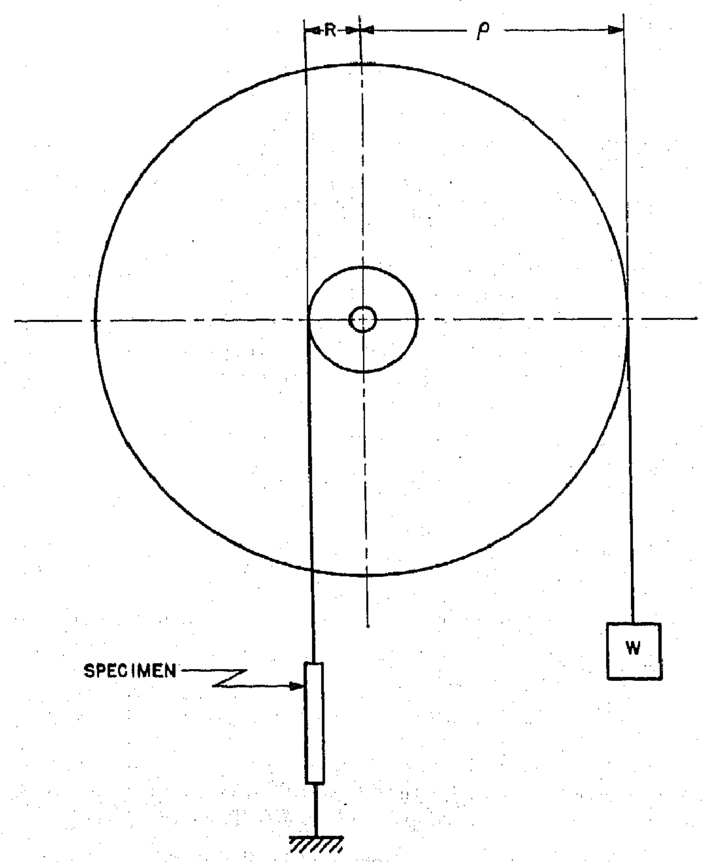

Fig. 1 Schematic diagram of constant-load system

constant. It then follows that PL also remains constant. Under equilibrium conditions, $P = Wr/R$, where W is the applied weight shown in Fig. 2 and r is the instantaneous moment arm of the applied weight. Thus, to maintain a constant stress the following condition must be satisfied:

$$rL = \text{constant} = r_0 L_0 \tag{1}$$

where L_0 is the initial specimen length and r_0 is the initial value of r.

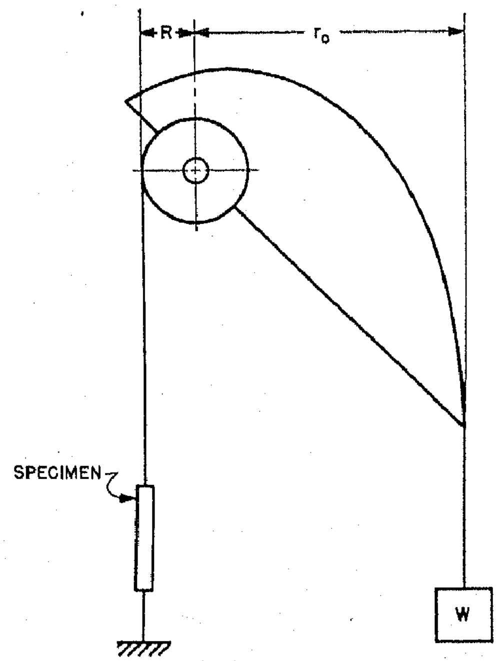

Fig. 2 Schematic diagram of constant-stress system

As the length of the specimen increases, the arc of contact on the small wheel increases by an equivalent amount. Thus the instantaneous specimen length may be written as

$$L = L_0 + (\theta - \theta_0)R \tag{2}$$

where θ_0 is the angle for the initial positioning of the constant-stress cam. Eliminating L from equations (1) and (2) leads to

$$r = \frac{r_0 L_0}{L_0 + R(\theta - \theta_0)} \tag{3}$$

This is the equation of the profile of a constant-stress cam.

