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DETERMINATION OF SURFACES OF CONSTANT INELASTIC STRAIN RATE AT ELEVATED TEMPERATURE*

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ABSTRACT

An experimental effort to perform special exploratory multiaxial deformation tests on tubular specimens of type 316 stainless steel at 650°C (1200°F) is described. One test specimen was subjected to a time-independent torsional shear strain test history, and surfaces of constant inelastic strain rate (SCISRs) in an axial/torsional stress space were measured at various predetermined points during the test. A second specimen was subjected to a 14-week time-dependent (creep-recovery-creep periods) torsional shear stress histogram SCISRs determinations made at 17 points during the test. The tests were conducted in a high-temperature, computer-controlled axial/torsional test facility using an Oak Ridge National Laboratory developed high-temperature multiaxial extensometer. The effort was successful, and for the first time the existence of surfaces of constant inelastic strain rate was experimentally demonstrated.

1. INTRODUCTION

In classical plasticity the concept of yield surfaces in multiaxial stress space plays a central role, not only in the definition of initial yielding but in determining subsequent plastic flow. At high temperatures the deformation behavior of structural alloys is strongly time dependent. Consequently, the significance of yield surfaces breaks down, and it has been proposed that in their place the concept of surfaces of constant inelastic strain rate might be utilized. Such surfaces, called SCISRs, can be shown to have a potential nature and thus constitute the basis of a rational multiaxial viscoplastic constitutive theory. To further pursue such a concept, exploratory multiaxial test results are required.

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The objective of this effort was to provide supporting data, in the form of surfaces of constant inelastic strain rate, for NASA's efforts to formulate constitutive theories.

A surface of constant inelastic strain rate (SCISR) is determined by loading the specimen at a constant effective stress rate in the two-dimensional axial/torsional stress state in various directions until a predetermined inelastic effective strain rate is reached. After each probe, the stress is returned to the initial starting point; thus a locus of points (surface or constant inelastic strain rate) is established.

Oak Ridge National Laboratory (ORNL) undertook the effort because of its experience in constitutive equation development and high-temperature testing and because of its existing multiaxial test facilities, including computer-controlled axial/torsional test machines and high-precision, high-temperature, multiaxial extensometers. This paper presents the experimental results of two SCISRs test series at 650°C (1200°F) on 316 stainless steel. One test investigated the effects of prior plastic "time-independent" deformations on subsequent SCISRs, while the second test investigated effects of prior creep "time-dependent" deformation.

The remainder of this paper is divided into four major sections. In the first, the multiaxial test facility and test specimen are briefly described. The software computer control programs are briefly described in the second section, while the third section contains a discussion of the test procedures, conditions, and data results. Finally, conclusions are stated in the last section.

2. TEST FACILITY AND SPECIMEN

The multiaxial test facility is a high-temperature facility designed to subject a tubular specimen to simultaneous axial and torsional loads as prescribed by a computer control system, function generator, or under manual control. The principal components of the multiaxial test facility (see Fig. 1) are an axial-torsional material testing system, a radio frequency induction heating system, a computer-based data acquisition and control system, a special ORNL-developed axial-torsional extensometer, and support equipment (plotters, filters, indicator, etc.).

The MTS model 810 material test system consists of an axial-torsional load frame, actuators, load cell, electronic control system, and hydraulic power supply. The load frame and actuators are rated for maximum loads of 222 kN (50 kips) and 2.8 N-m (25,000 in.-lb). An MTS load cell with reduced rated maximum load capacity, 111 kN (25 kips) and 1.4 N-m (12,500 in.-lb), is used for greater accuracy and resolution. The control system is based on the standard MTS model 442 controllers which provide closed-loop servo-hydraulic control with a selectable feedback; load, strain, or stroke. The system includes a cycle counter, a function generator, a phase shifter, and several X-Y flatbed plotters. The controllers and load cell were calibrated using a secondary standard (traceable to National Bureau of Standards) to four selectable maximum loads for each channel, axial and torsional. These maximum loads were 89, 44, 22, and 9 kN (20, 10, 5, and 2 kips) axially and 1130, 565, 128, and 57 N-m (10,000, 5000, 2000, and 500 in.-lb) torsionally. The hydraulic power supply is a constant volume 0.19 L/S (3 GPM) MTS model 502.03 system.

A 5 kW Lepel model T-5-3-KC-BW high frequency generator heats the specimen. The generator is closed-loop controlled with a Babber-Colman model 520 temperature controller and an intrinsic Chromel-Alumel thermocouple mounted on the outside surface of the specimen in the center of the gage length. A water-cooled copper load coil is mounted around the specimen.

The major features of the computerized control and data acquisition system are shown in Fig. 2. Control voltage signals are sent to the integrators via the digital-to-analog (D/A) converters, where fixed input voltages to the integrators give ramp-function set-point outputs to the MTS system. Run, reset, and panic switches are provided. The axial and torsional strain signals from the MTS are first conditioned (low-pass filtered) and then sampled by analog-to-digital (A/D) converters, which have an integrating feature to reject 60 Hz noise. The two set-point signals are also sampled by A/D converters.

The computer utilizes an expanded version of the DEC FOCAL language, a high-level interpreter language similar in structure to BASIC. The control program as written for the present system is stored on three disk files, which are swapped in and out of the core as required to execute the various types of programs. The execution speed of the FOCAL program and the operations of the A/Ds and D/As and other peripherals are such that the required computations can be accomplished for 1-s data sampling intervals. Extensive software programs developed to execute the SCISRs testing effort will be described in a later section of this paper.

An axial-torsional mechanical extensometer suitable for fatigue testing tubes at high temperature was developed several years ago at ORNL.[1,2] For the SCISRs tests, this original device was modified to provide greater accuracy, better resolution, minimal backlash, and minimal noise characteristics in a radio frequency environment. The extensometer in its present form is shown positioned on a test specimen in Fig. 3. The instrument's two quartz probes are located in indentations spaced 25.4 mm (1 in.) apart on the specimen. The differential axial displacement and differential rotation between the indentations are translated to proximity transducers through a system of Gimbal rings and swivels using flexural pivots for bearings. The flexural pivots eliminate backlash and reduce the friction to a constant small value. The HITEC Proximic proximity transducers are noncontacting, and their output using HITEC model 3200 signal conditioning units is a high-level signal, 0 to 10 DC volts for full-scale movement of 0.000 to 1.02 mm (0.000 to 0.040 in.). The electrical sum of two transducers gives a measure of axial strain while the difference of two transducers measures the torsional (one-half the engineering shear strain, γ) strain. Two additional ORNL-developed amplifier and filter modules are used to apply appropriate scaling factors to give a direct measure of axial and tensorial shear strain. The filter network is a three-pole low-pass Bessel filter with selectable time constants for reducing the inherent transducer noise and radio frequency induced noise.

