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DEVELOPMENT OF A COMPUTER-CONTROLLED HOT-DEFORMATION APPARATUS AT NIST

Yi-Wen Cheng
Yair Rosenthal
Harry I. McHenry

National Institute of Standards and Technology
U.S. Department of Commerce
Boulder, Colorado 80303-3328

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Yi-Wen Cheng
Yair Rosenthal[†]
Harry I. McHenry

Materials Reliability Division
Materials Science and Engineering Laboratory
National Institute of Standards and Technology
Boulder, Colorado 80303-3328

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[†]Guest worker, on leave from Nuclear Research Center-Negev, Beer Sheva, Israel



DEPARTMENT OF COMMERCE, Robert A. Mosbacher, Secretary
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, Raymond G. Kammer, Acting Director

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Yi-Wen Cheng
Yair Rosenthal*
Harry I. McHenry

Materials Reliability Division
National Institute of Standards and Technology
Boulder, CO 80303

This report describes a computer-controlled hot-deformation apparatus suitable for thermomechanical-processing (TMP) simulation of forging and steel plates. The apparatus was designed and built at the National Institute of Standards and Technology, and has the following main features: a servohydraulic load frame with a 250 kN capacity in tension or compression; a variable-actuator traveling speed up to $55 \text{ mm}\cdot\text{s}^{-1}$; a multiple-strike capability with controllable displacements and strain rates; a maximum heating rate of $150^\circ\text{C}\cdot\text{s}^{-1}$ with a 10 kW induction heater (for a cylindrical steel specimen 9 mm in diameter and 18 mm in height); a maximum cooling rate of $25^\circ\text{C}\cdot\text{s}^{-1}$ with helium-gas cooling; and vacuum to $1.33 \times 10^{-3} \text{ Pa}$ ($1 \times 10^{-5} \text{ Torr}$) within 25 min. Source codes of the computer programs that perform system control, data acquisition, and data analysis are included in this report. The apparatus has been used to perform the direct-quenching simulation of the ASTM A710 plate steel, and forging simulation of the directly cooled microalloyed AISI 1522 and 1141 steels. Results of these studies are presented.

Key words: computer control; continuous-cooling transformation; controlled rolling; direct quenching; forging; high-strength low-alloy steels; hot-deformation apparatus; microalloyed steels; physical simulation; thermomechanical processing.

* Guest worker, on leave from Nuclear Research Center-Negev, Beer Sheva, Israel.

I. INTRODUCTION

Over the last twenty years, one of the most significant advances in the steel industry has been the development and production of thermomechanically processed (TMP) high-strength low-alloy (HSLA) steel plates, which offer an excellent combination of strength, toughness, and weldability. Production schedules for TMP plates require careful control over each step including slab reheating, number of rolling passes, deformation and temperature for each pass, and cooling conditions throughout rolling. Numerous experiments are required to optimize these parameters for a new process or a new alloy system. Experiments in a pilot-scale rolling mill, as has been typically done in the past, are time consuming and costly, and measurements of rolling parameters are sometimes difficult. As a result, several small-scale laboratory simulation techniques, such as cam plastometry [1], torsion [2], and plane-strain [3] or axisymmetrical [4] hot compression have been developed to alleviate the problem. Small-scale laboratory simulations offer the obvious advantages of economy, versatility, and reproducibility.

Small-scale laboratory apparatuses have been used for the following studies:

- . To study the static recrystallization of austenite between intervals of hot working [5];
- . To estimate the hot-deformation strength of austenite during controlled rolling in a plate mill [6];
- . To study dynamic recrystallization [7];
- . To determine the nonrecrystallization temperature of austenite in microalloyed steels [8];
- . To simulate the direct quenching after controlled rolling of a HSLA steel [9].

In the past, the laboratory-scale apparatuses have been mainly applied to study plate steels. Such apparatuses, however, are also being used to study microalloyed steel wire [10] and seamless steel tube [11]. With the increased use of directly cooled forging steels, the apparatus can be used as an instrumented forging press for detailed study of these steels. This report

describes the development, at the National Institute of Standards and Technology (NIST), of a hot-deformation apparatus, which is suitable for TMP simulation of steel plates and forging. Examples of studies which have been done using the apparatus are presented.

II. DESCRIPTION OF THE HOT-DEFORMATION APPARATUS

The actual operations of a rolling mill for plate rolling and of a forging shop are very complex. The apparatus developed and described here is by no means capable of duplicating the actual operations. Instead, the apparatus has been designed only to simulate the idealized thermal and mechanical treatments a metal (in the present case, a steel) receives during a rolling or forging operation. The TMP sequences can be simplified and depicted as those shown in figure 1. The important parameters in TMP simulations include the reheating rate, the soaking temperature and time, the compression temperature (T), the time interval (Δt) between compressions, the amount of strain (ϵ) in each compression, and the strain rate ($\dot{\epsilon}$). The apparatus to be described here has the versatility to simulate a wide range of TMP sequences typically encountered in plate rolling or forging.

The hot-deformation apparatus is shown in figure 2 and the inter-connection among various components of the apparatus is given in figure 3. The apparatus can be loosely broken down and described by individual components according to their functions: loading system, heating and control system, cooling and control system, vacuum system, assembly for dilation measurement after deformation, computer and peripherals, and computer programs for system control, data acquisition, and data analysis.

Loading System: The load frame is a servohydraulic machine with a load capacity of 250 kN. The machine has been upgraded in terms of actuator travel speed. The upgrade includes the installation of a $5.7 \times 10^{-3} \text{ m}^3 \cdot \text{s}^{-1}$ servo-valve with a $3.8 \times 10^{-3} \text{ m}^3$ pilot manifold, which is set up for a $9.5 \times 10^{-3} \text{ m}^3$ accumulator mounted on the pressure side and a $1.9 \times 10^{-3} \text{ m}^3$ accumulator on the return side. This enables actuator control at speeds up to $500 \text{ mm} \cdot \text{s}^{-1}$, which is adequate for plate-rolling or forging simulations.

The design of the load train is detailed in figure 4. Taking the specimen as a cutoff line, we can treat the vertical load train as two separate portions. The top portion is the hydraulic actuator, which contains a loading ram (steel), a suspended piston (Ti alloy), a plug (Ti alloy), and a quartz platen. The upper end of the loading ram is connected to a load cell

and the hydraulic system, which controls the movement of the loading ram. The bottom of the loading ram is connected to the Ti piston with a spring. The separation of the top portion of the load train into a loading ram and a piston facilitates the measurement of the length change of a steel specimen during cooling and phase transformation. The measurement will be further discussed later in this report.

The use of fused quartz as a loading platen at elevated temperature was suggested by Ouchi [12] and has been proved to be satisfactory. Silicon nitride has also been used for the same purpose [13]. The advantages of fused quartz are low thermal conductivity, low thermal expansion coefficient, relatively high strength and toughness at elevated temperatures, ease of machining, and low cost. To ensure smooth surfaces, the contact surface of the platens are polished with 1 μm diamond powder before an experiment. The quartz platen is glued (with high-temperature epoxy) and physically clamped onto the Ti plug, which is in turn threaded into the piston. The bottom portion of the load train is stationary and contains the specimen. The load train is rigid and well aligned. The maximum diameter of a cylindrical steel specimen to be tested at 800°C is about 10 mm. Larger specimens often break the quartz platen during compression. This limits the load that can be applied to the platen to about 50 kN.

The most desirable deformation mode for plate-rolling or forging simulations is a constant true-strain-rate compression, which not only closely simulates the actual plate rolling but also eases data analysis and interpretation. The constant true-strain-rate compression is accomplished through interactive control of the load train by a personal computer (PC) using the equation

$$H(t) = H(0) \exp[-t\dot{\epsilon}] \quad (1)$$

Here $H(t)$ is the specimen's instantaneous height at time t , $H(0)$ is the initial height, and $\dot{\epsilon}$ is the desired constant true strain rate. Equation (1) is derived from the total strain equation with a constant $\dot{\epsilon}$:

$$\epsilon = \ln[H(0)/H(t)] = \dot{\epsilon}t \quad (2)$$

The implementation of eq (1) using a PC and its peripherals will be described later in this report.

Theoretically, there is no limit to the value of $\dot{\epsilon}$ that can be used according to eq (1). In practice, however, there are limitations on the value of $\dot{\epsilon}$ that can be obtained in an experiment. The limitations are not with the throughput of a PC or its peripherals; that is, the computation of eq (1) and the rate of digital-to-analog conversion, but with the responses of a servohydraulic system to its commands. Figure 5 shows examples of the responses of the servohydraulic actuator in the current apparatus to various $\dot{\epsilon}$ inputs. Ideally, the time-vs.-total true strain relation is a linear line, which is evident in the cases of $\dot{\epsilon}$ equal to 0.97 s^{-1} (fig. 5a) and 4.8 s^{-1} (fig. 5b). However, at higher $\dot{\epsilon}$, the actuator responds too slowly at the beginning, then too fast, and finally overshoots at the end of the stroke movement. This phenomenon has been observed at $\dot{\epsilon} > 9.5 \text{ s}^{-1}$, particularly those of 19.2 s^{-1} (fig. 5f) and 24 s^{-1} (fig. 5g).

Going too slowly at the beginning, then too fast, and finally overshooting at the end is typical of and inherent in the servohydraulic system at high $\dot{\epsilon}$. To overcome the problem in a compressive experiment, we retract the actuator at the beginning of a test so that the specimen is compressed using only the lower half of the total true strain. Then, the value of $\dot{\epsilon}$ is calculated using the actual signal from actuator responses, such as those shown in figure 5.

Heating and Control System: Major components of the system are a 10-kW, 450-kHz induction generator (rf frequency) and a programmable temperature controller. The heating is provided by the generator and controlled by the temperature controller, which has ramp-and-soak and multiple-set-point capabilities. Temperature is monitored with a type-S thermocouple (Pt-10%Rh) welded directly onto the specimen. Thermal cycles in an experiment are preprogrammed into the controller. The heating coil is a 4.76-mm-diameter Cu tube. The ON/OFF switch of the generator is connected to a PC through a relay for the ON/OFF control, which is important for a controlled cooling experiment.

Cooling and Control System: Cooling of a specimen is controlled with a PC by regulating gas flow onto the specimen through a 6.35-mm-diameter Cu coil concentric with the heating coil. The side of the cooling coil facing the specimen is perforated to provide a gas flow that cools the specimen uniformly. Either helium or nitrogen gas is used for cooling. Because of its higher specific heat (5230 vs. 1030 J·kg⁻¹·K⁻¹ at 25°C) and greater mobility, helium gas is more efficient than nitrogen in rapid cooling. For a cylindrical steel specimen 10 mm in diameter by 18 mm in height, the cooling rate is controllable to a maximum rate of 25°C·s⁻¹.

In the initial design for cooling control, a process controller was used to control the gas flow rate. After a few trials, we found that the time needed for the process controller to interact with a flow-rate meter, and then to control a gas regulating valve was too long. Therefore, the controlling function of the process controller could not be properly realized. The current practice has been to use a PC to open the gas regulating valve at a predetermined value. Cooling rates were calibrated from experiments with various settings in the gas regulating valve. To date, the system can set only one flow rate for one experiment. This means that the system cannot perform constant cooling-rate experiments because cooling is faster at higher temperatures than at lower temperatures due to larger thermal differentials between a specimen and its surrounding (constant ambient temperature) at higher temperatures. This cooling profile, however, closely resembles that of forging parts which are force-cooled while being transported through a conveyer.

Vacuum System: A vacuum is provided mainly to prevent specimen oxidation at high temperatures. The vacuum also provides additional stability in temperature control. The vacuum system consists of a stainless-steel chamber, and a 100-mm diffusion pump with associated equipment such as a mechanical pump, pressure gages, and a valve controller. The system can achieve a vacuum of 1.33×10^{-3} Pa (1×10^{-5} Torr) within 25 min. The chamber is 381 mm long, 381 mm wide, and 432 mm high, and is made of a 9.5-mm-thick stainless-steel plate. The bottom of the chamber is fastened to a stationary steel plate (see figs. 2 and 4). The outside of the chamber is reinforced with welded

stainless-steel webs to provide rigidity, which is essential for precision in dilation measurements.

View ports and various feedthroughs, such as those for instrumentations, thermocouples, rf frequency power, and liquids, were provided with the chamber. O-rings were used to seal the top and bottom portions of the load train. It should be mentioned here that at a pressure of about 1.33×10^{-1} Pa (10^{-3} Torr), gases will be ionized between the specimen and the heating coils. At this pressure, it is impossible to heat the specimen because the rf field arcs and shuts off the rf generator.

Assembly for Dilation Measurement After Deformation: The temperature and time at which the transformation of austenite occurs during continuous cooling plays an important role in determining the microstructure and, therefore, the properties of a steel. A knowledge of transformation temperature and time can be valuable in understanding the effects of composition, processing, and cooling rate on the microstructure and properties, and can thus aid the development of new and improved steels.