To design an actual cam profile it is desirable to transform equation (3) into a fixed Cartesian co-ordinate system x, y. To do this it is convenient to consider the rotating co-ordinate system r, z shown in Fig. 3 which is related to the fixed system x, y by the equations,

$$x = r\cos\theta + z\sin\theta \tag{4}$$

$$y = r\sin\theta - z\cos\theta \tag{5}$$

and

$$\frac{dx}{dy} = -\tan\theta \tag{6}$$

Eliminating x and y from these equations and using equation (3) gives

$$z = -\frac{dr}{d\theta} = \frac{r_0 L_0 R}{[L_0 + R(\theta - \theta_0)]^2} \tag{7}$$

Substituting this equation and equation (3) into equations (4) and (5) gives the fixed Cartesian co-ordinates of a constant-stress cam in terms of the single parameter, θ.[3] Thus,

$$x = \frac{a}{1 + b\theta}\left[\cos\theta + \frac{b\sin\theta}{1 + b\theta}\right] \tag{8}$$

and

$$y = \frac{a}{1 + b\theta}\left[\sin\theta - \frac{b\cos\theta}{1 + b\theta}\right] \tag{9}$$

where $a = \dfrac{r_0 L_0}{L_0 - R\theta_0}$ and $b = \dfrac{R}{L_0 - R\theta_0}$.

The cam profile is completely determined by the values of the constants a and b. For the cam designed in this work, $a = 7.19$ inches and $b = 1$.

In a given creep test, the constant-stress cam is used in conjunction with a specimen wheel of given radius R and a specimen of given length L_0. The initial setting of the cam is made by setting the initial moment arm r_0, which according to the definition of the cam constants a and b is given by

$$r_0 = \frac{a}{b}\left(\frac{R}{L_0}\right) = 7.19\,\frac{R}{L_0} \tag{10}$$

It is important to note from this relation that the initial cam setting depends upon the ratio of the wheel radius R to the specimen length L_0. In the test results to be discussed later $L_0 = R = 1.44$ inches. Thus the mechanical advantage r_0/R, for the apparatus employed in this work is 5. Specimens of different initial lengths may be used with the same cam and wheel, but the initial setting must be changed to satisfy the relation $b = \dfrac{R}{L_0 - R\theta_0}$. For the present apparatus, $b = 1$ and $R = 1.44$ inches.

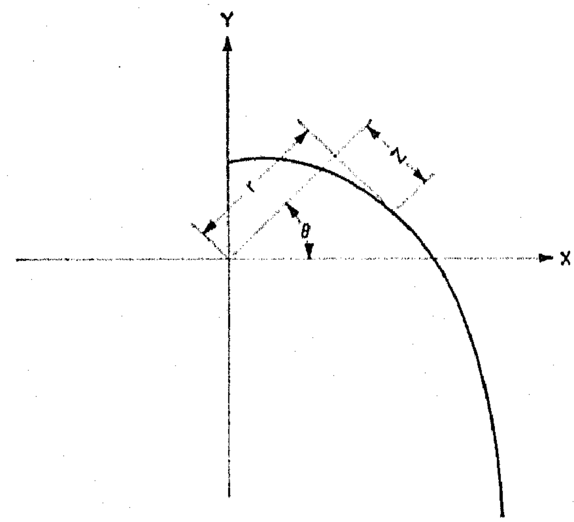

Fig. 3 Diagram showing co-ordinate systems for cam profile

Therefore the initial angular setting for any value of initial length L_0 can be determined from

$$\theta_0 = \frac{L_0}{R} - \frac{1}{b} = \frac{L_0}{1.44} - 1 \tag{11}$$

An advantage of the analytical design is indeed the facility with which the initial position can be determined when it becomes necessary with the same apparatus to change L_0.[4] The mechanical advantage r_0/R also changes in accordance with the relation

$$r_0/R = \frac{a}{bL_0} = \frac{7.19}{L_0} \tag{12}$$

For the cam designed here the x and y values determined from equation (8) and (9) are given in Table 1. A design of the constant-stress cam lever is shown in Fig. 4. For purposes of weight

[3] A different parameter has been used by Ward and Marriott [7], leading to somewhat more complex parametric equations.