These tests were conducted on tubular specimens fabricated from 51-mm (2-in.) bar stock of 316 stainless steel, ORNL reference heat 8092297. The specimens had a nominal 34.8-mm (1.37-in.) working section with a 26.04-mm (1.025-in.) outside diameter and a 1.91-mm (0.075-in.) wall thickness, as shown in Fig. 4. The specimens were solution annealed by heating to 1065°C (1950°F), holding for 30 minutes, and then forced-argon rapid cooled to minimize residual stresses. The heat treatment process was performed in an ert atmosphere of argon gas which produced no visible oxidation.

A room-temperature SCISR test was performed using the facility and procedures described in this paper to access the high-temperature extensometer system. A specimen was installed and aligned in the facility. The axial and torsional extensometer outputs were adjusted to the equivalent strain readings of full bridge foil gage systems for both axial and torsional elastic load changes. The two crosstalk parameters between the extensometer channels were adjusted for their minimum values of ±3 με axial strain for approximately ±200 με tensorial shear strain and ±3 με tensorial shear strain for approximately ±300 με axial strain. Crosstalk strain-vs-strain loops averaged 3 to 5 με hysteresis at zero load or strain. The torsional stress-strain histogram shown in Fig. 5 was executed on the virgin specimen, and SCISRs were determined at the four indicated points. Only a description of the extensometer performance during this test will be presented since high-temperature test results are of most interest here. Analog load-strain plots of the extensometer outputs and the full bridge foil gage outputs were nearly identical for all probes and preloads. For example, during the preload from point 2 to 3, the torsional foil gage bridge read a change in strain of 0.8965% while the extensometer read a change of 0.8380%, for approximately a 6% difference. This is good agreement since the bridge was composed of 3.8-mm (0.125-in.) foil gages in a bending compensating configuration while the extensometer was essentially a quarter bridge 25.4-mm (1-in.) noncompensating device. Also, during the same preload, the axial foil bridge read a change of +27 με while the axial extensometer channel read a change of +63 με, thus verifying good torsional-to-axial crosstalk characteristics.

3. DESCRIPTION OF TEST CONTROL PROGRAM

The computer exercises control over the axial and torsional stress set point voltage inputs sent to the MTS system. Typically, a probe will begin at a point near the center of the surface of constant inelastic strain rate and proceed slowly outward at a prespecified rate and angle in the axial-torsional stress plane. The elastic strain rate is measured and used as a reference against which subsequent measurements are compared to determine the inelastic strain rate (ISR). When the measured (total) strain rate exceeds the elastic rate plus a specified ISR value (100 με/min for the tests described here), the stress and strain values at that point are recorded, and the set points are driven back to the starting point.

When the program is executed, the operator is first asked to supply scale factor information for the stress and strain signals, the values of estimated elastic stress-to-strain ratios, the desired load rate (typically 10 ksi/min) and ISR (100 με/min), and (optionally) preload target information for up to two preload sequences to be run before the SCISR test.

After the set point ramps begin, the two strain signals are sampled once per second for eight seconds to determine, by a least-squares fit procedure, the individual strain rate values. From that point on, once every second the stress and strain signals are sampled, and a new measured effective strain rate, using RMS weighting of the axial and torsional rates, is calculated every 3 s. This process continues until the ISR exceeds the limit (typically 100 με/min).

When the limit is reached, the set point integrators' input voltages are set to zero (stopping the ramps), and the end point values of stresses, strains, and strain deviations are recorded. The stress set point trajectory is reversed (180°) immediately to minimize creep at the surface; then, after the set points reach their initial values, the program begins again at the next preprogrammed angle, etc., until all 16 probes are completed. All pertinent data from the runs are stored on hard disk (and later saved on mag tape) for further analysis.

3. TEST PROCEDURES, CONDITIONS, AND DATA RESULTS

Each specimen tested was instrumented with four rectangular strain gage rosettes prior to installation in the MTS axial-torsional test system. These gages were used for alignment purposes to ensure correct application of the loads. After alignment, the gages were calibrated in a full-bridge arrangement, which compensated for bending, to read axial and tensorial shear strain in order to check out and calibrate the high-temperature extensometer. Ten intrinsic Chromel-Alumel thermocouples were used to measure the temperature profile; six of these were mounted on the outside surface of the central 25.4-mm (1-in.) specimen gage length while four were attached to the 28.58-mm (1.125-in.) outside diameter shoulder. The induction heater load coil was adjusted to obtain a uniform temperature profile over the specimen gage length at 650°C (1200°F). Final calibration at 650°C of the extensometer in the elastic range was performed by adjusting its output to the calculated strain values using the **Nuclear Systems Materials Handbook**[3] material property values for 316 stainless steel and the room-temperature measured strain values. These gage factor changes varied with the largest being approximately 5% and the smallest less than 1%.

Each of the two high-temperature tests was conducted using the above described control system and SCISR program with the MTS testing machine under load control. The target inelastic effective strain rate was 100 με/min) and the probe loading rate was 0.069 MPa/min (10 ksi/min) for both tests. The nominal torsional stress-strain histogram for the first 650°C SCISR test program was that shown in Fig. 5, with the SCISRs corresponding to the numbered points with one significant exception. After applying the initial preload shear strain of 0.5%, the initial probe for SCISR No. 2 was made in the positive shear strain direction (the same direction as the preload). Because the stress-strain curve was relatively flat, very abrupt yielding apparently occurred during the probe, and as a result an additional 0.34% shear strain was accumulated. Thus, the initial preload was effectively 0.84% rather than 0.5%, and the second SCISR surface corresponded to a preload of 0.84%. Following determination of SCISR No. 2, the specimen was returned to zero load and strain, and SCISR No. 3 was determined. The −0.5% preload was then applied and the test continued. Figure 6 shows the results for all the surfaces of this test. Note that two duplicate sets of probes were done for two of the SCISRs. The square symbols on these plots represent the initial probe results and the circles and triangles represent results from repeat probes which were occasionally done to check questionable points. Load changes during the preloads were conducted at a constant strain rate of 500 με/min.