The methods available [14] to determine transformation and time include thermal analyses, metallographic techniques, electrical-resistivity measurements, magnetic-properties measurements, X-ray diffraction analyses, and dilatometry. Among these methods, thermal analyses and dilatometry are the most commonly used techniques for the detection of austenite transformation during continuous cooling. For the application described in this report, our experience shows that dilatometric measurements give more definite and precise transformation temperatures than thermal analyses. In this section, a dilatometric-measurement device capable of detecting the decomposition of austenite in steels cooled directly from the finish deformation operation is described.

The principles of dilatometry are associated with the dimensional changes accompanying the decomposition of austenite. An acceleration or reversal of dimensional changes during cooling indicates the occurrence of a solid-to-solid phase transformation, which may be correlated subsequently with the temperature and time at which it occurs.

As noted in the Loading System section, to facilitate the measurement of length change of a steel specimen during cooling and phase transformation, the top portion of the load train was separated into a loading ram and a piston, which were connected by a spring (fig. 4). In an experiment, the loading ram is retracted after the end of a compressive deformation so that a gap of approximately 5 mm is maintained between the loading ram and the piston. This leaves a force of about 40 N resting on the specimen during dilatometric measurements. The force, which is required to maintain a constant contact between the upper platen and the specimen, includes the spring loading plus the weights of the piston, the plug, and the quartz platen.

Any changes in specimen's length during cooling and phase transformation will result in axial movements of the piston, which are monitored by a displacement gage. In order for the displacement gage to monitor the piston movement, the displacement gage has to be placed before an experiment, at the precise position at which the bottom end of the piston is anticipated to rest after the end of a compressive deformation. The displacement gage has a resolution of 0.9 μm and a travel range of 3.5 mm. From the measured length change-vs.-temperature data, such as that shown in figure 6, phase-transformation temperatures are determined using statistical techniques.

Computer and Peripherals: The computer used is a 20-MHz 80386 personal computer, equipped with a board-level analog-to-digital (A/D) plug-in board having a 45-kHz throughput and with an IEEE GPIB board. The A/D board contains eight differential A/D channels (for input) and two digital-to-analog (D/A) channels (for output). The peripherals of the computer include a 20-MHz 80387 math coprocessor, a line printer, a 60-MByte hard disk, a 1.2-MByte floppy disk drive, and a 360-kByte floppy disk drive.

The hot-deformation apparatus is also equipped with a programmable digital storage oscilloscope and a programmable waveform generator. The oscilloscope includes four 15-bit 100-kHz digitizers and is used for high-speed data acquisition (each channel can store up to 4000 data points when all four channels are operating simultaneously); the waveform generator is used to provide 5 V for opening a gas valve in controlled cooling experiments.

Computer Programs for System Control, Data Acquisition, and Data Analysis:

Computer programs were written in a scientific, stack-oriented, incrementally compiled programming language [15,16]. Two programs, (1) System Control and Data Acquisition program, and (2) Data Analysis and Summarizing Report Production program, were written to perform system control, data acquisition, and post-test data analysis. The source codes of the computer programs are attached in Appendixes 1 and 2.

The program for system control dictates the sequence of operations of the various components of the hot-deformation apparatus. A detailed flow chart of the System Control and Data Acquisition program is given in figure 7. With reference to the figure, the thermal cycle from heat-to-soak temperature to the last compression is controlled by an autonomous programmable temperature controller, as described in the section on Heating and Control System. During an experiment, the computer continuously reads the thermocouple signals through an A/D channel, because temperatures determine when a compression is to take place. (Alternatively, time can be used as the controlling parameter). As soon as the predetermined testing temperature is reached, the computer triggers the oscilloscope for data acquisition through the GPIB bus and then sends a string of signals through a D/A channel for controlling the movement of the stroke, which performs the actual compression. The same sequence is repeated until the completion of the last compression; then the computer commands the oscilloscope for transferring the data onto floppy disks, turns off the induction heating generator, and opens a pneumatic valve for controlled cooling. To turn off the induction-heating generator, the computer sends a 5-V signal, through a programmable waveform generator on the GPIB bus, to break the heating circuit.

In an experiment, a compression is specified by the original height, $H(0)$, and the final height, $H(f)$, of the specimen and by the deformation mode, such as constant $\dot{\epsilon}$. For a constant $\dot{\epsilon}$ compression, the total true strain is

$$\epsilon = \ln[H(0)/H(f)] = \dot{\epsilon} t_t \quad (3)$$

and the total compression time, t_t , is

$$t_t = \epsilon / \dot{\epsilon} = \ln[H(0)/H(f)] / \dot{\epsilon} \quad (4)$$

Using eqs (1) and (4), the computer computes a string of exponentially decreasing numbers, which are converted to voltages and calibrated to represent displacement in millimeters, and sends the numbers to the stroke controller through a D/A channel. Figure 8 shows a typical output of the D/A channel and the stroke response of the hydraulic testing machine. With reference to the computer output signals, the stroke response has a delay and a small overshoot at the end of the curve. These are due to the inherent characteristics of the servohydraulic system at high $\dot{\epsilon}$. The response delay and the overshoot diminish at lower $\dot{\epsilon}$.

Because of the discrete nature of digital signals, such as the inputs to the D/A channel from the computer, it is desirable to have as many points as possible for a compression test in order to obtain a continuous, smooth output from the D/A channel. However, the number of data points that can be used in a compression test is limited by the computation time needed by the computer and the execution time needed by the D/A channel. For the present computer system at a $\dot{\epsilon}$ of 15 s^{-1} , the maximum number of data points that can be processed while maintaining a satisfactory result is about 200. This number of data points can be used with $\dot{\epsilon}$ as low as 1 s^{-1} . At lower $\dot{\epsilon}$, more points are required to maintain a continuous, smooth signal.

The communication between the PC and the various devices is through eight A/D channels, two D/A channels, and the IEEE GPIB bus. The desired direct measurements from an experiment typically include load, stroke movement, temperature, and the specimen's length change with respect to temperature. The apparatus was originally designed to use three of the eight A/D channels to acquire these measurements. After a few trials, we found that simultaneously one PC alone could not satisfactorily control the stroke movement through one D/A channel and acquire the data of load, stroke movement, and temperature through three A/D channels. When one PC performs these functions simultaneously, a maximum of only 50 data points can be executed for stroke control at a $\dot{\epsilon}$ of 10 s^{-1} ; this produces discontinuous signals with discrete steps. The problem lies in the fact that after the

computer sends one stroke-controlling signal through a D/A channel, it has to open three A/D channels to receive data of load, stroke movement, and temperature. The time needed to complete a set of this sequence is too long to be satisfactory.

Therefore, in high $\dot{\epsilon}$ experiments the functions of stroke control and data acquisition must be performed by separate, autonomous devices. This can be done with a second PC equipped with high-speed A/D boards or other data-acquisition devices. In the present apparatus, we used a programmable digital storage oscilloscope, which equips with two floppy-disk drives for instant data storage. For a multiple-strike experiment, the signals of load, stroke movement, and temperature are captured with the oscilloscope and saved onto the floppy disks. This sequence is repeated for every compression. The time required for saving the signals from the oscilloscope onto the floppy disks is about 6 s, which is the minimum time required between two consecutive compressions.

Because of the high-speed nature of a plate-rolling or forging simulation (one compression is typically completed within 0.1 s), synchronization of the stroke-control subprogram and the data-acquisition subprogram is crucial. Without proper timing in triggering the oscilloscope for data acquisition and storage, the information needed from an experiment would be lost. The synchronization is complicated by the different command execution times required by different devices. In our case, the time required to activate the stroke-control sequence through the D/A channel is much shorter than that required to trigger the oscilloscope through the GPIB bus. Thus, the activation of the stroke-control sequence must be delayed after the triggering commands have been sent to the oscilloscope. The optimum delay times between different devices were obtained by trial and error.

The raw data saved on the oscilloscope's disks are load vs. time, stroke movement vs. time, temperature vs. time, and the specimen's length change vs. time. These data on floppy disks can not be retrieved directly by a PC because of differences in disk formats. A specially programmed digital-processing software [17] must be used to enable the PC to read the data from the disks. Depending on the purpose of a simulation experiment, the program

for post-test analysis can calculate the various material properties from load-vs.-stroke movement data. The properties include Young's modulus, proportional limit, yield strength, engineering σ - ϵ curve, true σ - ϵ curve, and strain-hardening characteristics. From the specimen's length change-vs.-temperature data, the program can produce dilation-vs.-temperature curves (fig. 6), from which continuous-cooling transformation (CCT) diagrams can be generated. The operation of the analysis program is interactive and is summarized in figure 9.

III. EXAMPLES OF USING THE APPARATUS

The hot-deformation apparatus described in the previous section is being used to perform the following studies: the direct-quenching simulation of ASTM A710 steel, and forging simulation of the directly cooled microalloyed AISI 1522MV and 1141 forging steels.

Direct-Quenching Simulation of ASTM A710 Steel: Controlled rolling followed by direct quenching (CR-DQ) eliminates the re-austenitizing-and-quenching step required in the conventional quenched-and-tempered (Q-T) heat treatment; thus, it saves energy and reduces manufacturing costs. The CR-DQ process also increases strength and improves the notch toughness of microalloyed steels, when compared to the conventional rolling and direct-quenching process [18].

The conventional process of producing Q-T steel plates is summarized as follows:

1. A slab is reheated to and held at a reheating temperature for a predetermined soaking time.
2. The slab is subjected to several passes of rough rolling.
3. The slab then receives several passes of finish rolling to become a finished plate.
4. The plate is air-cooled to ambient temperature.
5. The plate is reheated to an austenitizing temperature for a predetermined length of time.
6. The plate is quenched and then tempered.

In a CR-DQ process, the slab reheating temperature is lower than that of conventional processes. Step 3 is done at temperatures below the austenite recrystallization temperature. Step 3 is followed by step 6; thus, steps 4 and 5 are eliminated. The objective of the study is to understand the general response of the ASTM A710 steel to the CR-DQ treatments.

Material: The material used for this simulation study was a copper precipitation-strengthened steel: ASTM designation A710 [19]. The chemical composition of the steel in weight percent is

<u>C</u>	<u>Mn</u>	<u>S</u>	<u>Si</u>	<u>P</u>	<u>Nb</u>	<u>V</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>Cu</u>
0.03	0.54	0.002	0.33	0.009	0.052	0.005	0.96	0.93	0.217	1.04

The steel was received in a 19-mm-thick plate form and was conventionally processed, that is, hot-rolled to a thickness of 19 mm, air-cooled, re-austenitized, quenched, and aged. Cylindrical specimens, 10 mm in diameter by 18 mm in height, were taken from the plate; the cylindrical axis coincided with the long transverse direction. A specimen before and after deformation is shown in figure 10.

Experimental Details: In this study, the sequence of CR-DQ was simplified and simulated by two compressions. The simplified temperature-deformation sequences are described in table 1. The first compression simulates the rough rolling and the second compression represents a heavy reduction in the nonrecrystallized austenite region. All specimens were quenched with gas (either helium or nitrogen) immediately after the second compression.

The selection of 900 and 850°C for the second compression, as described in table 1, was based on the results obtained using a double-deformation test [5,8]. As shown in figure 11a, there is no softening in the second compression, indicating no recrystallization at 950°C. Softening is observed in figure 11b, which shows the results tested at 1000°C. Based on figure 11, we conclude that recrystallization occurred between 950 and 1000°C.

Results and Discussion: Figure 12 shows the microstructures and diamond-pyramid microhardness (DPH) measurements of different thermomechanically treated specimens in the as-cooled condition (without aging). Figures 12a and 12b are microstructures of specimens reheated to 910°C, held for 10 min, and then cooled slowly in vacuum with heater power off (fig. 12a) and helium-gas quenching (fig. 12b), respectively. These specimens were not deformed.

Table 1. Temperature-deformation sequences for simplified CR-DQ simulations.

*reheat temperature:	1150°C for 5 min followed by slow cooling at a rate between 0.5 and 1.1°C·s ⁻¹
*first compression:	30% reduction at 1050°C
second compression:	
treatment (a):	30% reduction at 900°C followed by helium-gas quenching at a rate of 16°C·s ⁻¹ between 800 and 500°C
treatment (b):	30% reduction at 850°C followed by helium-gas quenching at a rate of 17°C·s ⁻¹ between 800 and 500°C
treatment (c):	40% reduction at 850°C followed by nitrogen-gas quenching at a rate of 9°C·s ⁻¹ between 800 and 500°C

*applied to all CR-DQ specimens

Figures 12c through 12e are microstructures of specimens with treatments (a) through (c), respectively, as described in table 1. The corresponding DPH numbers are also given along with each microstructure at the upper left corner of each micrograph in figure 12.

Three distinct microstructural features are shown in figure 12. Figure 12a shows that the main constituent is the equiaxed polygonal ferrite (white areas) with randomly dispersed second-phase patches (dark areas), which are thought to be a mixture of pearlite, bainite, and martensite. With increasing cooling rate, a portion of the polygonal ferrite becomes acicular in shape, as shown in figure 12b; the predominant feature is still polygonal ferrite. With the simplified CR-DQ processing, the predominant microstructural features of some specimens change drastically from polygonal ferrite to granular bainite (acicular ferrite) [20], as shown in figures 12c, 12d, and 12e. The second-phase islands in these microstructures (figs. 12c, 12d, and 12e) are thought to be a mixture of retained austenite and martensite [21,22]. The changes in microstructures are also reflected in the DPH measurements as indicated in figure 12.

