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THE TRUE STRESS-STRAIN PROPERTIES OF
BRITTLE MATERIALS TO 5000° F

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Report To

U. S. ATOMIC ENERGY COMMISSION

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U. S. ATOMIC ENERGY COMMISSION

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THE TRUE STRESS-STRAIN PROPERTIES OF BRITTLE MATERIALS TO 5000° F

FOREWORD

This is the sixth monthly report on Contract No. AT-(40-1)-2694 for the development of a system for the evaluation of the true stress-strain properties of brittle materials at temperatures up to 5000° F. There are three general areas of development in this program: (1) to measure strains in specimens to 5000° F optically, (2) to grip and load the specimen with true uniaxial loading, and (3) to heat the specimen radiantly with an external source with minimum temperature gradients within the gage length.

SUMMARY

Additional furnace work using the 25-KW induction power supply has indicated reliable long time performance at 4500° F. As time permits, this range will be extended to 5000° F.

The detailed check out of the prototype, flat, gas bearing has been completed. Bearing operation is very stable at 0.0005" gap. The design of the spherical bearing has been started.

The grips were checked with a single graphite specimen and indicated satisfactory performance with specimen failure at the anticipated ultimate stress.

The loading system has been assembled, aligned, and operational check out completed.

A design study of the optical strain analyzer has continued. Some components are ordered and others are being fabricated.

During the next month, the work will proceed in the following areas:

1. The preliminary resistance-type furnace will be checked out using a graphite specimen in place in the furnace.
2. The reliability of the induction-type furnace will be established to 4500° F by repeated runs.

3. The design of the spherical gas bearing will be completed and fabrication started.
4. Little will be done on the grips.
5. The load system will be checked out on a steel specimen.
6. The design study and preliminary fabrication of parts for the optical strain analyzer will continue.

FURNACE

A preliminary induction furnace has been assembled and checked out. Using this preliminary design, 1" carbon rods have been heated to 4800° F with very small power settings on the 25-KW generator.

More work is necessary in this area before any conclusions can be reached concerning (1) coil configurations necessary to match the load and (2) the influence of the induction field on the reflectors, furnace parts, and components of the load frame in close proximity.

Flowmeters, check valves, and pipes to mix the furnace purge gases have been installed on the control panel.

GAS BEARING

During the last month, the setup for the evaluation of the gas bearings was employed to obtain the necessary data required for the final design. Many runs were made at various loads, clearance gaps, supply pressures, and orifice conditions. Evaluation of the data is very encouraging and indicates that the desired performance of the gas bearing will be achieved with a minimum amount of difficulty.

After consideration of all factors, it was decided to incorporate the existing prototype bearing into the final system. It was further decided that one spherical bearing, in conjunction with the translation bearing, should prove sufficient. These changes will result in large savings of cost and time while not adversely affecting the over-all performance.

Shop drawings for the spherical bearing are now being made. During the next month, these will be completed along with detailed drawings of the modifications to the prototype bearing to adapt it to the system. A preliminary check has revealed that the cost and time required for the fabrication of the above items should be reasonable. Effort will be concentrated on securing these items during the next month.

GRIPS

Due to the concentration of effort on the evaluation of the gas bearings, the work on grip development during the month was very limited. One specimen made of graphite rod was loaded to failure at 1300 psi (near ultimate) using the same procedure as described with the steel specimen in the last report. This one test is not sufficient evidence of grip performance, but it does indicate that no serious problems should arise.

LOADING SYSTEM

The basic load frame has been leveled, grouted, bolted in place, and the running mechanism checked out for general performance.

The worm-gear jack has been revised to guarantee alignment of the screw shaft. The entire mechanical loading system has been aligned. The mechanical loading system operates smoothly and should perform satisfactorily.

The hydraulic system has been connected and checked out, but the strain rate must be recalibrated. The complete loading system will then be operable.

A linkage arrangement for pulling standard steel tensile specimens is being made. When it is completed, some standard specimens will be pulled. By pulling these standard specimens, familiarity with the operating characteristics of the load frame will be obtained. Also, in this preliminary work, the specimen will be instrumented with strain gages to determine any bending moments that may be induced in the specimen by nonuniaxial loading. This instrumented specimen will be run in other standard testing machines,

as well as the Atomic Energy Commission load frame, in order to obtain some data on the bending moments produced in a specimen by commercially available testing machines. These experiments should provide a concrete indication of the requirements of the gas bearings. Later, a comparison of this data with data obtained using the gas bearings will indicate their real performance.

OPTICAL STRAIN MEASUREMENT

During October, the design study of the optical strain analyzer was continued, and the principal areas of interest are listed below.

1. Mechanical design study of shutter wheel and adjustable apertures.
2. Detailed optical study of dual objective lenses.
3. Detailed design of lens tubes for dual objectives.
4. Design study of servo system.

The detailed mechanical and optical design will be continued into the month of November and will be discussed in a later report. Fabrication of some of the special components is now in progress, and other standard components are on order. The servo system under consideration is described in the following paragraphs.