The initial SCISR is smoothly defined by two separate sets of probes. The results show that the virgin specimen contained just a small amount of anisotropy (the initial SCISR is not quite centered at zero), but the SCISR is well described as a Mises type surface. Subsequent surfaces show a little less consistency, and they move (up or down) along the torque shear stress axis in the same direction as the last previous preload. The amount of bias varies from 15 to 35% while the width along that axis is relatively constant for the four surfaces.

A 14-week time-dependent SCISRs testing program at 650°C with torsional creep loads was subsequently executed on a new virgin specimen. Whereas the SCISRs determinations in the first test series were after "time-independent" preloads, the emphasis of this second test was on time-dependent effects. Figure 7 depicts the planned or nominal program with a duration of 14 weeks (98 days) and 17 points of SCISR determinations. The test was executed with several exceptions to this planned program; therefore, the actual torsional stress vs time histogram for the time-dependent portion of the test is shown in Fig. 8.

A torsional stress level, τ_o, of 88.3 MPa (12.8 ksi) was chosen to produce an expected creep shear strain, $\gamma/2$, accumulation of about 0.5% in 1008 h (42 days) of testing. The virgin specimen was cycled at 650°C under strain control to introduce isotropic hardening and minimize the plastic strain on the initial loading. Forty-five cycles were performed with a tensorial shear strain range of ±0.173% and a strain rate of 0.05%/s. A constant axial compressive stress of approximately 24 MPa (3500 psi) was accidentally applied to the specimen during these cycles because of an inducted zero shift in voltage on the axial load channel. After the cycling, the axial load cell cable was rerouted away from a radio frequency cable which eliminated the zero shift. Peak-to-peak torsional shear stresses of ±90.1 MPa (±13.07 ksi) were attained by the last cycle.

The specimen was loaded to the target torsional stress level, 88.3 MPa, under MTS load control after determination of two initial SCISRs. A large plastic tensorial shear strain, which the cycling was supposed to prevent, occurred (approximately 0.43%) and a consequent large creep rate was obtained (approximately 0.05%/h after 4 hours). The torsional stress level was therefore lowered to 40 MPa (5.8 ksi) at the end of the fourth hour.

The test continued without incident until a plant power failure occurred between SCISR Nos. 9 and 10 (with no load on the specimen). The specimen was reheated and the test continued. Several subsequent surfaces after the power outage showed a definite bias in the negative axial direction. A possible explanation for this behavior is that an overload could have occurred in the negative axial direction during the power failure. This is possible since the hydraulic power supply provides some pressure while spinning down after a power loss, but control of the servovalve is immediately lost.

The torsional shear stress level was increased to 60 MPa (8.7 ksi) between SCISR Nos. 14 and 15 because most of the earlier surfaces were similar and more time-dependent creep deformation could be accumulated at the higher stress. This increase led to exceeding the calibrated strain limit of 1%, but no strain measurement degradation was observed.

A total of 35 SCISRs was determined, at least two at each histogram point (see Figs. 7 and 8). Figure 9 shows the first initial surface (SCISR No. 1, Figs. 7 and 8), the last surface after the first creep period (SCISR No. 7, Figs. 7 and 8), the last surface after the recovery period (SCISR No. 13, Figs. 7 and 8), and the last surface after the final creep period (SCISR No. 17, Figs. 7 and 8). A small amount of contraction along the axial stress axis and slight movement in the plus shear stress direction of SCISR No. 7 relative to SCISR No. 1 can be observed. There appears to be no changes in the remaining surfaces, either quantitatively or qualitatively.

5. CONCLUSIONS

A key result of this testing effort is that surfaces of constant inelastic strain rate exist and can be determined or measured at an elevated temperature, 650°C. This conclusion is validated or deduced by the execution of the test programs and by the consistency of the surface results, especially the repeated surfaces. To our knowledge, this is the first successful determination of high-temperature surfaces of constant inelastic strain rate.

Although conclusions regarding the effect of these SCISRs data on different theories will be left to the constitutive equation developers, several results can be stated. First, the surfaces did not move or change shape in the axial/torsional stress state by any large significant amount. Second, by comparing Figs. 6 and 9, a deduction that plastic deformations have a larger effect than creep deformations can be stated. Last, SCISRs determined immediately after large plastic deformation (see Fig. 6) show more inconsistent results than SCISRs which have not undergone immediate prior plastic deformations. It is believed that this behavior is real and not a result of the testing system. Therefore, the state of the material may not have been in a steady-state condition at the time of the SCISR determinations.

Another conclusion of the effort is that the extensometer system and software control system performed extremely well in a difficult application. It was first necessary to measure high-temperature strains (axial and torsional) which were decoupled, then to differentiate these signals with as little noise as possible to attain a reasonably small target inelastic strain rate, which, in turn, would minimize changes in state of the material during a surface determination. Plus, the above process took place in a noise generating radio frequency induction heating environment.

6. REFERENCES

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2. J. R. Ellis and W. K. Sartory, "Evaluation of a Capacitance-Based Tension-Torsion Extensometer," pp. 35-51 in **High-Temperature Structural Design Program Prog. Rept. Dec. 31, 1982**, ORNL-5948, Union Carbide Corp., Nuclear Division, Oak Ridge Natl. Lab., Oak Ridge, Tenn.