We considered two ways to explain the change in microstructure from polygonal ferrite as shown in figures 12a and 12b to granular bainite as shown in figures 12c, 12d, and 12e. First, we considered the higher cooling rates;

that is, the polygonal ferrite nose was missed during cooling and granular bainite was obtained. According to the continuous-cooling transformation (CCT) diagram, as shown in figure 13, for the ASTM A710 steel [23], it is necessary to cool the steel from 800 to 500°C in less than 1 or 2 s in order to obtain a predominantly granular bainite microstructure. However, in the present investigation, it took from 18 [treatment (b)] to 35 s [treatment (c)] to cool from 800 to 500°C. Therefore, these cooling rates were not expected to cause the observed drastic change in microstructure.

Second, we considered the increased (bainitic) hardenability of the steel due to the simulated CR-DQ process. This means that the polygonal ferrite nose in the CCT diagram is shifted to the right, as schematically shown in figure 14, and granular bainite forms at slower cooling rates. This best explains the observed microstructures. But what are the mechanisms that cause the hardenability to increase? Deformed, unrecrystallized austenite, as a result of controlled rolling, has been shown to decrease the hardenability of various steels [24,25]; this is contrary to what we observe here.

Hardenability is increased by an increase in austenite grain sizes before transformation [26]. After soaking at 1150°C for 5 min, the austenite grain sizes were about 40 μm in the present study, compared with 10 μm for the CCT diagram [23]. The other probable cause of increased hardenability is a larger amount of alloying elements dissolved in the austenite before transformation; this reduces the rates of ferrite nucleation and growth. The alloying elements come from more dissolution of carbides and/or carbonitrides at the soaking temperature of 1150°C. The dissolution of alloy carbides or carbonitrides is not possible in a conventional Q-T treatment with the austenitizing temperature of 900°C.

The microstructures shown in figure 12 were taken from the middle of the specimens. The microstructures of the specimens without compression (figs. 12a and 12b) are uniform throughout the specimen. For the simulated CR-DQ-processed specimens, the microstructure varies from the surface to the middle of the specimen, as shown in figure 15. The variation of microstructure within a specimen is directly related to nonuniform deformation in cylindrical compression due to barreling. The total strain and the strain

rate reach maxima at the middle of the specimen. They reach minima at points just beneath the contact surfaces; this area is called the "dead zone." The observed microstructures correlate well with this strain-pattern analysis: large strains at the middle of the specimen resulted in small and "pancaked" austenite grains, as shown in figure 15b; small strains near the surface resulted in large and equiaxed austenite grains, as shown in figure 15a. In light of this observation, we should be cautious in interpreting results obtained from a small-scale simulation.

The true σ -vs.- ϵ characteristics of each compression during the CR-DQ simulations are shown in figure 16. The initial flow stress for the second compression is considerably lower than the final flow stress during the first compression, which shows a strong indication that the austenite was already fully recrystallized before the second compression (by considering the true σ -vs.- ϵ characteristics of the second compressions). Figure 16 also shows a strong influence of temperature on true σ - ϵ curves.

The size of a sample after TMP processing with the hot-deformation apparatus is about 20 mm in diameter and 10 mm in height. This size is insufficient for machining a standard tension-test specimen. Therefore, the tensile strengths cannot be measured directly and must be inferred from other types of measurements. In the present study, using specimens taken from the same steel plates, we showed that there are good correlations between (1) yield strengths in tension and yield strengths in compression (fig. 17), and (2) tensile strengths and Knoop hardness numbers (fig. 18).

Studies of Directly Cooled Forging Steels: The directly cooled microalloyed (MA) forging steels have been introduced to the automotive industry as economical substitutions for some quenched-and-tempered (Q-T) grades. These MA steels can achieve tensile strengths comparable to those of Q-T steels, but with lower impact properties. Research to improve the toughness of directly cooled MA steels is increasing. Several approaches to raise the toughness while lowering the ductile-to-brittle transition temperature have been cited in the literature [28,29,30]. These include: (1) lowering the carbon content from 0.5% to 0.35 or 0.25%; (2) lowering the reheating temperature and the finish-forging temperature to control the austenite grain size; (3) adding Ti

(to produce TiN particles) to control austenite grain size; (4) modifying the steel chemistry, such as increasing Mn or Si content; (5) controlling MnS inclusions to increase intragranular ferrite nucleation; and (6) producing low-carbon bainitic steels.

Our study is to provide metallurgical data measured during simulated forging processes so as to optimize forging design and forging procedures. The data will include the true σ - ϵ characteristics of MA steels at high temperature under high $\dot{\epsilon}$, CCT diagrams determined under different forging parameters (reheating temperature, finish-forging temperature, deformation rate), microstructure, and hardness characterization. This is an ongoing research, and this report presents the preliminary results obtained to date.

Materials: The materials used in this study are two MA steels: AISI 1141, a ferritic-pearlitic steel, and AISI 1522, a bainitic steel. The steels were supplied as 25.4-mm (1141) and 31.75-mm-diameter (1522) round bars in the as-rolled condition, produced from continuous casters. The chemical compositions in weight percent are

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Nb	Sn	Al
1141	0.42	1.49	0.015	0.099	0.26	0.16	0.06	0.06	0.009	--	0.039	0.006	--
1522	0.24	1.67	0.014	0.028	0.39	0.42	0.14	0.17	0.22	0.11	---	0.013	0.006

Experimental Details: Cylindrical specimens, 9 mm in diameter by 18 mm in height, were taken from the bars. For 1522 steel, specimens were reheated to 1093°C and held for 10 min. Specimens were then cooled to ambient temperature with different cooling rates using forced helium gas for establishment of a CCT diagram. To investigate the effects of deformation on the CCT diagram and final microstructure, a series of specimens were heated to 1260°C and held for 5 min. Specimens were then cooled to 1093°C, at a rate of about 1°C·s⁻¹. At 1093°C, the specimens were compressed 50% with a $\dot{\epsilon}$ of 10 s⁻¹. Following the compression, the specimens were cooled to ambient temperature with different cooling rates to establish the CCT diagram. This experiment also produced true σ - ϵ curves at 1093°C under $\dot{\epsilon}$ of 10 s⁻¹. To date two specimens have been

tested with these treatments. This series of experiments is continuing, and plans include experiments with different combinations of reheating temperature, deformation temperature, and $\dot{\epsilon}$.

For 1141 steel, specimens were reheated to 1218°C, and held for 5 min. Specimens were then cooled to ambient temperature with different cooling rates using forced helium gas to establish a CCT diagram. Future plans for this steel are the same as those for 1522 steel, that is, we will study the effects of different combinations of reheating temperature, deformation temperature, and $\dot{\epsilon}$.

For both steels, selected specimens processed with different processing parameters will be characterized and evaluated using optical metallography or electron microscopes, if necessary, and a microhardness tester.

Results and Discussion:

1522 Steel: Results obtained to date include the CCT diagram with specimens under heating and cooling (no deformation), microstructure of selected specimens, and true σ - ϵ curves at 1093°C with a $\dot{\epsilon}$ of 10 s⁻¹. The CCT diagram is shown in figure 19. The far-right cooling curve in figure 19 is comparable to that of a 25-mm-diameter round bar transported on a conveyer. This cooling rate is typical of an automotive component (with the same size) transported on a conveyer after forging without forced cooling. The microstructure produced at this cooling rate is predominantly bainite, as shown in figure 19. This is confirmed by the light micrograph presented in figure 20b. Figure 20a shows the martensite produced after fast cooling, corresponding to the far-left curve in figure 19.

The temperatures at which phase transformation occurs can be best determined by dilatometric measurements. Figure 6 shows that the determination of phase-transformation temperature is not straightforward. In order to minimize the human factors in determining the phase-transformation temperatures, we use statistical techniques to analyze the dilation-vs.-temperature data, such as that shown in figure 6. First, we performed the direct derivation on dilation-vs.-temperature data. The results produced too much scatter to give definite phase-transformation temperatures. Then, we

used the seven-point incremental polynomial technique to smooth the data; this approach yielded results with less scatter. Representative curves obtained from this analysis are given in figure 21.

Although the polynomial technique makes it easier and less ambiguous to determine the phase-transformation temperatures, subjective judgement is still needed. This is especially true in the case of the martensite-finish temperature, M_f . This is clearly indicated in figure 21. The reason for the difficulty in M_f determination (in this study) is that the temperature difference between the M_f temperature and the ambient temperature is relatively small, about 100 to 150°C. This produces a relatively short linear portion in the derivative (dl/dT) of dilation with respect to temperature. Any deviation (the M_f temperature) from the linear line becomes ambiguous and is thus difficult to determine with certainty.

A true σ - ϵ curve is calculated from the load-vs.-stroke movement data acquired during compression. A representative curve obtained at 1093°C with a $\dot{\epsilon}$ of 10 s⁻¹ is given in figure 22.

1141 Steel: Using the same procedures described earlier, we produced a CCT diagram of the MA 1141 steel as shown in figure 23. Also included in figure 23 is the cooling profile (dashed line) typically found in a forging without forced cooling [31]. This cooling profile is similar to that shown in the far-right curve on figure 23. Selected microstructures corresponding to different cooling rates are presented in figure 24. Figure 24a is a ferritic-pearlitic microstructure produced with the slowest cooling rate in this investigation. Martensite with a small fraction of bainite (fig. 24d) is observed with the fastest cooling. Figures 24b and 24c represent the microstructures obtained with intermediate cooling rates. Microstructure in figure 24b is a mixture of pearlite with small areas of ferrite (Widmanstätten) and bainite. Bainite plus martensite is the microstructure observed in figure 24c.

IV. CONCLUSIONS AND SUMMARY

A computer-controlled laboratory-scale hot-deformation apparatus has been designed and built at the National Institute of Standards and Technology (NIST). The use of this apparatus for studying thermomechanical processing of metals has the obvious advantages of economy, versatility, and reproducibility. In the past, the laboratory-scale apparatuses have been mainly applied to study plate steels. With the increased use of directly cooled forging steels, the apparatus described in this report can be used as an instrumented forging press for detailed study of these steels.

The apparatus has the following main features: a servohydraulic load frame with a 250 kN capacity in tension or compression; a variable-actuator traveling speed up to $55 \text{ mm}\cdot\text{s}^{-1}$; a multiple-strike capability with controllable displacements and strain rates; a maximum heating rate of $150^{\circ}\text{C}\cdot\text{s}^{-1}$ with a 10 kW induction heater (for a cylindrical steel specimen 9 mm in diameter and 18 mm in height); a maximum cooling rate of $25^{\circ}\text{C}\cdot\text{s}^{-1}$ with helium-gas cooling; and vacuum to $1.33 \times 10^{-3} \text{ Pa}$ ($1 \times 10^{-5} \text{ Torr}$) within 25 min.

The apparatus has been used to simulate direct quenching of ASTM A710 steel and forging followed by direct cooling of microalloyed AISI 1522 and 1141 steels. For the A710 steel, the results indicated that bainitic (granular) hardenability was greater with the controlled rolling followed by direct quenching (CR-DQ) than with the conventional quenching-and-tempering (Q-T) process. The positive implication of the observation is that the strength of the steel can be increased with CR-DQ processing, or the amount of alloying elements can be reduced while maintaining the same strength level.

For the MA 1522 and 1141 steels, CCT diagrams were determined from the derivatives of the dilation-vs.-temperature data using the seven-point incremental polynomial technique. Although the technique using the smoothed derivatives helps to make the determination of phase-transformation temperatures less ambiguous, subjective judgement is sometimes still needed, especially in the case of martensite-finish temperature. Microconstituents, such as ferrite, pearlite, bainite, and martensite, shown in the CCT diagrams

were confirmed with microstructures revealed by optical metallography. In addition to producing CCT diagrams and microstructures of specimens cooled at different rates, we will also conduct experiments in forging simulation to develop the information needed for the optimization of forging processes. The information includes high-temperature, high strain-rate flow characteristics and the effects of reheating temperature and finish-forging temperature on the CCT diagrams and final properties.