The system consists of two telescopes; each telescope follows a pair of flags or markers diametrically opposed on the gage points of the test specimen. A reference or tracking telescope follows the motion of the top pair of flags and causes the entire telescope assembly to follow the motion of the upper gage points. A lower or measuring telescope is mounted on the reference telescope and driven with respect to it to determine the elongation of the gage length of the specimen as the flags move relative to one another. The telescope servos provide a coarse measurement of relative displacement of the flags. A more sensitive measurement is provided by two optical servos operating directly from the photoelectric image analyzer.

In order to explain the servo system, the coordinate system will first be discussed, and the equation representing the measurement

scheme will be presented. The error in measurement due to the difference in performance between an ideal system and a practical system is pointed out. The system that is currently being studied for mechanizing the measurement scheme is then presented and its operation described.

Coordinate System

The coordinates for the extensometer telescopes in Figure 1 are drawn with respect to an arbitrary inertial reference. Here X_{F1} represents the location of the top flag and X_{F2} the location of the bottom flag. The initial separation of the flags is defined as the gage length and is represented here by Δ . The extension of the flag separation in excess of the initial Δ is represented by δ .

The telescope positions are characterized by their optical axes; X_{T1} represents the top or tracking telescope, and X_{T2} represents the bottom or measuring telescope. Initially, the telescopes are aligned so that each focuses on its respective flag. The telescope separation is then Δ . Any change in separation from Δ is defined as x_2 and represents the relative motion of the telescopes.

Displacement of a flag relative to the optical axis will cause a corresponding shift of the image relative to the optical axis in a proportion defined as S_T ; this shift is defined as d_1 and d_2 as shown in Figure 1.

If the parallel plate angle, denoted by θ_1 (or θ_2), is not zero, there will be a further shift in the image at d_1 (or d_2) by the amount of X_{W1} or X_{W2} . The proportionality factor, S_W , is the ratio of image displacement to plate angle.

Based on these coordinates, we obtain the following equations for d_1 and d_2 .

$$d_1 = (X_{F1} - X_{T1}) S_T + S_W \theta_1 \quad (1)$$

$$d_2 = [(X_{F1} - X_{T1}) + (\delta - x_2)] S_T + S_W \theta_2$$

These equations depend only on the parallel plate angles, the relative motion of the telescopes, the extension of the sample, and the error of

the tracking telescope. We notice that if we cause d_1 and d_2 to be zero, then subtraction of the equations eliminates the error of the tracking telescope and gives δ in terms of measurable quantities. Thus we obtain

$$\delta = \left(\frac{S_w}{S_T} \right) (\theta_1 - \theta_2) + x_2 \quad (2)$$

where θ_1 and θ_2 are measurable parallel plate angles and x_2 is measurable relative telescope travel. The equation represents the coarse mode of operation. For the fine mode, the telescopes are clamped so their relative motion is zero. Thus equation (2) represents the fine mode when x_2 is set equal to zero.

The quantities d_1 and d_2 are converted to electrical signals and used to operate the servo systems, which are diagrammed in Figure 2 and will be described shortly. Since the servo systems are physical systems, they may not be able to cause d_1 and d_2 to be zero, but only be reduced to some minimum value:

$$d_1 = E_1$$

$$d_2 = E_2$$

Now we obtain the effect of servo error on the measured value of extension δ . Equation (2) becomes

$$\delta = \left(\frac{S_w}{S_T} \right) (\theta_1 - \theta_2) + x_2 + \left(\frac{E_2 - E_1}{S_T} \right) \quad (3)$$

This equation defines the mechanization of the system that is required to measure the extension δ and includes the effect of system error. The servo system must be designed to minimize the errors E_1 and E_2 .

Servo System

A. Coarse Mode

The servo system presently being studied is sketched in a simplified form in Figure 2. Each telescope measures the difference

between a flag and its optical axis and provides an indication of d_1 (or d_2). In a similar manner, each optical parallel plate causes an indication also.

Consider first the tracking telescope system (Figure 2). For the moment, assume that the difference $(X_{F1} - X_{T1})$ is a constant. The optical servo is a position servo, and so the angle θ_1 will increase negatively until d_1 is exactly zero. Since $(X_{F1} - X_{T1})$ is a constant, it follows that θ_1 is a constant. Now, consider the tracking servo loop: this loop has the property that a constant θ_1 will cause the telescope to move at a constant rate, or X_{T1} will increase (or decrease) linearly with time. Under this condition, the assumed constant, $(X_{F1} - X_{T1})$, will decrease to zero, θ_1 will also decrease to zero. Thus if the flag is stationary, (X_{F1} is constant) eventually X_{T1} will exactly match X_{F1} and the difference becomes zero. When the difference is zero, the angle θ_1 must be zero, and as a result X_{T1} must be stationary. Therefore, the tracking telescope will align itself exactly with the flag.

In the coarse mode, the operation of the measuring telescope is similar. In fact, the optical servo systems are identical for both systems. If the telescope position X_{T2} does not agree with the flag position X_{F2} , the telescope will move so as to cause exact agreement.