[4] Kennedy [8] has suggested a more complicated method for allowing a change in L_0. This method involves a secondary cam.

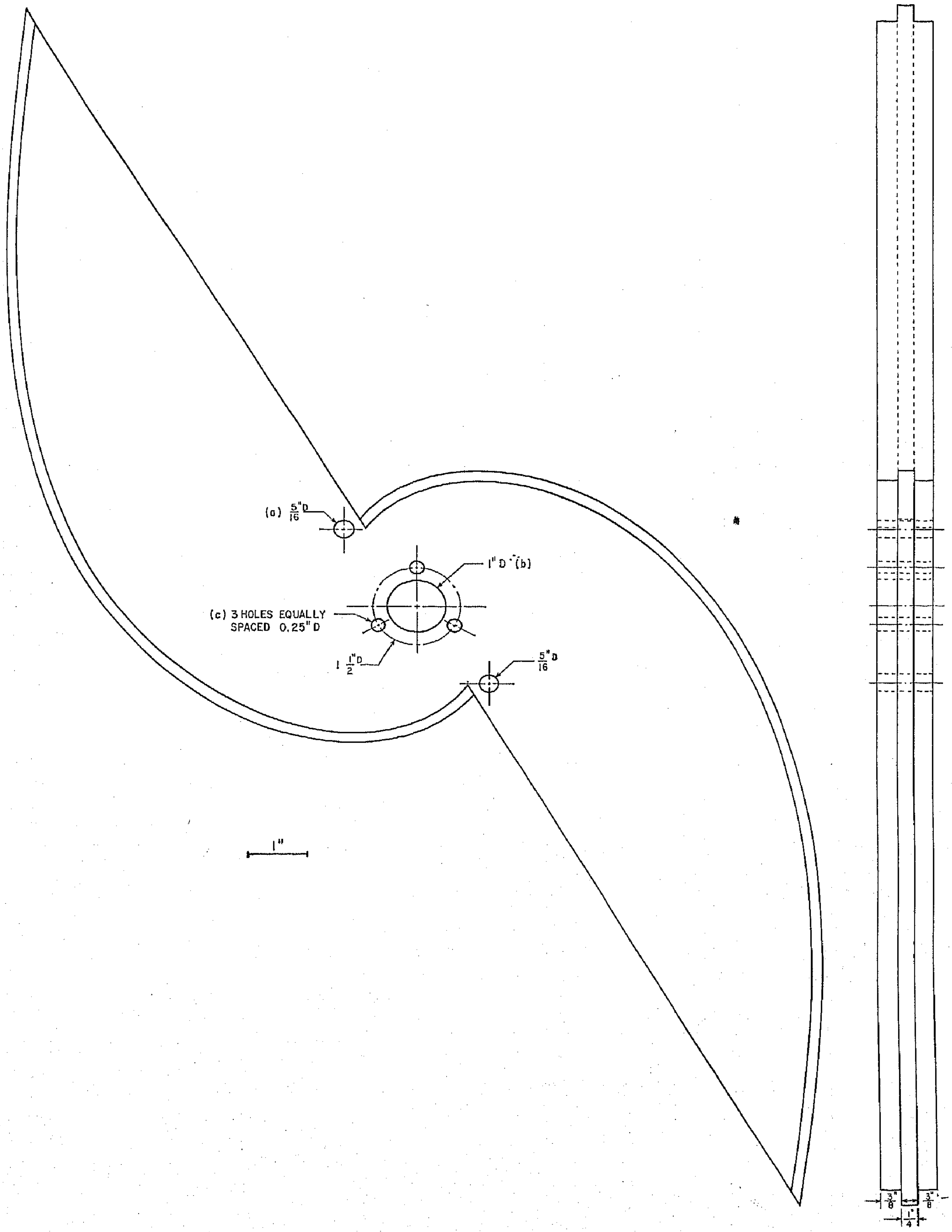

Fig. 4 Design drawing for constant-stress cam lever