V. ACKNOWLEDGMENTS

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Controllable Parameters

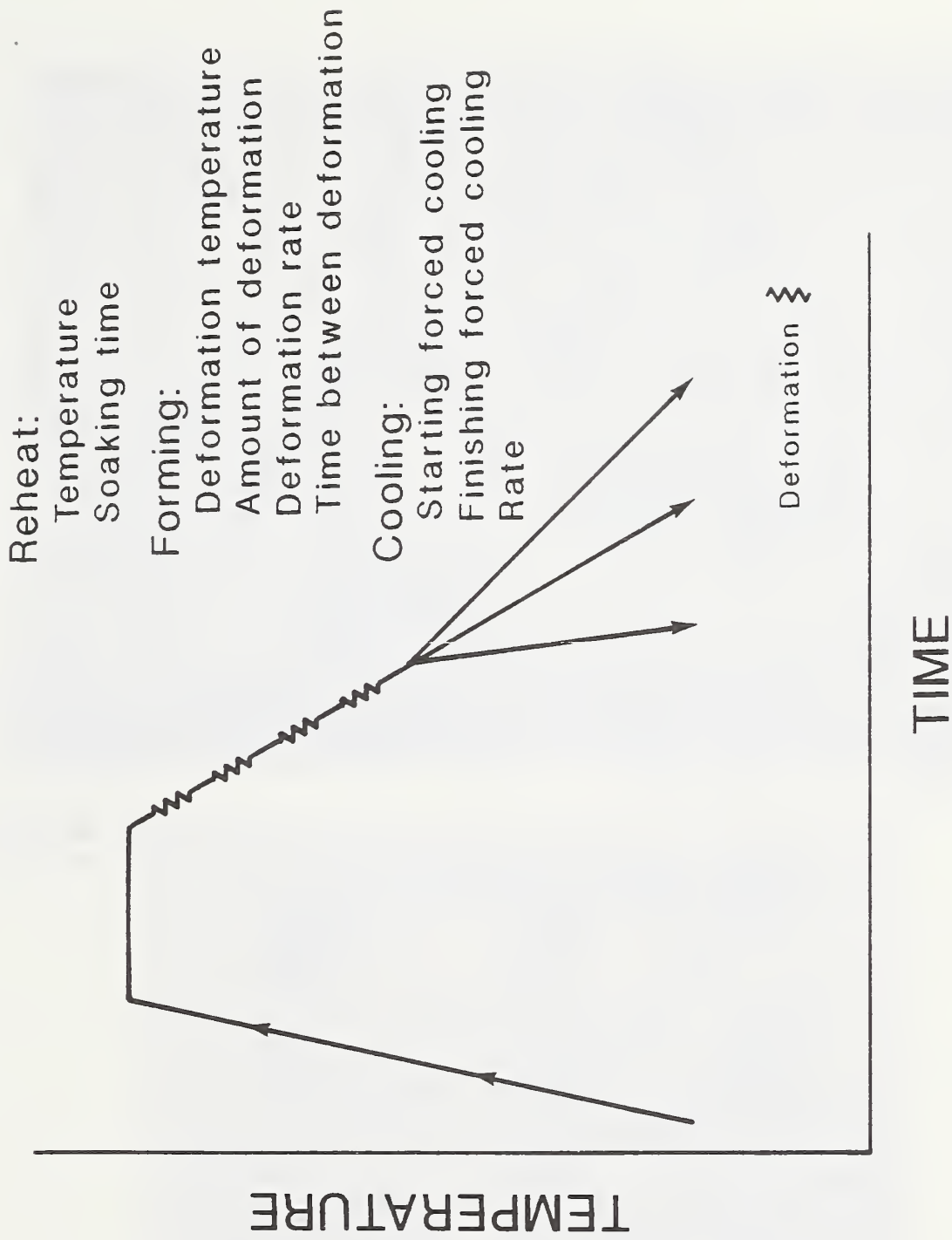
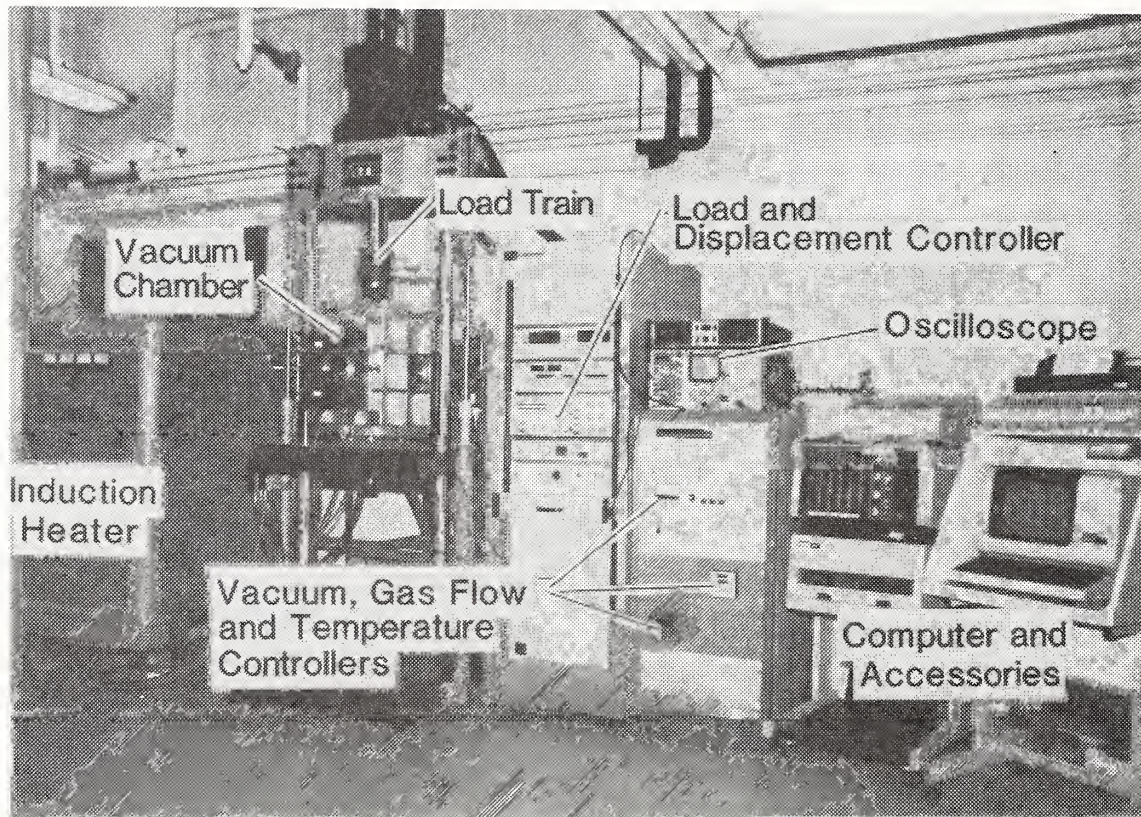
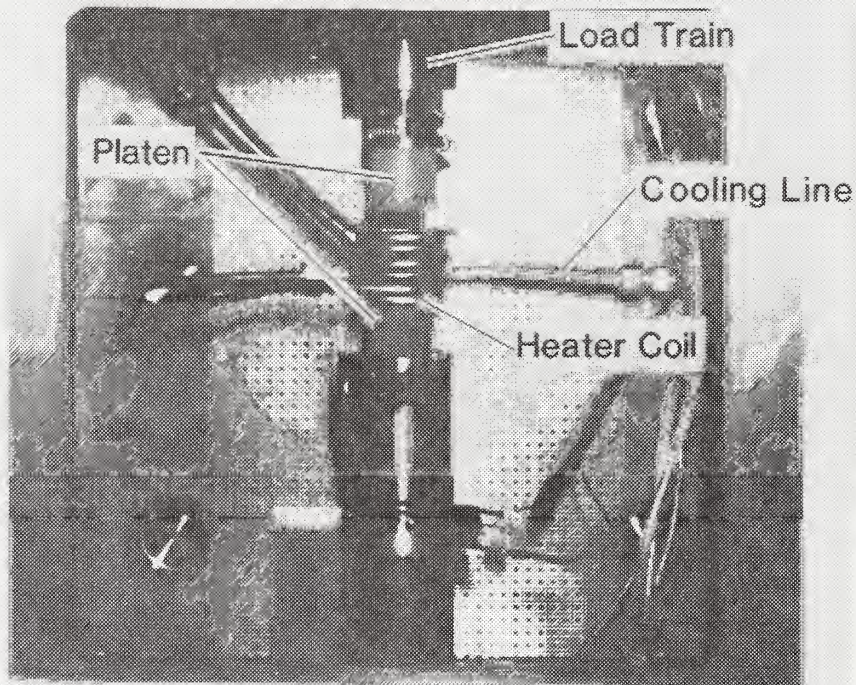


Figure 1. Thermal and mechanical treatments in a thermomechanical processing (TMP) simulation.



(a)



(b)

Figure 2. Hot-deformation apparatus. (a) overall view; (b) interior of the vacuum chamber.

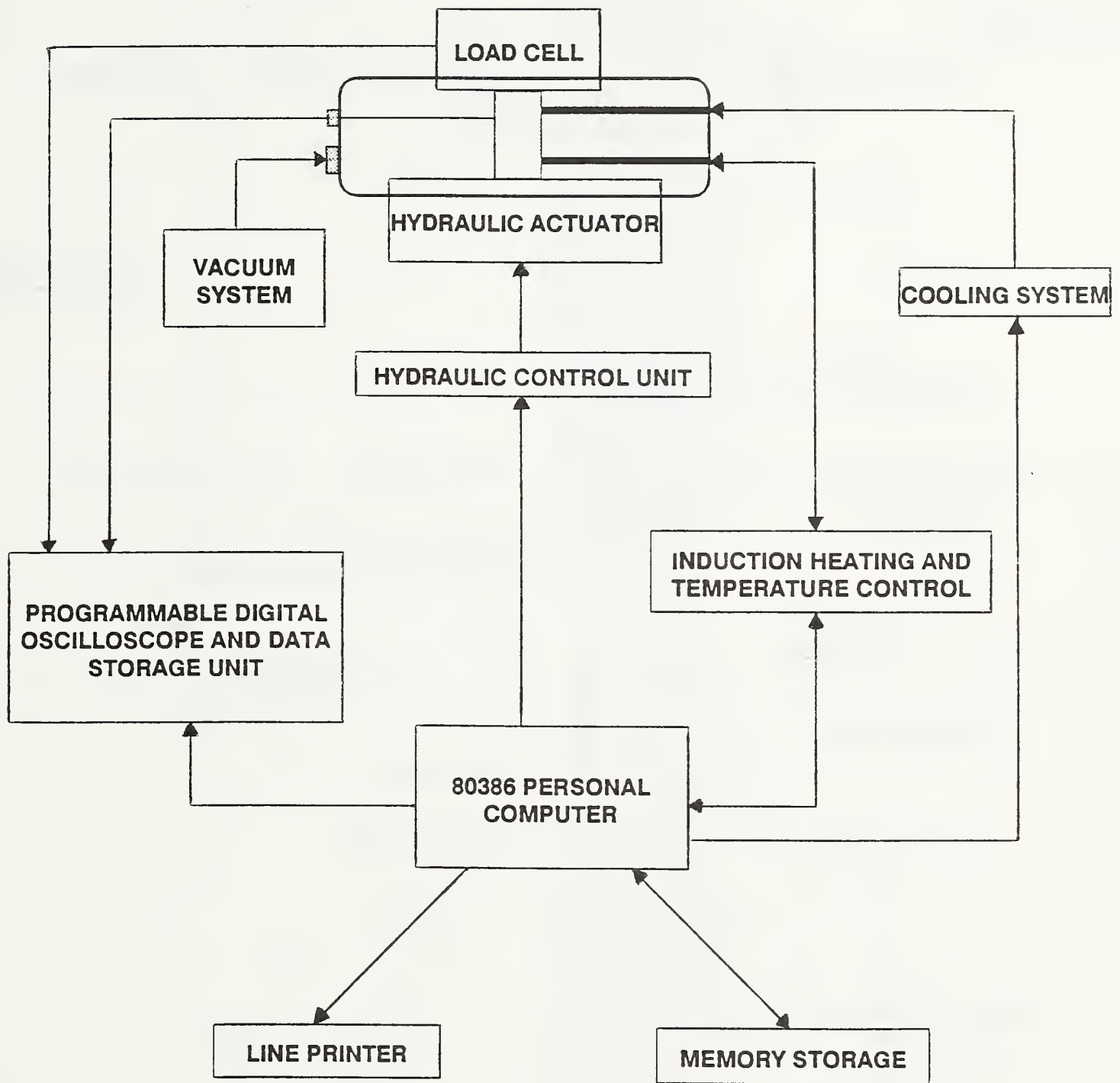


Figure 3. The basic components of the hot-deformation apparatus.