3. U.S. Department of Energy, **Nuclear Systems Materials Handbook**, Oak Ridge Natl. Lab., Oak Ridge, Tenn.

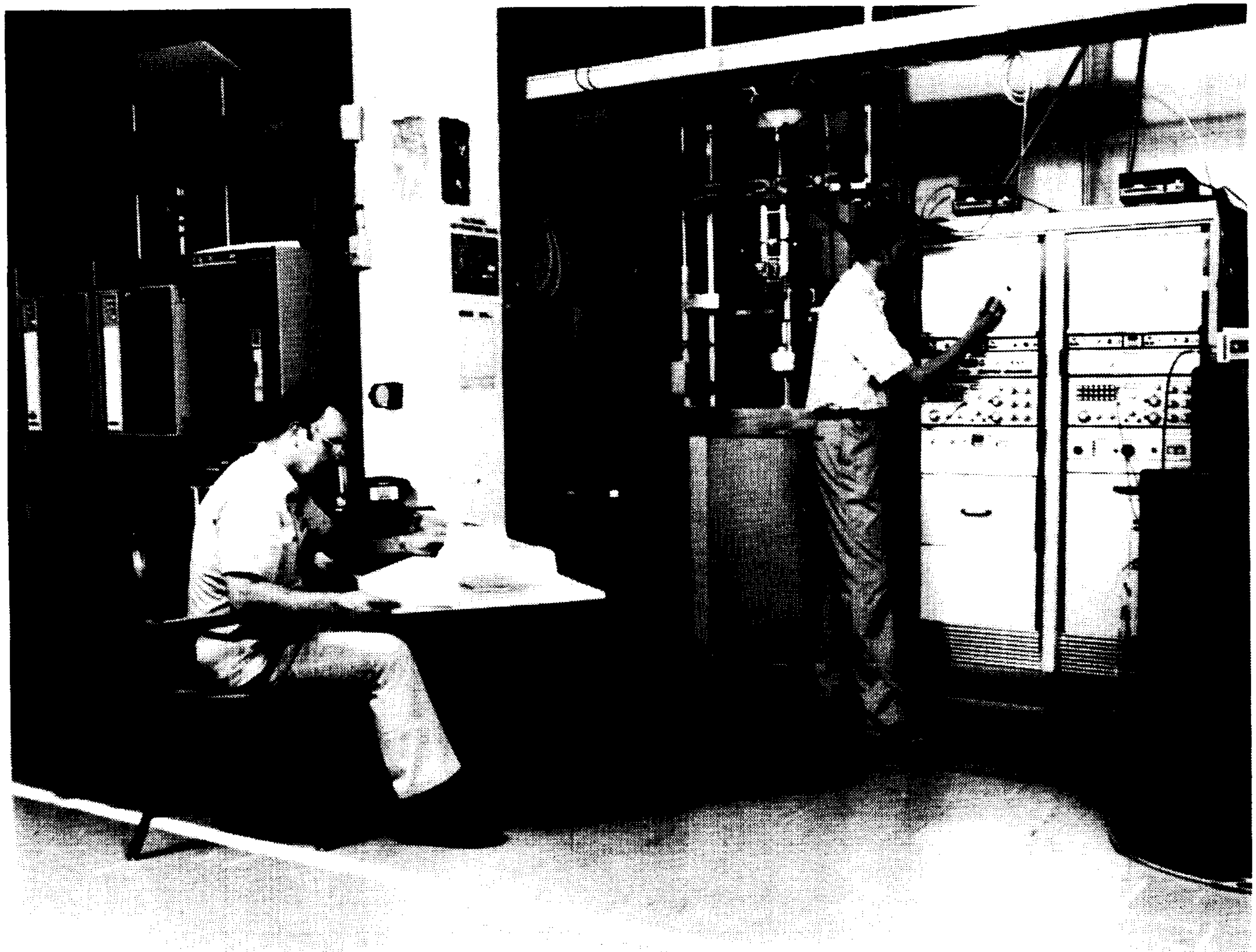


Fig. 1. Multiaxial test facility used in SCISRs tests.

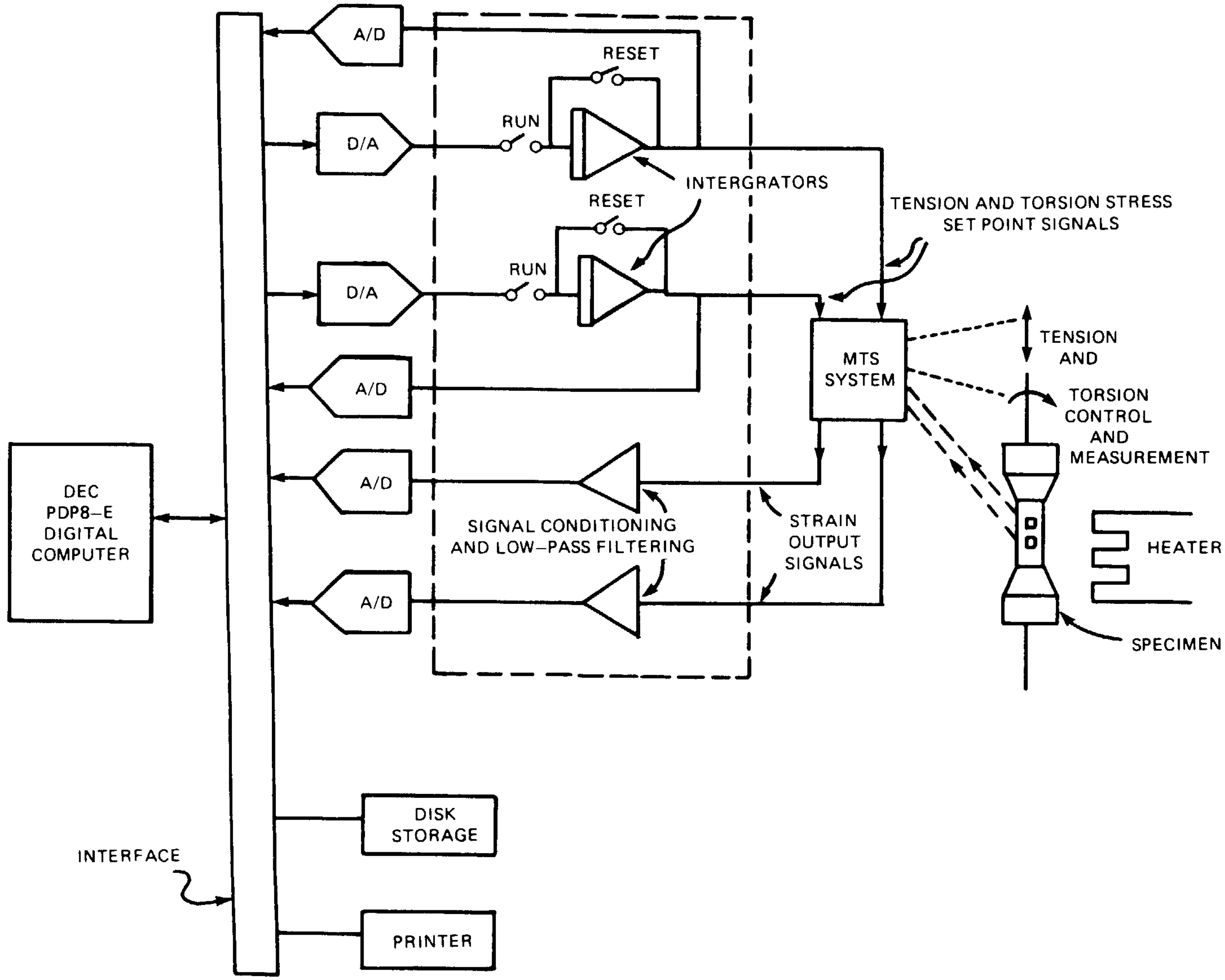


Fig. 2. Computer control system block diagram.