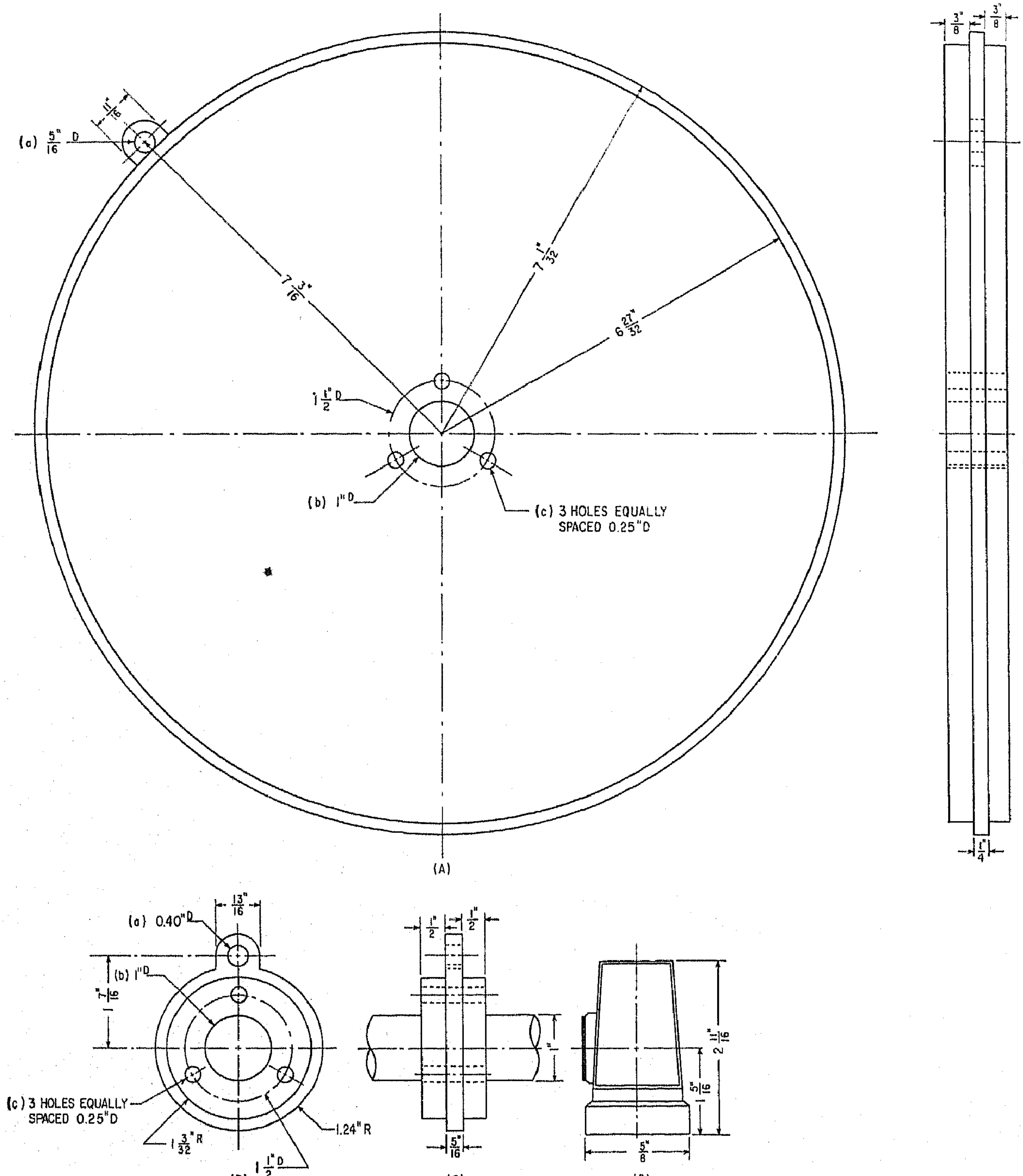

Fig. 5 Design drawings for (A) constant-load wheel, (B) specimen loading wheel, (C) shaft assembly, and (D) ball bearing pillow block