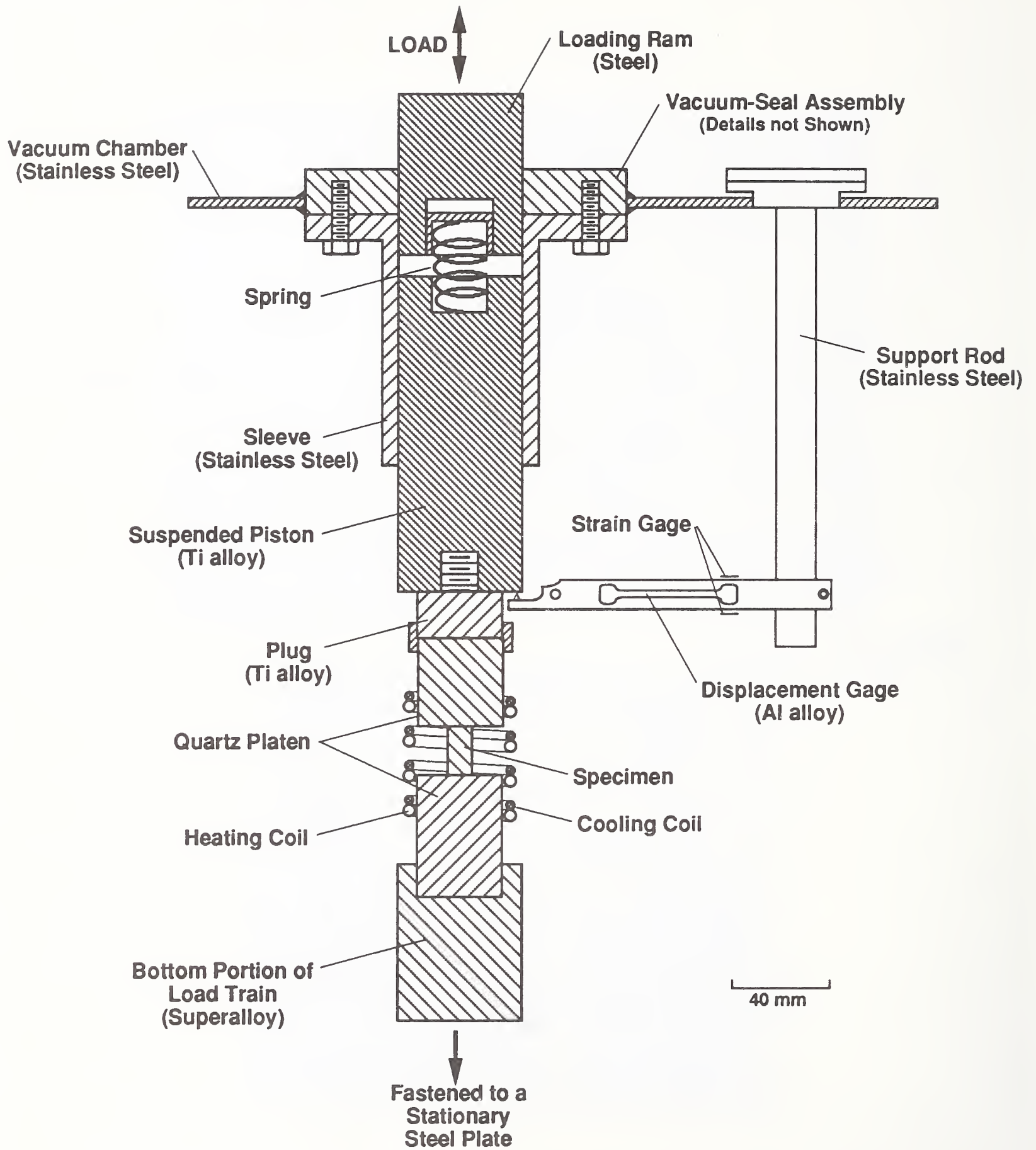


Figure 4. Drawing of the load train and the device for measurement of length change during cooling and phase transformation.

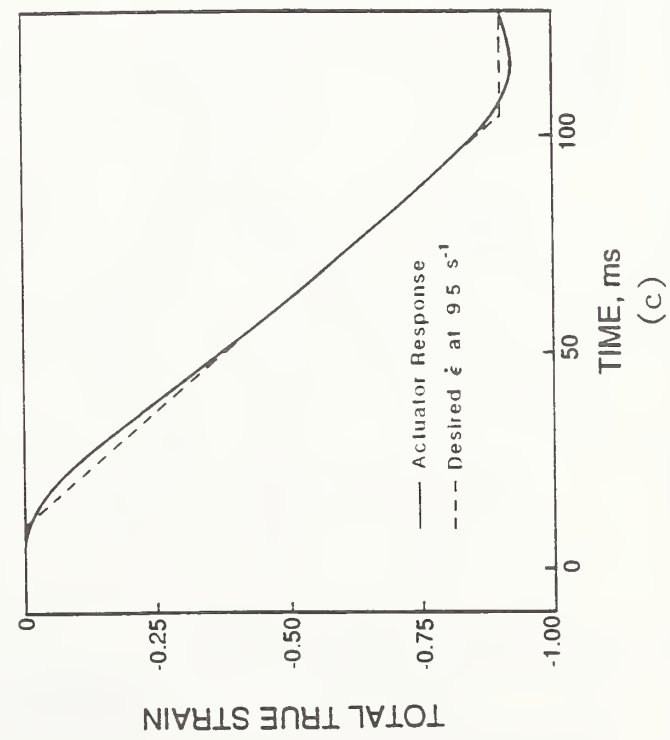
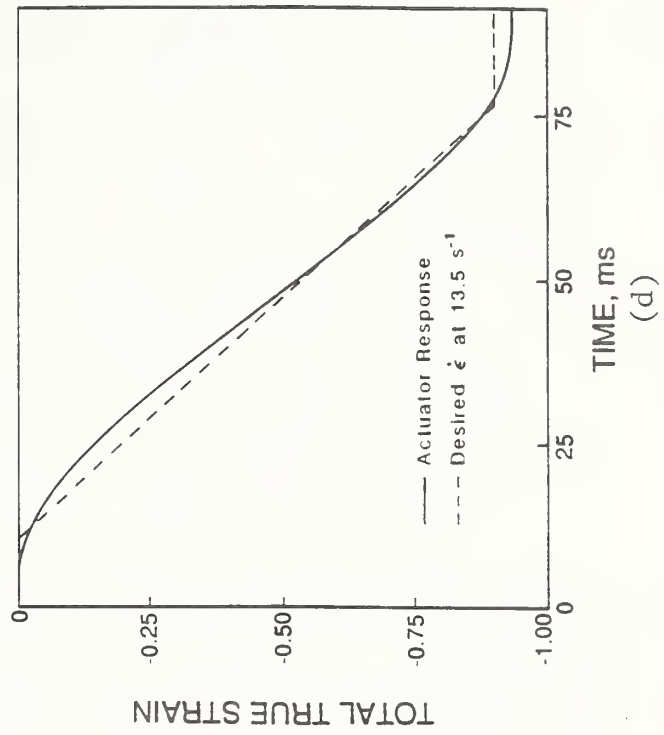
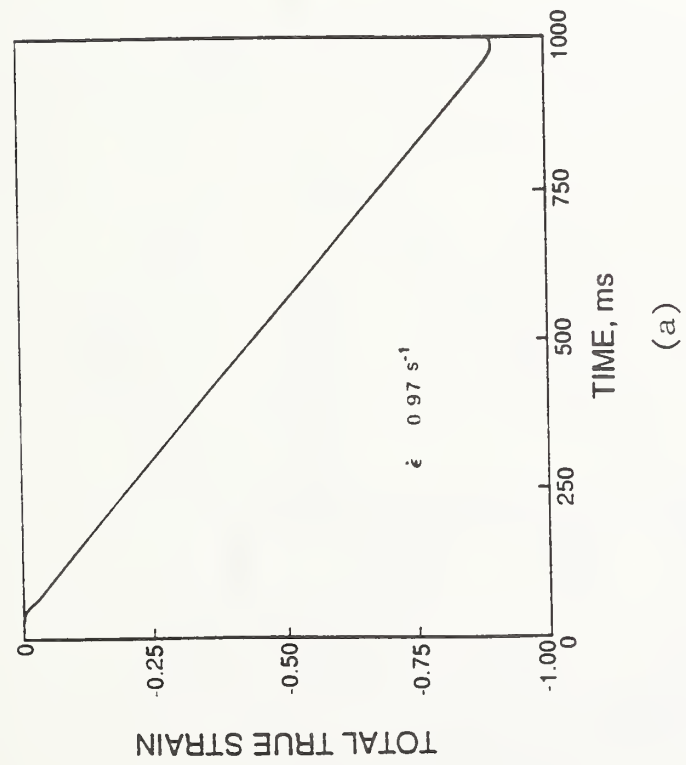
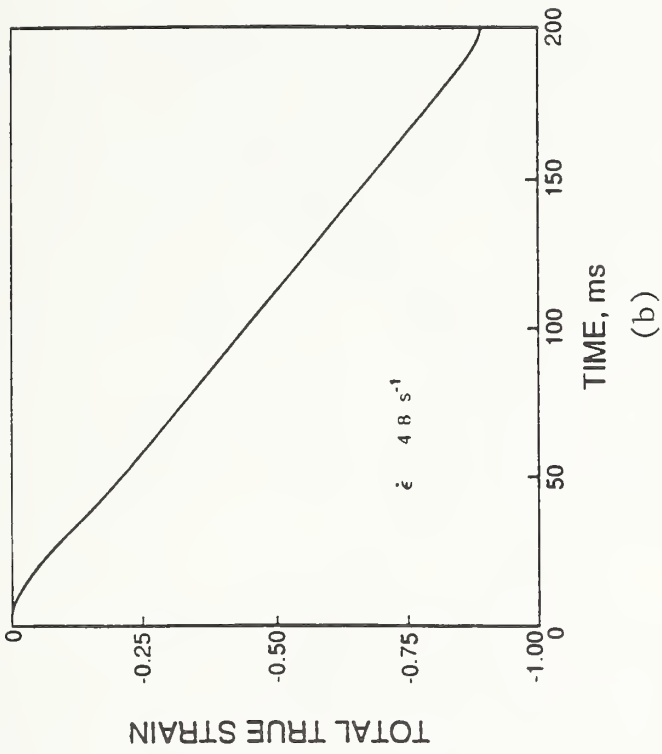


Figure 5. The responses of the servohydraulic actuator to commands of various strain rates ($\dot{\epsilon}$); (a) $\dot{\epsilon} = 0.97 \text{ s}^{-1}$; (b) $\dot{\epsilon} = 4.8 \text{ s}^{-1}$; (c) $\dot{\epsilon} = 9.5 \text{ s}^{-1}$; (d) $\dot{\epsilon} = 13.5 \text{ s}^{-1}$; (e) $\dot{\epsilon} = 17 \text{ s}^{-1}$; (f) $\dot{\epsilon} = 19.2 \text{ s}^{-1}$; (g) $\dot{\epsilon} = 24 \text{ s}^{-1}$.

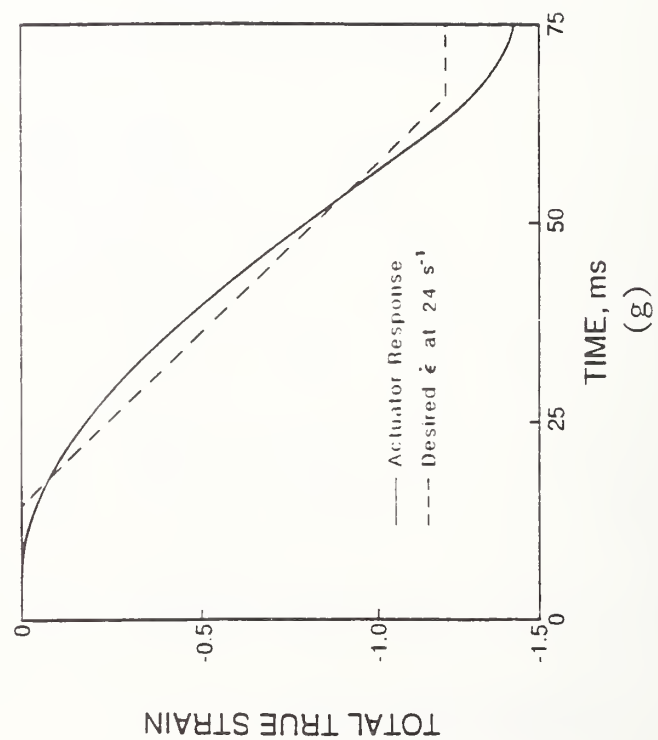
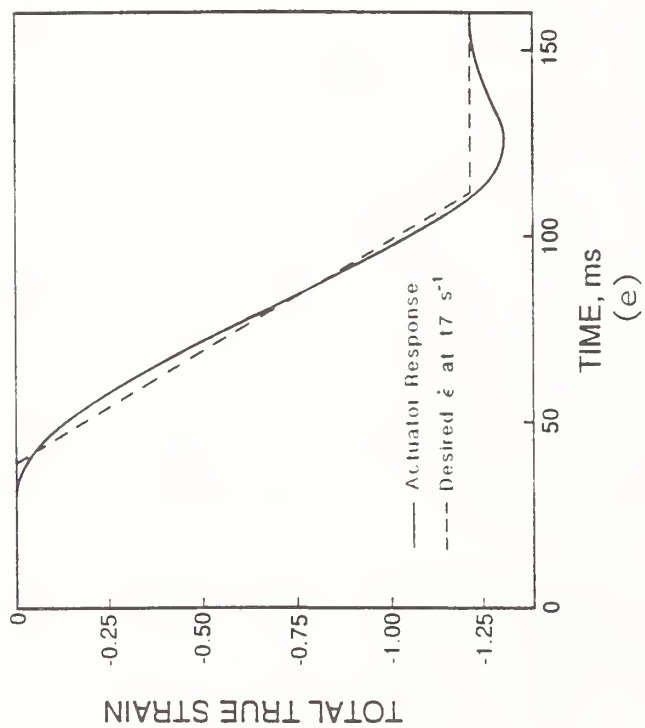
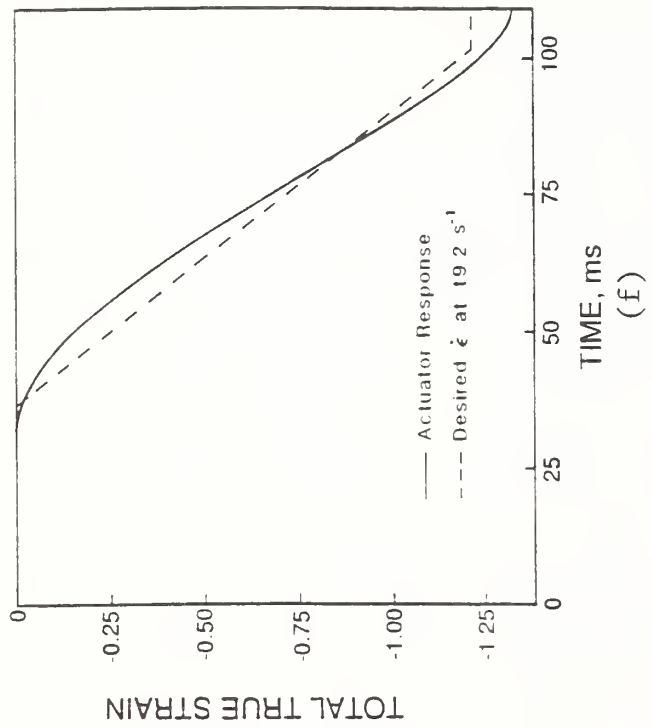