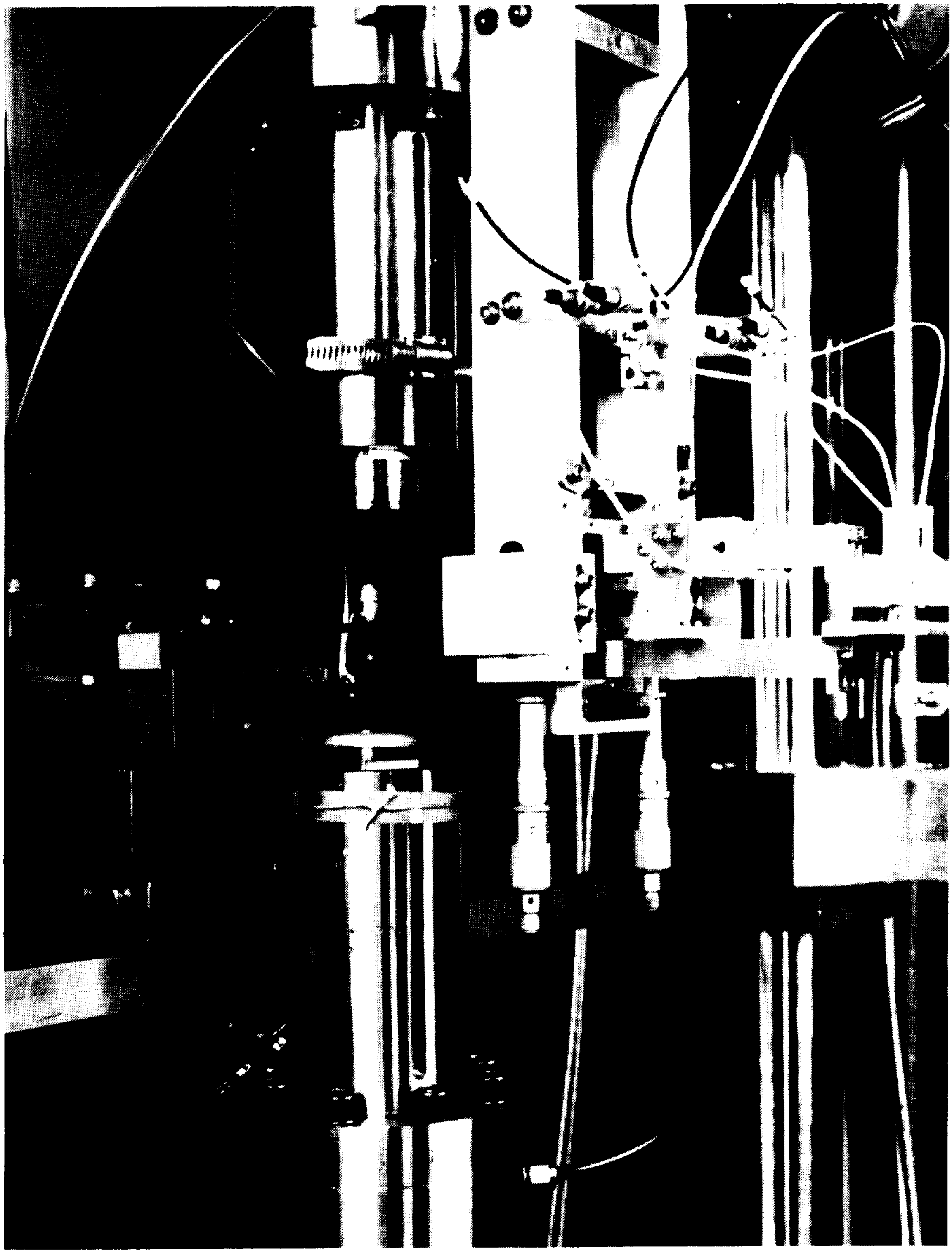


Fig. 3. Axial/torsional high-temperature extensometer mounted on the test specimen.