Table 1 Co-ordinates for constant-stress cam profile

$a = 7.19 \quad b = 1$

θ, degrees	x, inches	y, inches
−20	4.58	−19.72
−15	5.99	−15.26
−10	6.74	−11.90
−5	7.09	−9.28
0	7.19	−7.19
5	7.12	−5.48
10	6.93	−4.07
15	6.67	−2.89
20	6.36	−1.89
25	6.01	−1.04
30	5.63	−0.32
35	5.24	0.29
40	4.84	0.81
45	4.44	1.25
50	4.04	1.62
55	3.64	1.93
60	3.24	2.18
65	2.85	2.39
70	2.47	2.54
75	2.11	2.66
80	1.75	2.74
85	1.41	2.78
90	1.09	2.80
95	0.78	2.78
100	0.48	2.74
105	0.21	2.68
110	−0.05	2.60

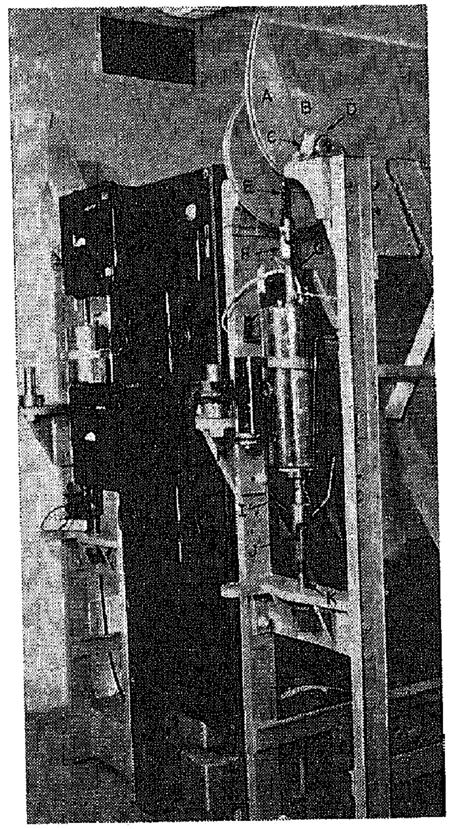

Fig. 6 Photograph of apparatus

balancing an inverted cam is included to the left of the assembly and only the cam to the right is employed for loading. The load is transmitted through a roller chain which is connected to the cam by a pin inserted through the hole at (a). The rollers of the chain rest on the raised middle ridge of the cam. Thus the distance r of equation (4) is measured from the center of the large hole (b) to the center of the roller at the point on the cam where the chain is tangent to the cam. The loading is accomplished by application of dead weights on a loading pan attached to the free end of the chain.

The cam is attached rigidly to a shaft and specimen loading wheel assembly, shown in Figs. 5(B and C). The shaft of this assembly fits into the large hole (b) of the constant-stress cam and the latter is attached to the assembly by means of bolts through holes (c). The constant-stress cam is attached on one side of the specimen loading wheel, and the constant-load wheel shown in Fig. 5(A) is attached on the opposite side in a similar manner. For constant-load tests the load is transmitted through a roller chain attached to the constant-load wheel by a pin inserted through (a). In a similar manner the load to the specimen is transmitted by a roller chain. One end of this chain is attached to the specimen loading wheel by a pin inserted through (a) of Fig. 5(B). The other end is attached to a universal joint and extension arm as shown in the photograph of the apparatus in Fig. 6. Since the direction of loading does not change, this apparatus has the advantage of an intricate level-beam machine. The radii R and ρ for the specimen-loading wheel and the constant-load wheel are measured from the center of the assembly to the centers of the respective rollers.