Figure 5. (continued)

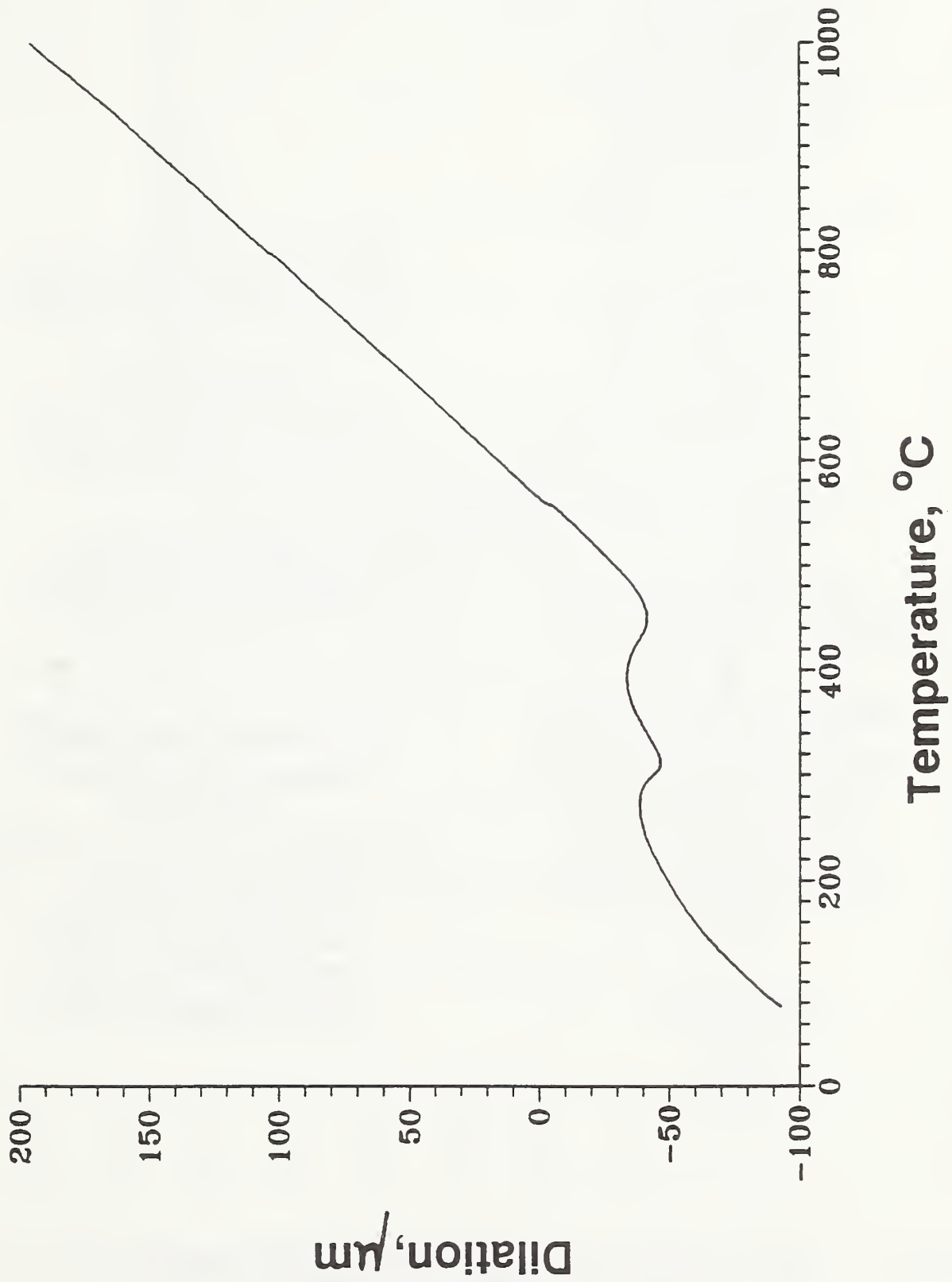


Figure 6. Example of length change (dilation) vs. temperature during continuous cooling and phase transformation of a steel specimen.

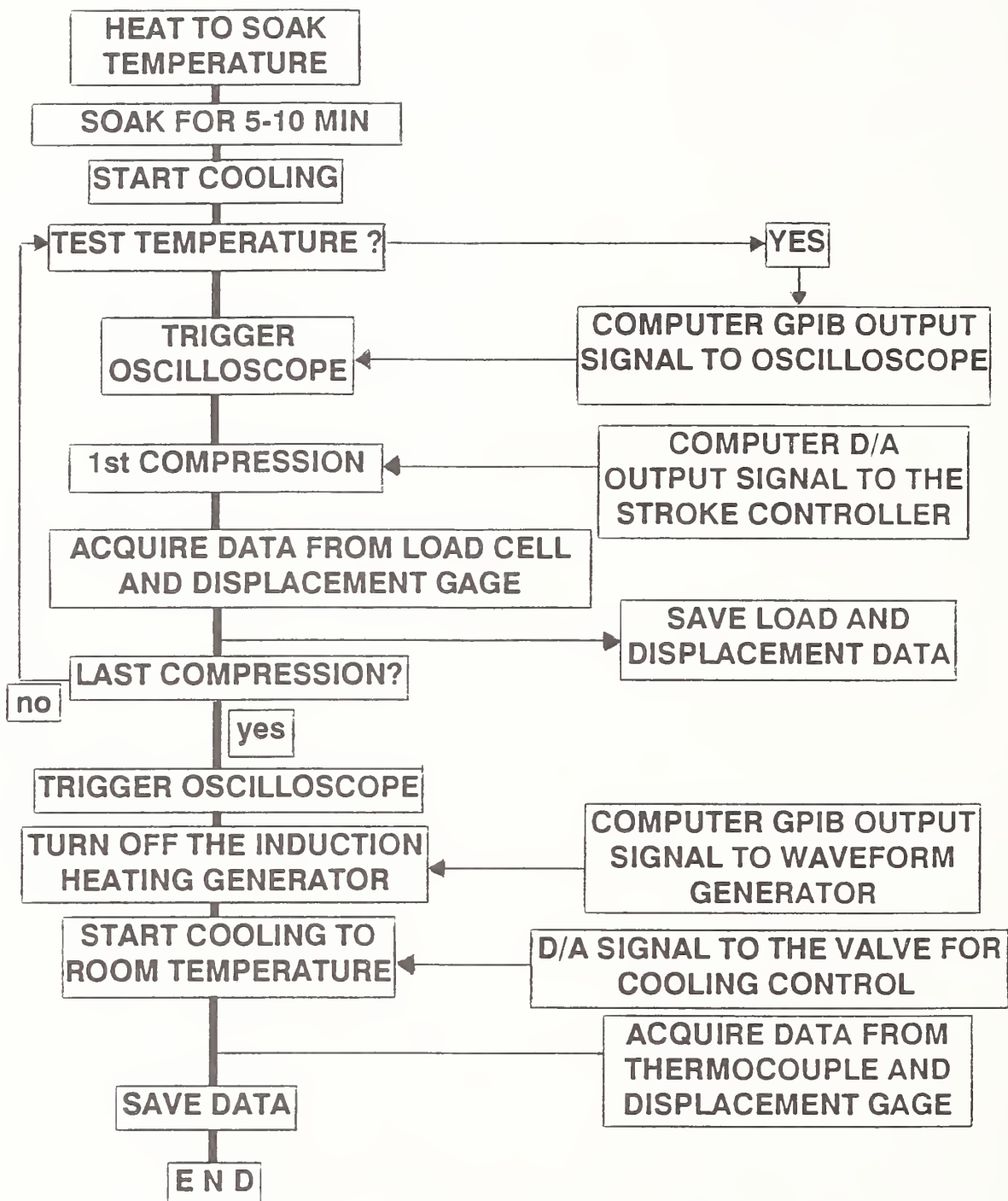


Figure 7. The detailed flow chart of the program for system control and data acquisition.

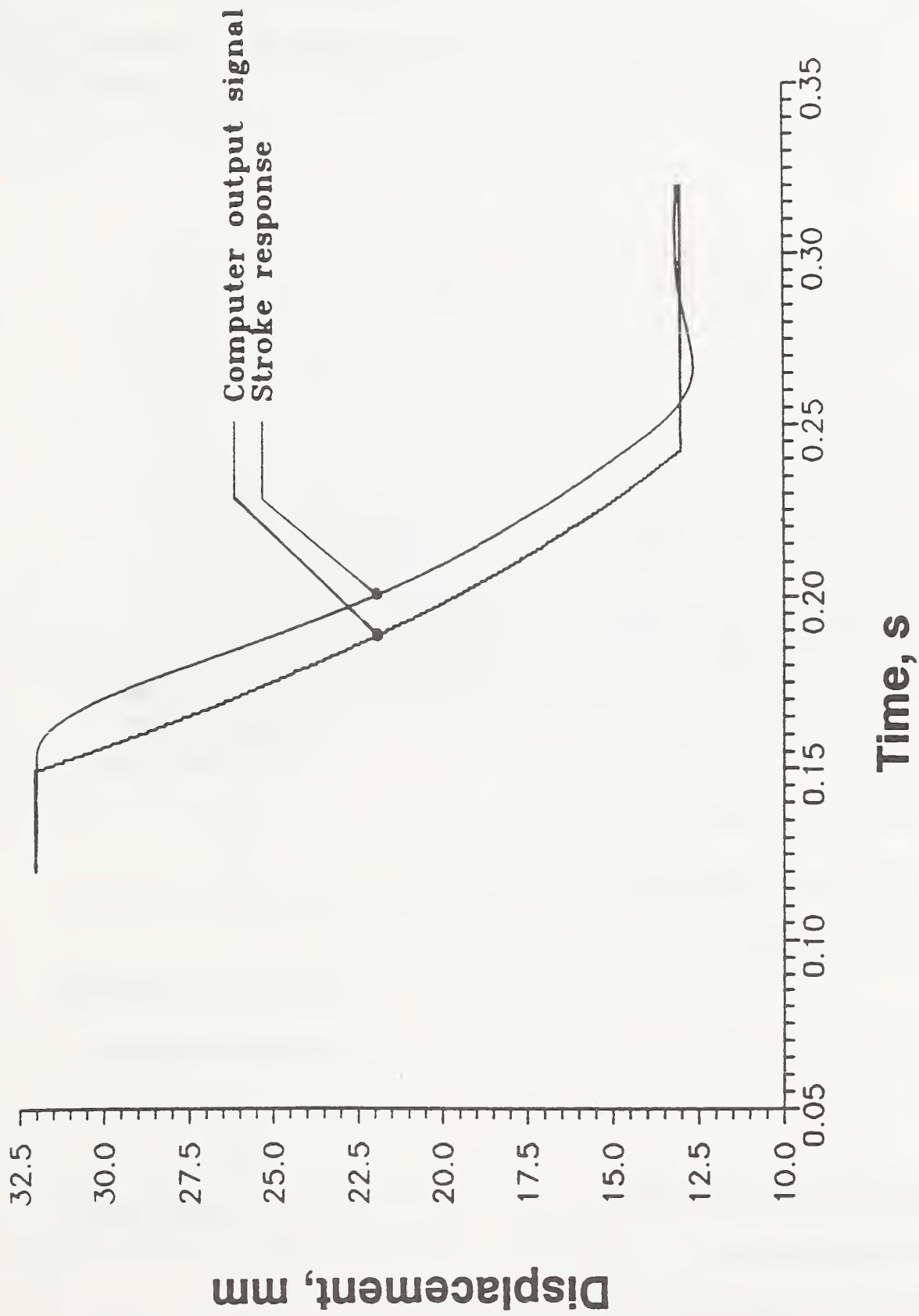


Figure 8. Computer command signals and the corresponding servohydraulic stroke responses at a strain rate of 10 s^{-1} .