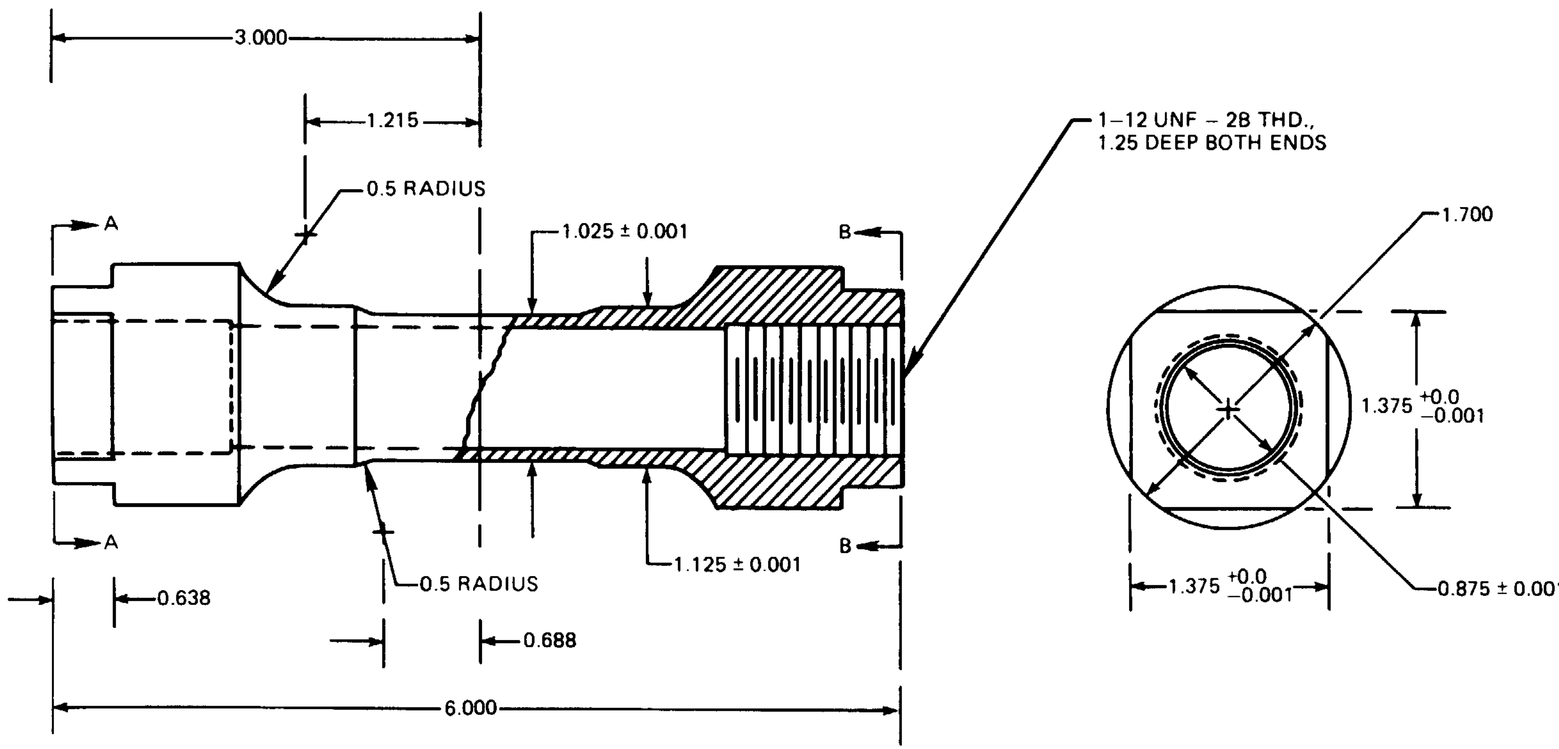


Fig. 4. Schematic of the test specimen. Dimensions in inches. (1 in. = 25.4 mm)

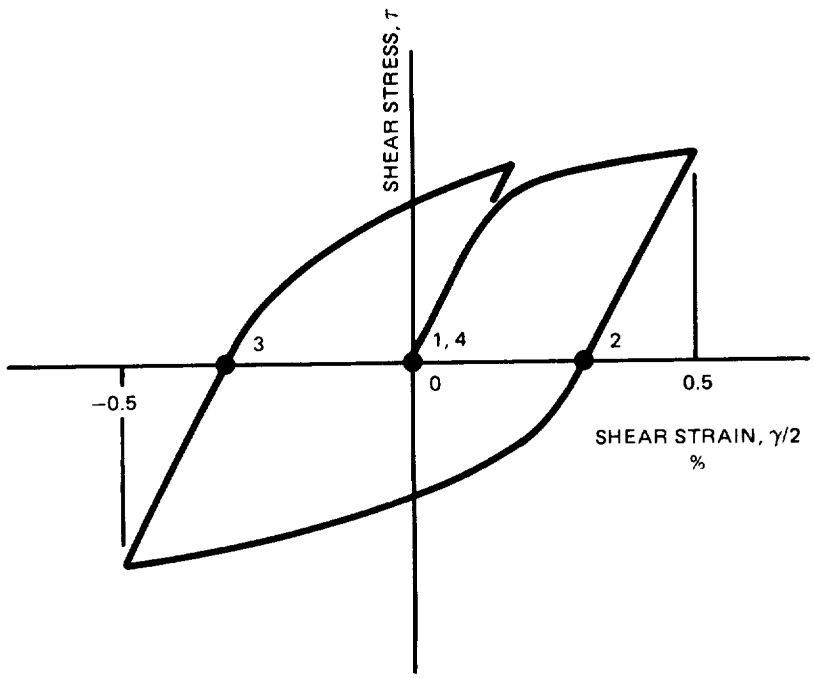
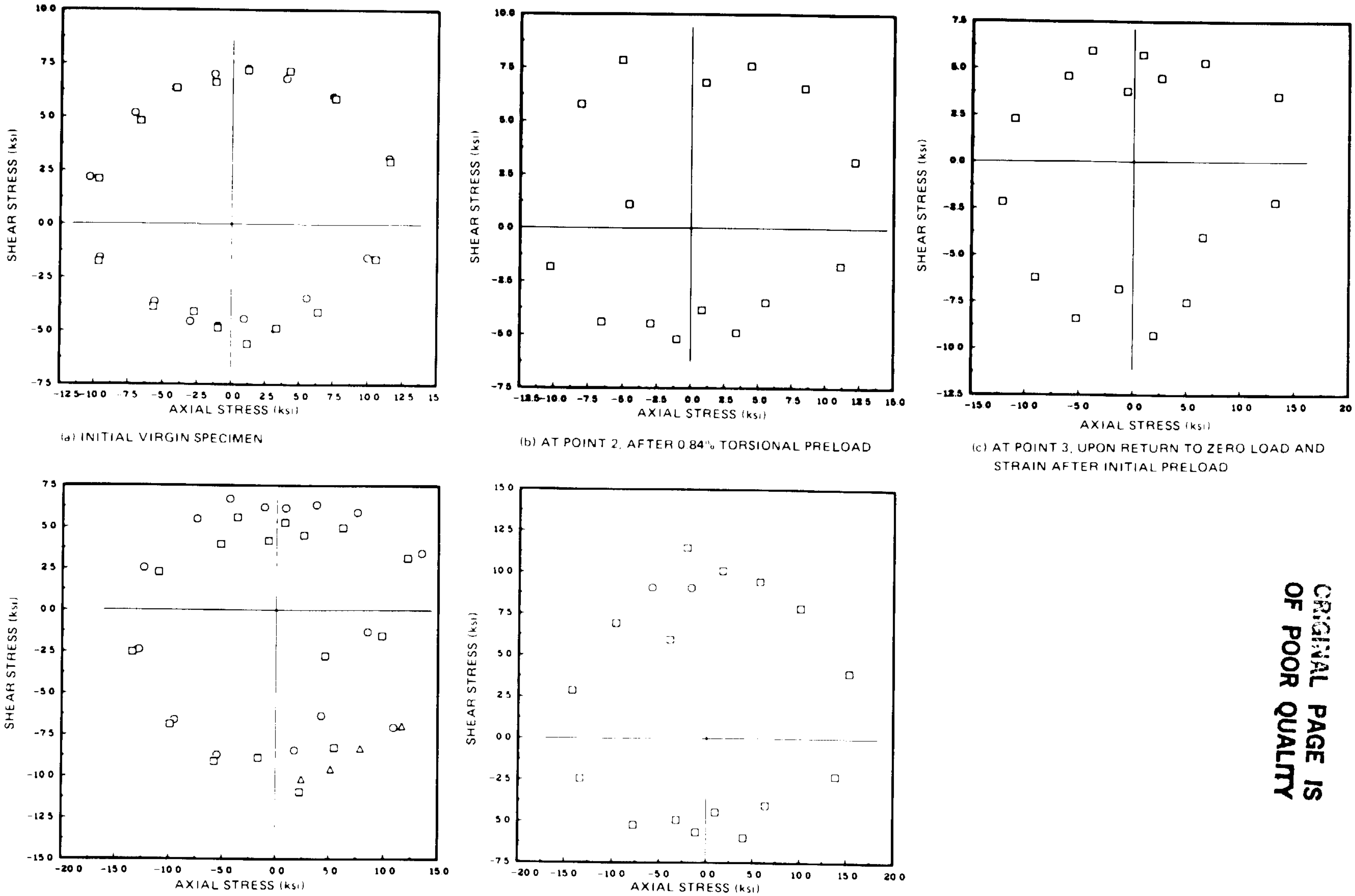