The shaft of the specimen-loading wheel is supported at each end by heavy-duty roller bearings encased in pillow blocks similar to the one drawn in Fig. 5(D). The roller bearings and pillow blocks employed in the present apparatus have each a capacity of 5000 pounds at ten revolutions per minute. The pillow blocks are rigidly attached to the frame of the creep tester shown in Fig. 6.

Calibration of Apparatus

It has been shown previously that PL = constant during a constant stress test. It follows then that

$$L/L_0 = P_0/P \tag{13}$$

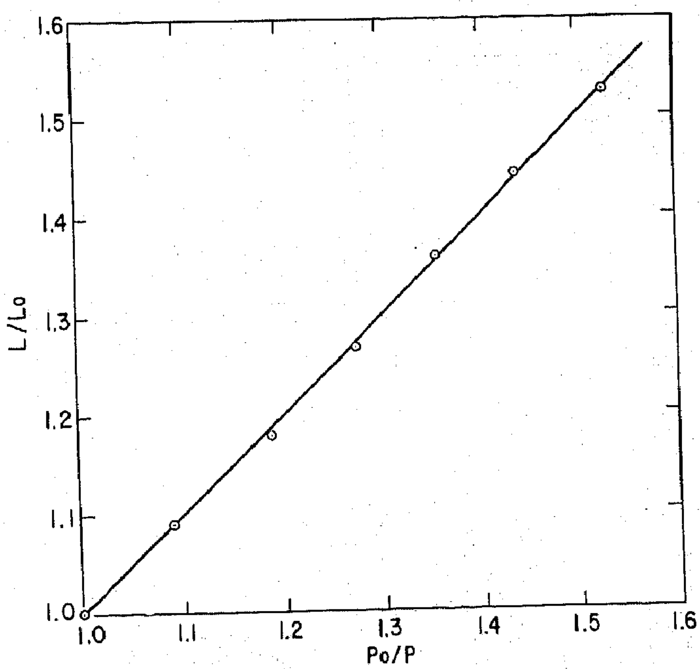

Fig. 7 Load calibration of constant-stress cam lever

where P_0 is the initial load on the specimen. Equation (13) must be satisfied for any angle θ at any level of P_0.

The present apparatus has been calibrated by checking the agreement between measurements of L and P and predictions of equation (13). These measurements were made in the following manner: The furnace shown in Fig. 6 was removed from the apparatus and a resistance-gage type dynamometer sensitive to a change of 0.5 pounds or less was attached to the upper extension arm. Weights were placed on the loading pan until the cam assembly balanced at the initial position of θ marked by a scribed line on the constant load wheel. An initial reading at zero load was taken on the dynamometer which was then attached to the lower extension arm. A total load of 49.7 pounds was placed on the loading pan. If the initial position of θ shifted because of elimination of slack, the lower connecting rod, which is in contact with the machine frame by means of a semispherical seat, was adjusted to reset the cam assembly. A reading was taken on the dynamometer and the position of a line scribed on the upper extension arm was fixed on an optical comparator which is sensitive to a change of 10^{-4} inches and is shown in Fig. 6. The comparator remains fixed with respect to the frame.

In calibrating the equipment the lower connecting rod is unscrewed a certain amount out of the lower universal joint. This results in a change in θ, a displacement in the scribed mark on the upper extension rod, which is equivalent to a change in L, and a change in the load P indicated by the dynamometer. The lower connecting rod is adjusted so that the change in θ is at intervals of 5 deg up to a total of 30 deg and measurements of L and P are made after each interval. A typical calibration plot is shown in Fig. 7. As predicted by equation (13) a linear relationship with a slope of unity is found in Fig. 7 for a plot of L/L_0 against P_0/P. Calibration of several such creep machines shows an average variation of 0.6 per cent in the measured load P from that predicted by equation (13).