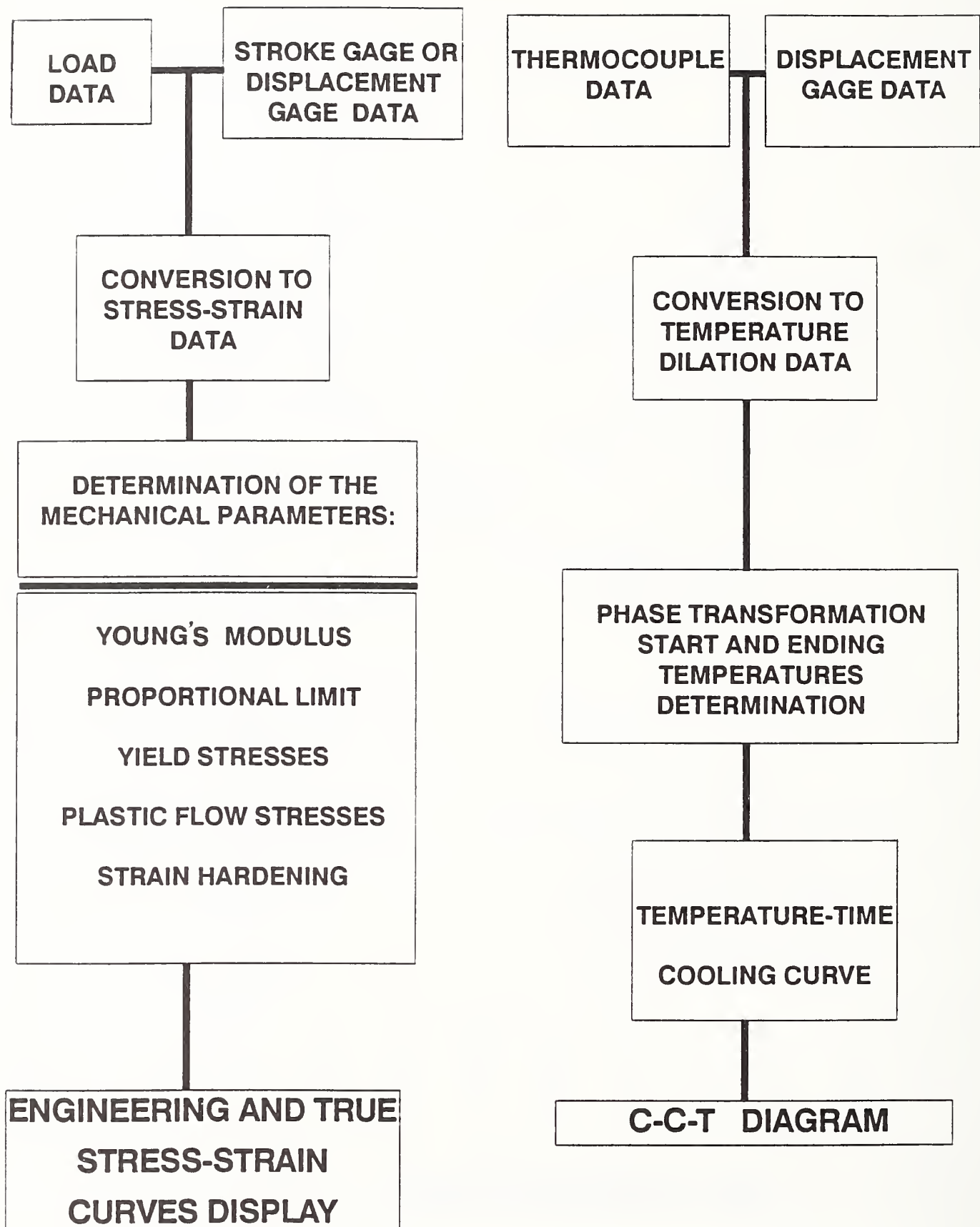


Figure 9. The flow diagram of the post-test analysis program.

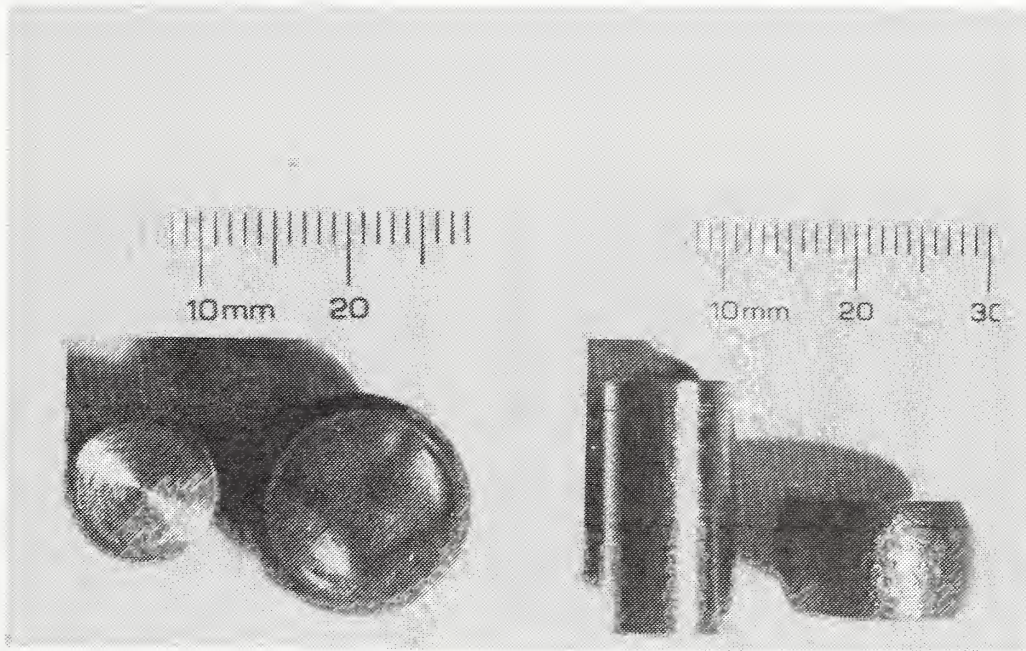
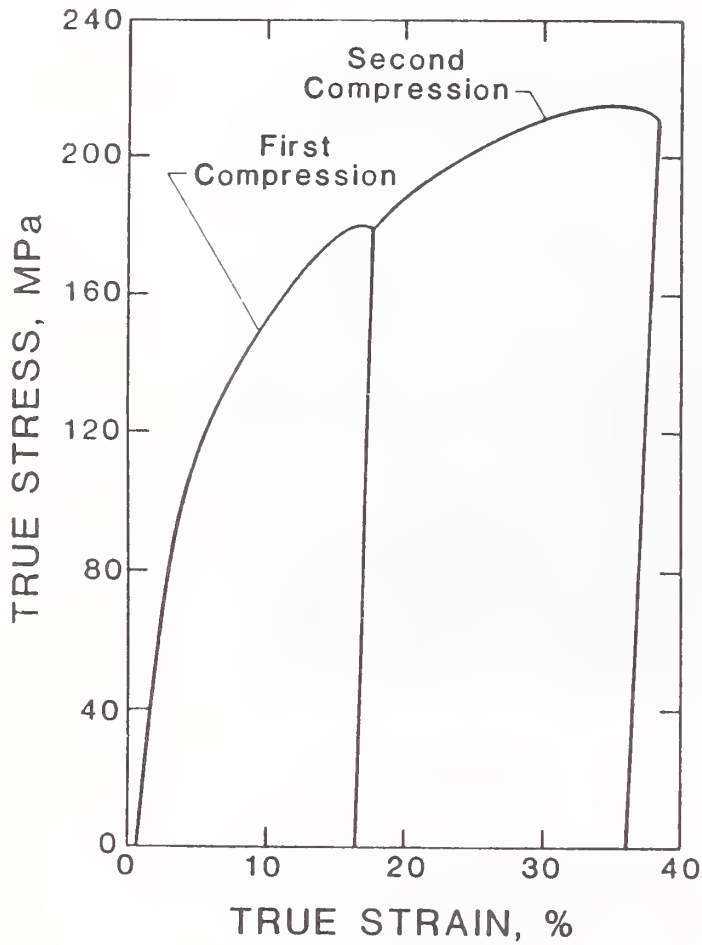


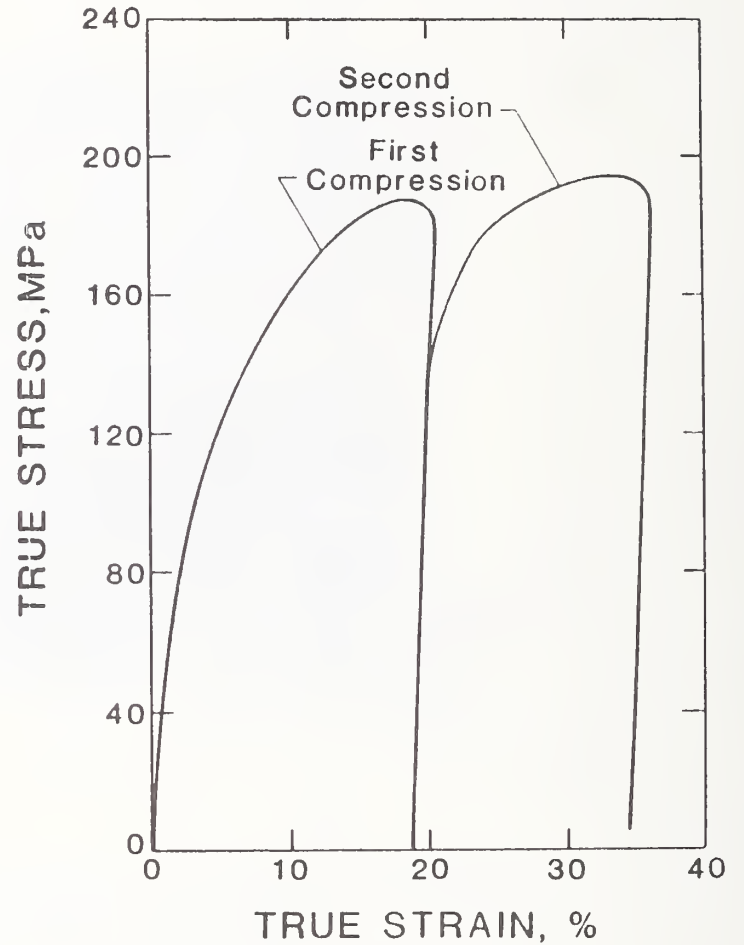
Figure 10. Pictures of the specimen used in the direct-quenching simulation study; before and after deformation.

ASTM A710 HSLA Steel
Reheated at 1150°C for 10 min
Soaked at 950°C for 10 min
Compressed Twice at 950°C
Time Between Compressions: 0.5 s



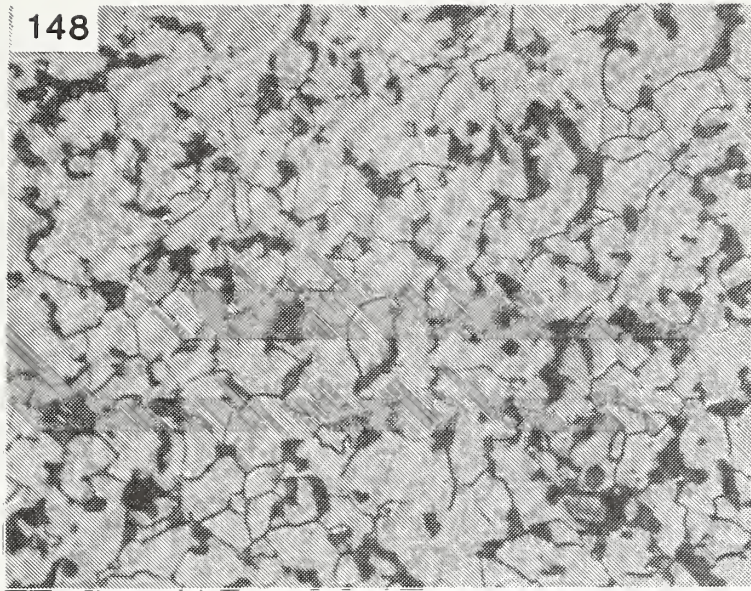
(a)

ASTM A710 HSLA Steel
Reheated at 1150°C for 10 min
Soaked at 1000°C for 10 min
Compressed Twice at 1000°C
Time Between Compressions: 30 s



(b)

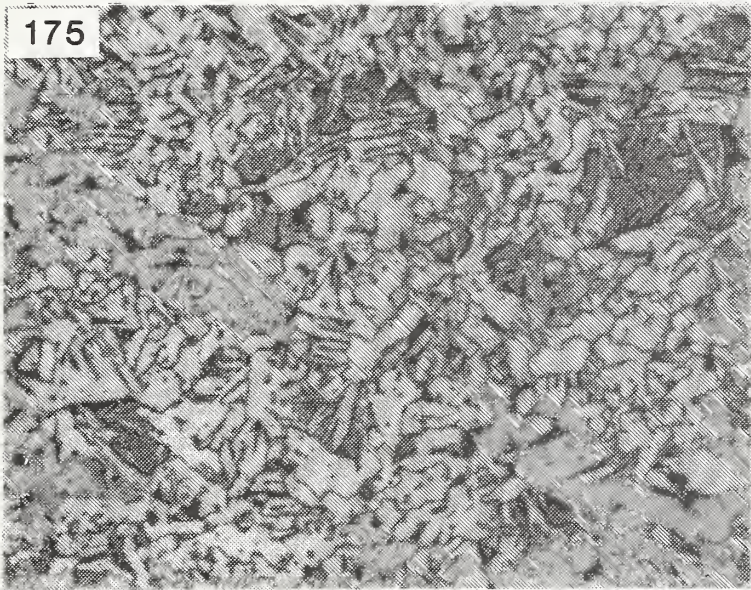
Figure 11. Results of double-deformation test on ASTM A710 steel. (a) no softening in the second compression indicating no recrystallization occurred; (b) softening in the second compression indicating some degree of recrystallization occurred.