Fig. 5. Torsional stress-strain history for reference SCISRs test program. SCISRs were determined at the four labeled points. Each SCISRs measurement consists of 16 sequential probes to a maximum effective inelastic strain rate of 0.01%/min. The shear strain is tensorial strain (one-half the engineering shear strain, γ).



(a) INITIAL VIRGIN SPECIMEN

(b) AT POINT 2, AFTER 0.84% TORSIONAL PRELOAD

(c) AT POINT 3, UPON RETURN TO ZERO LOAD AND STRAIN AFTER INITIAL PRELOAD

(d) AT POINT 4, AFTER −0.5% TORSIONAL PRELOAD

(e) AT POINT 5, AFTER RETURN TO ZERO LOAD AND STRAIN

Fig. 6. Measured 650°C surfaces of constant inelastic strain rate for reference SCISRs test program. Note that the initial torsional preload was effectively 0.84% rather than 0.5% and that an extra SCISR (point 3) was determined.

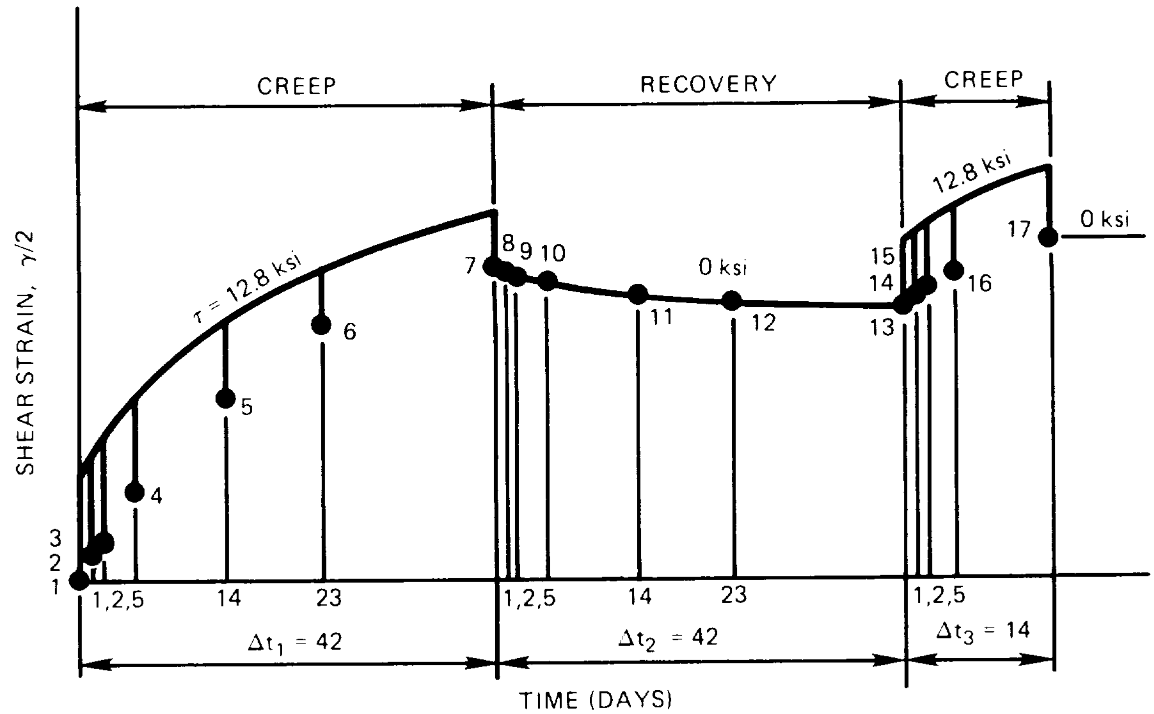


Fig. 7. Nominal time-dependent tensorial shear strain–time history for the second test program. SCISRs were to be determined at the 17 labeled points.