Test Procedures and Results

A limited number of tests under constant-stress conditions have been made with the apparatus described here. Dimensions of the creep specimens employed are shown in Fig. 8. The initial gage length is taken as the total length of the reduced section. The extensometer used is a platinum, tube-rod type shown in Fig. 9. Each end of the extensometer is clamped by means of set-screws, shown in Fig. 9, to the shoulders of the specimen. Extension is determined during a creep test by measuring with the optical comparator the distance between scribed marks on the tube and rod of the extensometer. A window in the furnace permits focusing of the optical comparator onto the extensometer.

The specimen with the extensometer attached is threaded into the upper and lower extension arms and the entire assembly lowered into the furnace and threaded into the universal joints. A small weight is placed on the loading pan so that contact is made in the spherical seat between frame and connecting rod.

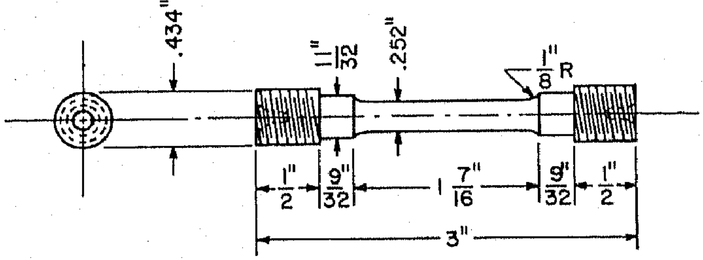

Fig. 8 Dimensions of creep specimen

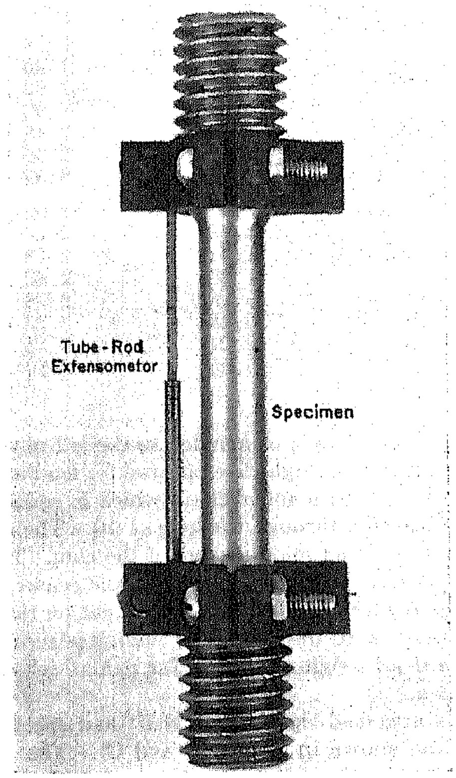

Fig. 9 Photograph of extensometer clamped on to a creep specimen

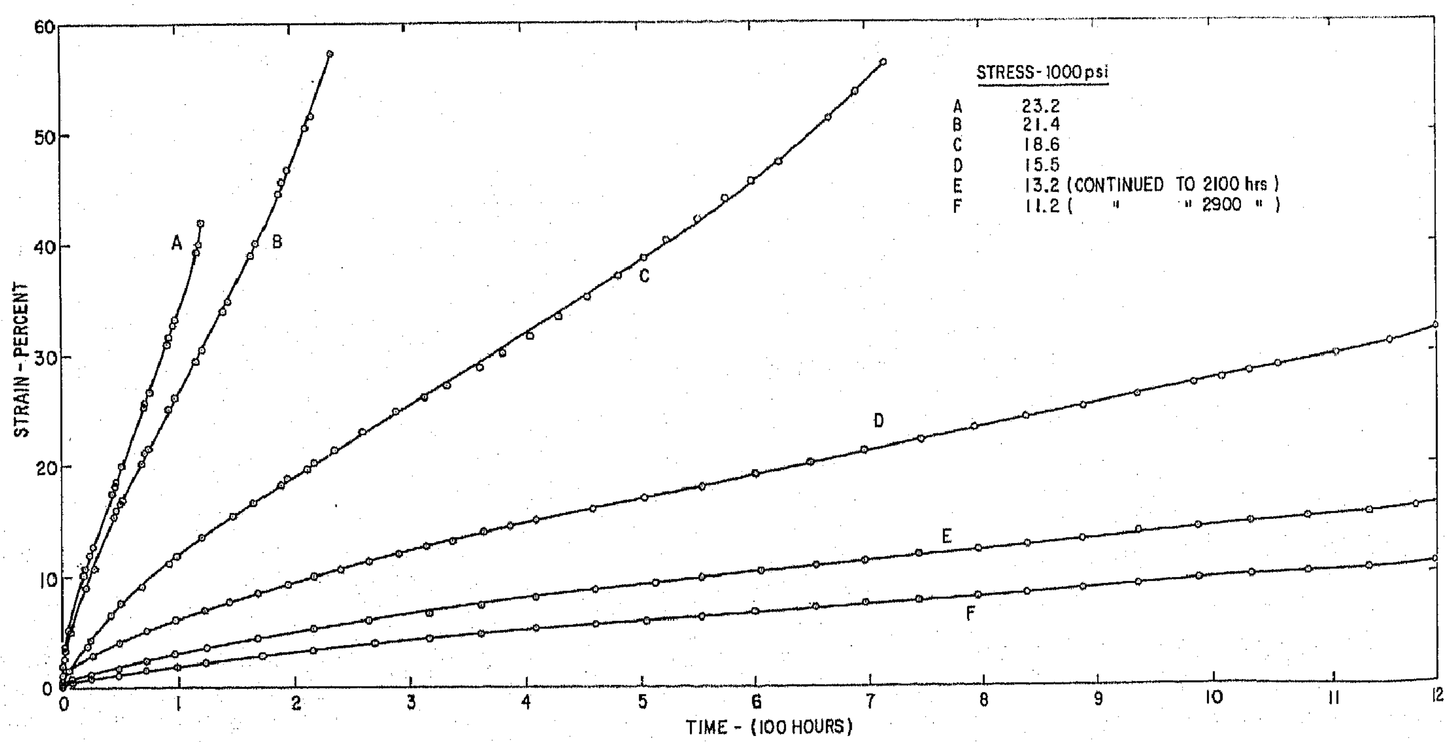

Fig. 10 Typical creep curves obtained at 1300°F for a Type 316 austenitic stainless steel