In actual usage, the top flag X_{F1} will move downward at a more or less constant rate. The lower flag also will move down at the same rate plus an additional rate caused by the extension δ . If we consider the tracking system only, we see that a constant telescope rate is required. In the steady state, the difference $(X_{F1} - X_{T1})$ will be a constant if both X_{F1} and X_{T1} have the same rate but differ in instantaneous position. This is shown in Figure 3. As was pointed out, the constant difference $(X_{F1} - X_{T1})$ results in a constant θ_1 , which in turn generates a constant telescope rate. For the optical servo, since θ_1 is constant, d_1 is zero, and therefore the error E_1 is zero.

In the measuring telescope system a slightly different action occurs. Initially the system caused X_{T2} to equal X_{F2} ; therefore θ_2 and x_2 are zero, assuming that the x_2 potentiometer is effectively zeroed initially. Refer again to Figure 2 and consider that the elongation δ is zero and X_{F1} is increasing. Since X_{F2} and X_{T2} increase as X_{F1} and X_{F2} , there must be a constant at d_2 . Therefore, the measuring telescope system will cause x_2 to increase until d_2 is zero and then stop.

Further relative motion x_2 is unnecessary due to the tracking action of the first servo. Since d_2 is zero, both θ_2 and E_2 are zero. This behavior is in agreement with equation (3). We have assumed $\delta = 0$, but

$$\theta_1 \neq 0$$

$$E_1 = 0$$

$$E_2 = 0$$

$$\theta_2 = 0$$

and x_2 has a value as is required to balance the equation.

Consider further the coarse mode and examine the behavior when the elongation is not zero but tends to increase somewhat linearly with time. From Figure 2 it is seen that the linear increase in δ requires a similar increase in x_2 . The difference $(\delta - x_2)$ is a constant and produces a constant θ_2 , which generates the required linear increase in x_2 . Under these conditions, the error E_2 will still be zero. Thus in equation (3), all quantities are measurable, and the system errors are zero.

It must be pointed out that there will be a steady error in both systems for accelerations of X_{F1} and δ , but the error due to velocity is zero. This will not be true for the fine mode of operation.

B. Fine Mode

In the fine mode of operation, the telescopes are clamped together to prevent relative motion. The measuring telescope servo is turned off; hence x_2 is zero. The tracking telescope follows the flag as previously described and carries the measuring telescope with it. In the fine mode, the total elongation δ is small and the rotating parallel plates provide the desired accuracy and sensitivity of translation of the images.

As before, first consider δ to be zero. The difference $(X_{F2} - X_{T2})$ which results from the tracking telescope system will cause θ_2 to assume a constant value. Thus the error E_2 of the measuring optical servo due to the tracking error $(X_{F1} - X_{T1})$ is zero.

Next, examine the effect of simultaneously applying a linearly increasing δ ; but first note that θ_2 is a constant and d_2 is zero. Thus the effect of δ may be considered independently of the over-all translation. For the lower optical servo system, a linearly increasing δ yields a linearly increasing θ_2 and requires that the error E_2 be nonzero. Since this error is due to the rate of increase of the input, it is termed the velocity error. Thus in the fine mode, equation (3) shows that the measurement of δ has an inherent error due to E_2 . It is a design criterion for the optical servo that the velocity error be small.

Summary

The system has been described in a simplified manner by presenting only the steady-state behavior. It is the problem of the control system design to determine parameters for hardware such that the dynamic response of the system yields the desired steady-state behavior in an acceptable time interval. It is also necessary to determine the dynamic behavior so that the errors E_1 and E_2 due to dynamic behavior are less than the specified maximum.

Present Work

At present, the system described in the previous section is being studied to determine its properties, the possible response times, and possible sources of error in order to produce specifications for hardware. Under way is a study to outline the realizable range of dynamic operation for the optical servo, subject to the constraint that the error in δ due to E_2 shall be less than a specified number.

When this is completed, the dynamics of the tracking telescope system will be determined. The telescope carriage-drives are basically nonlinear in that the operation is dependent on coulomb friction. Furthermore, a number of cross-coupling effects are present which have been omitted in the simplified block diagram of Figure 2. The behavior of the over-all system in the presence of these effects must be considered in the determination of numbers for the final system design.

ACKNOWLEDGMENTS

The furnace and loading frame phases of the work are being performed by Paul T. Howse, Jr. Frank J. Digesu is developing the gas bearing. The optical strain analyzer is being developed under the direction of Albert L. Thomas, Jr., Head of the Instrument Development Section. The mechanical design of the analyzer is being carried out by Norman L. Francis and W. O. Watkins. Alvin N. Bird, Jr., is responsible for the optical design. The servo system analysis is being done by Mr. Robert R. Bairnsfather, Senior Engineer.

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Figure 1. Coordinates for Extensometer Servo System.

From Figure 1,
 $X_{F2} = X_{F1} + \Delta + \delta(t)$
 $X_{T2} = X_{T1} + \Delta + x_2$

Figure 2. Simplified System Block Diagram for Extensometer.

Figure 3. Tracking Action of Tracking Telescope.