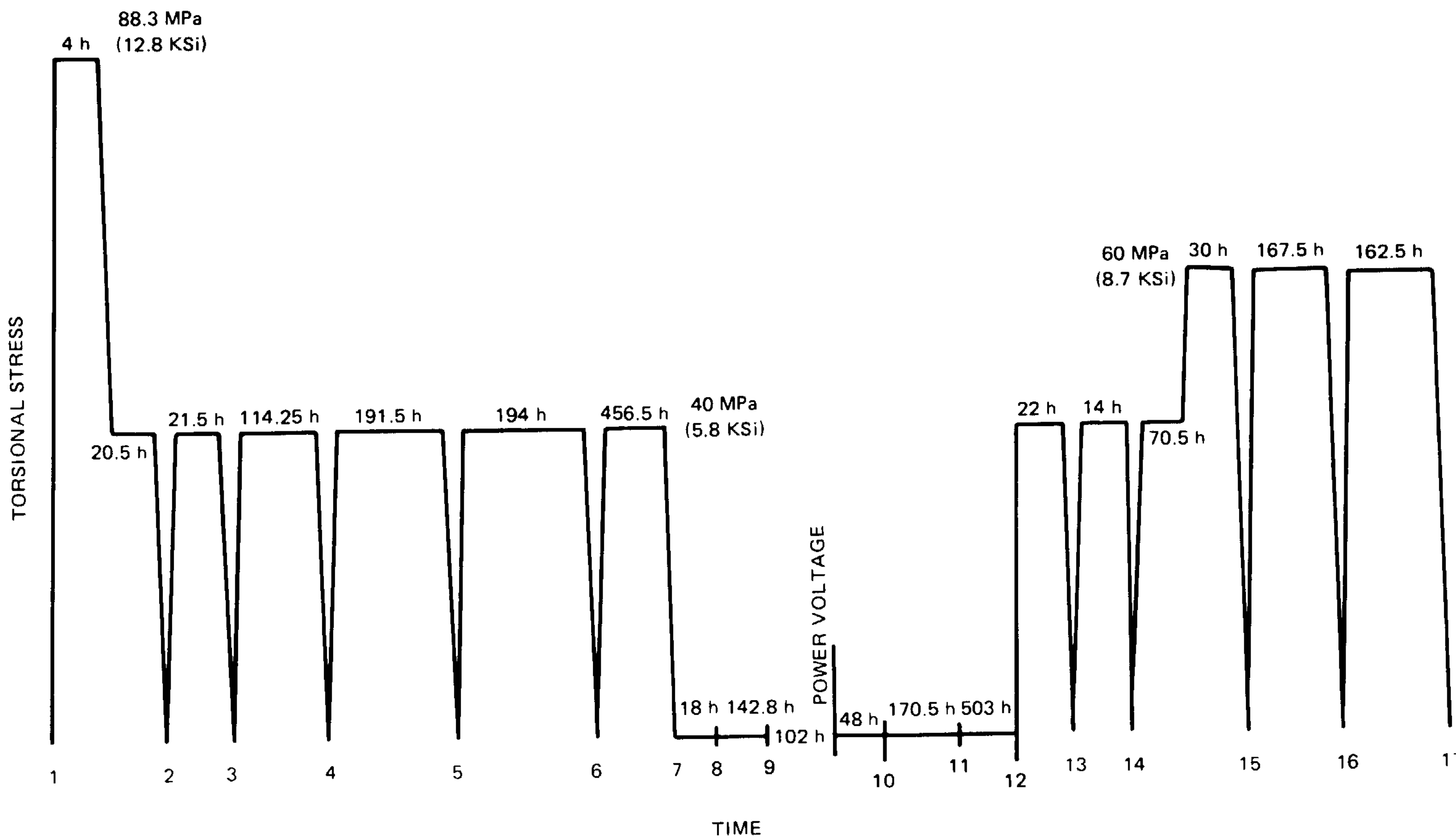


Fig. 8. Actual torsional shear stress–time history for the time-dependent test program. SCISRs were determined at the 17 labeled points.

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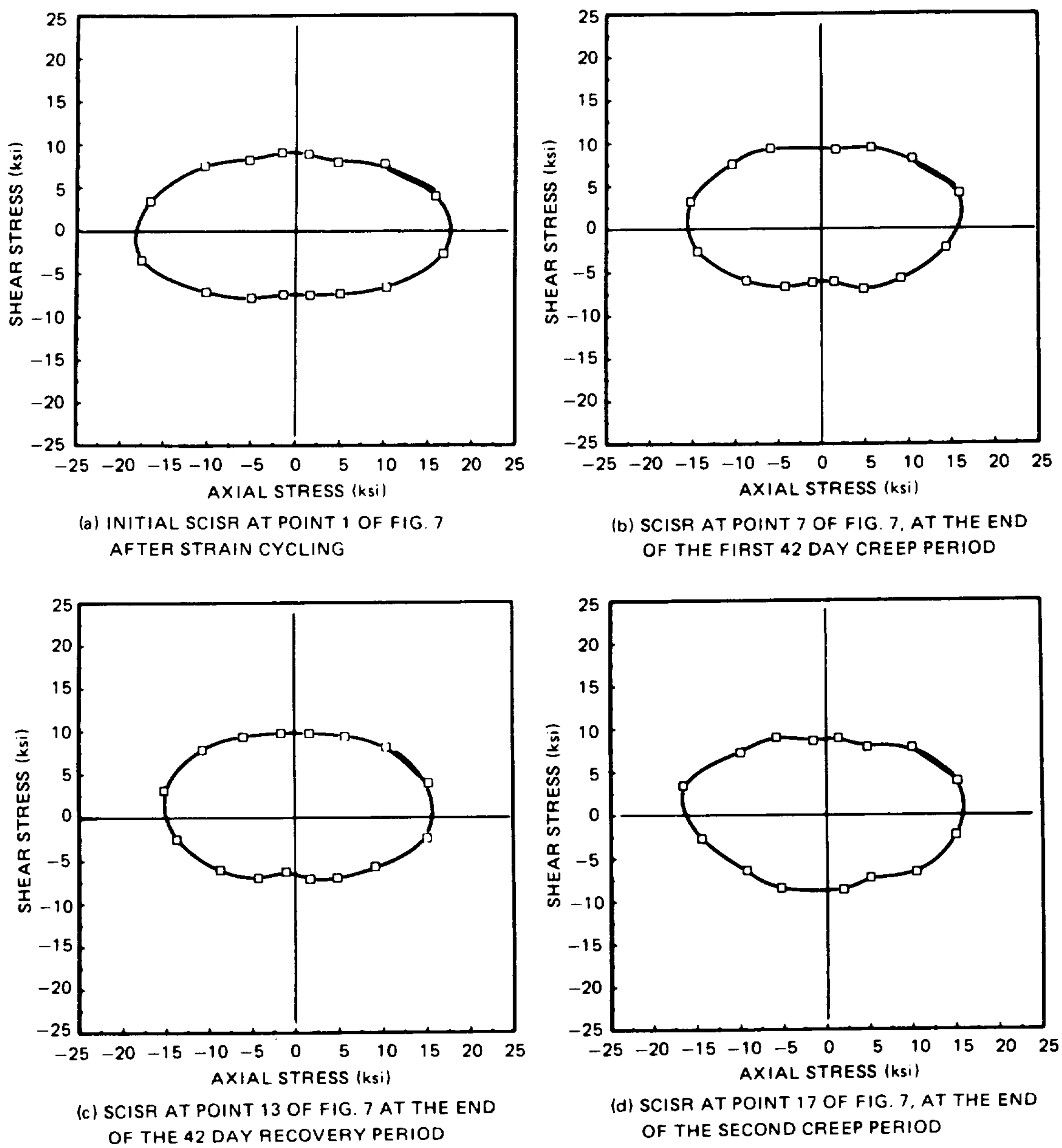

Fig. 9. Measured 650°C surfaces of constant inelastic strain rate for the time-dependent test program. (1 ksi = 6.895 MPa)