Upon reaching the desired temperature the cam assembly is positioned to θ_0 by adjusting the connecting rod. After the temperature is stabilized for a period of at least one hour an initial reading is taken on the extensometer. The desired load is placed on the loading tray which is now supported by a mechanical jack. The jack is then lowered and the load applied gently. A reading is taken on the extensometer upon loading and at various intervals thereafter. The manner of temperature measurement and control has been reported previously [9].

The material tested thus far is a Type 316 austenitic stainless steel having the following composition: C, 0.07%; Mn, 1.94%; P, 0.01%; S, 0.021%; Si, 0.38%; Cr, 18%; Ni, 11.4%; Mo, 2.15%; Al, 0.003%; and N, 0.043%. Typical creep curves obtained on this material at 1300 F are shown in Fig. 10. In each case the test was ended soon after tertiary creep began. The maximum strain reached in these tests is slightly less than 60 per cent. However, the apparatus is designed to cover uniform strains of at least 100 per cent.

The research work which will be conducted in part with the present apparatus will deal with the stress and temperature dependence of transient and steady-state creep, the nature of the accompanying substructural changes and initiation of fracture, particularly of the intercrystalline type [6]. It is hoped that this type of information will lead to a better understanding of the basic aspects of creep behavior. Constant-strain-rate and constant-load tests are also contemplated to check theories formulated on the basis of the present work.

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