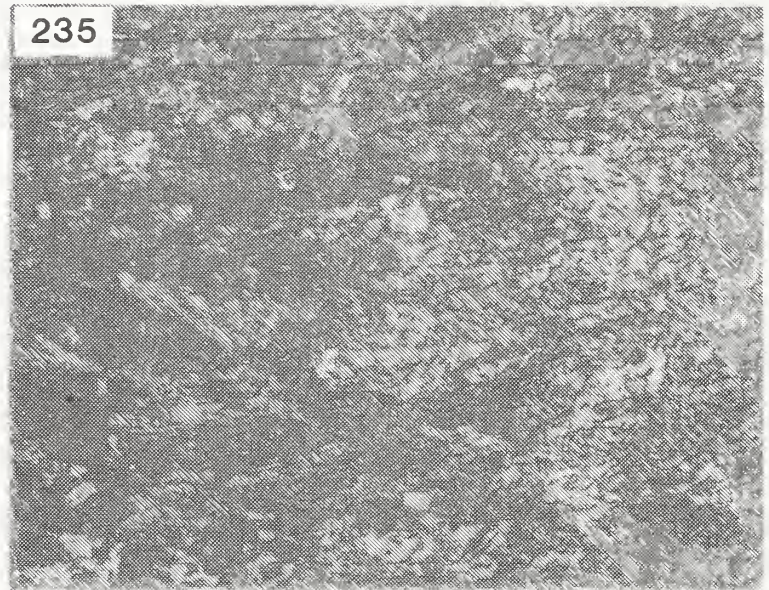
(a)



(c)

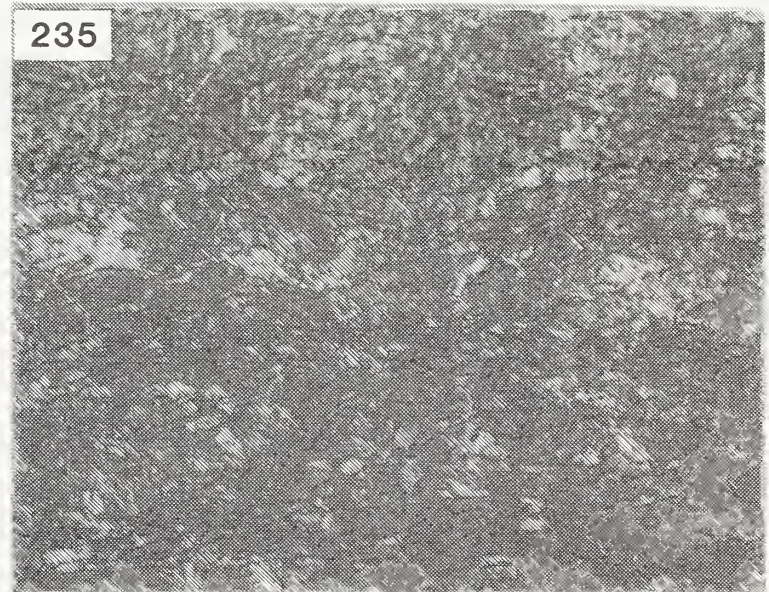


(b)



(d)

Figure 12. Microstructures of ASTM A710 steel specimens with different thermomechanical treatments; (a) and (b): reaustenitized at 910°C then cooled slowly and gas quenched, respectively, without deformation; (c) through (e): treatments a through c described in table 1. Etch: 3% nital.



(e)

40 μm

CONTINUOUS COOLING TRANSFORMATION DIAGRAM FOR HSLA-80

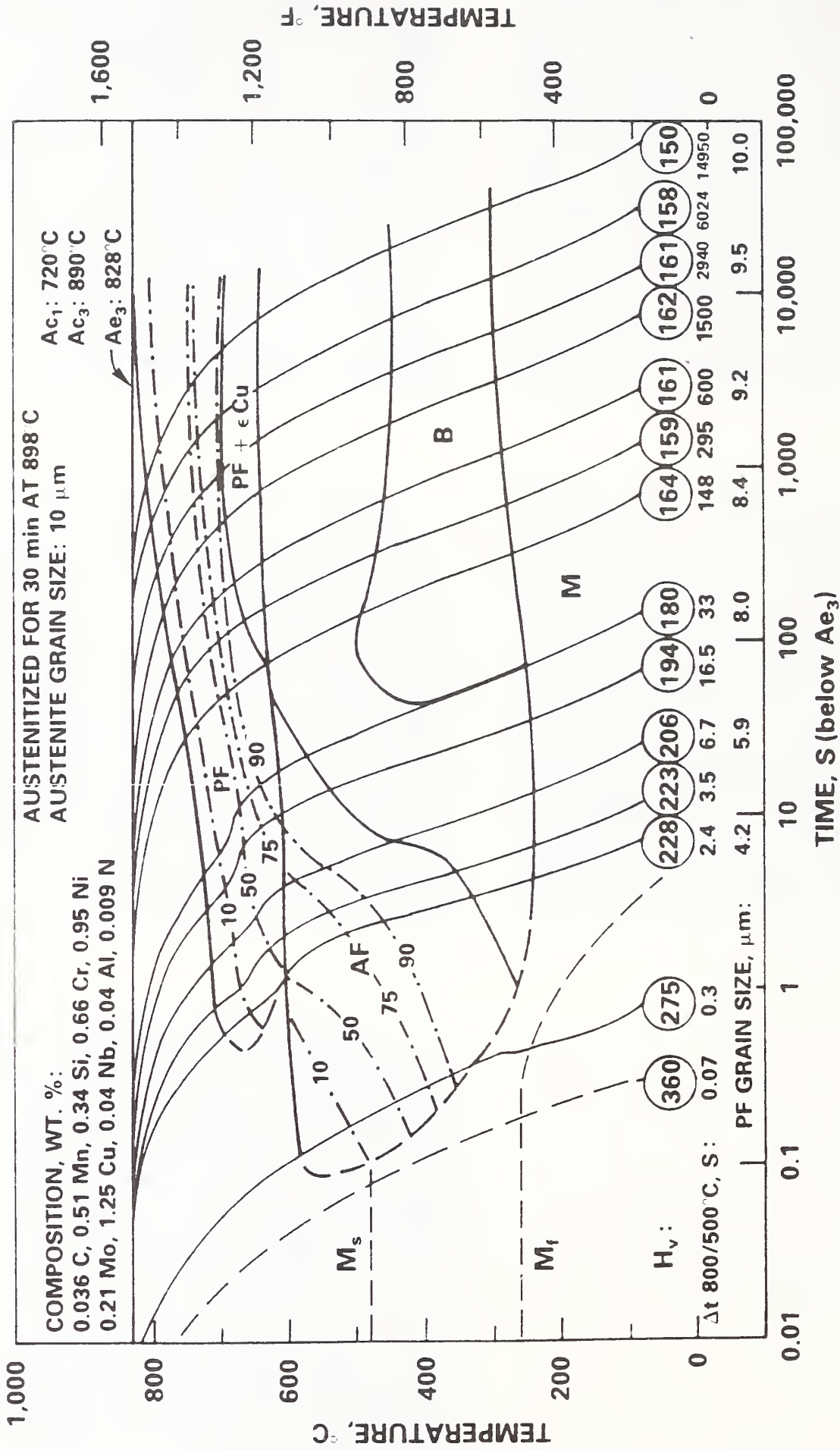


Figure 13. Continuous-cooling-transformation (CCT) diagram for ASTM A710 steel; from Ref. 23.

CONTINUOUS COOLING TRANSFORMATION DIAGRAM FOR HSLA-80 STEEL

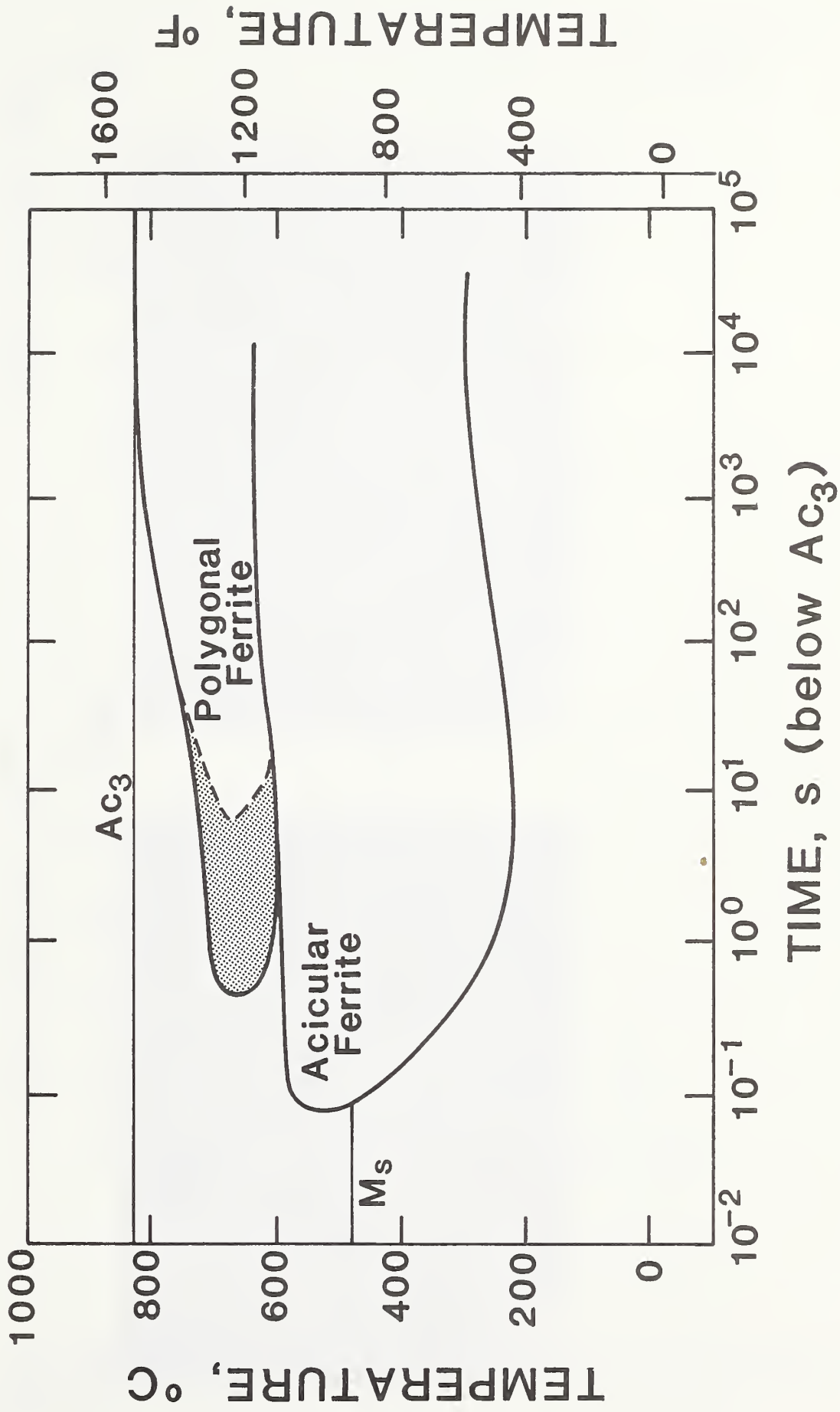


Figure 14. Schematic illustration of increasing acicular ferrite (granular bainite) hardenability by shifting the polygonal ferrite nose to the right (shaded area).

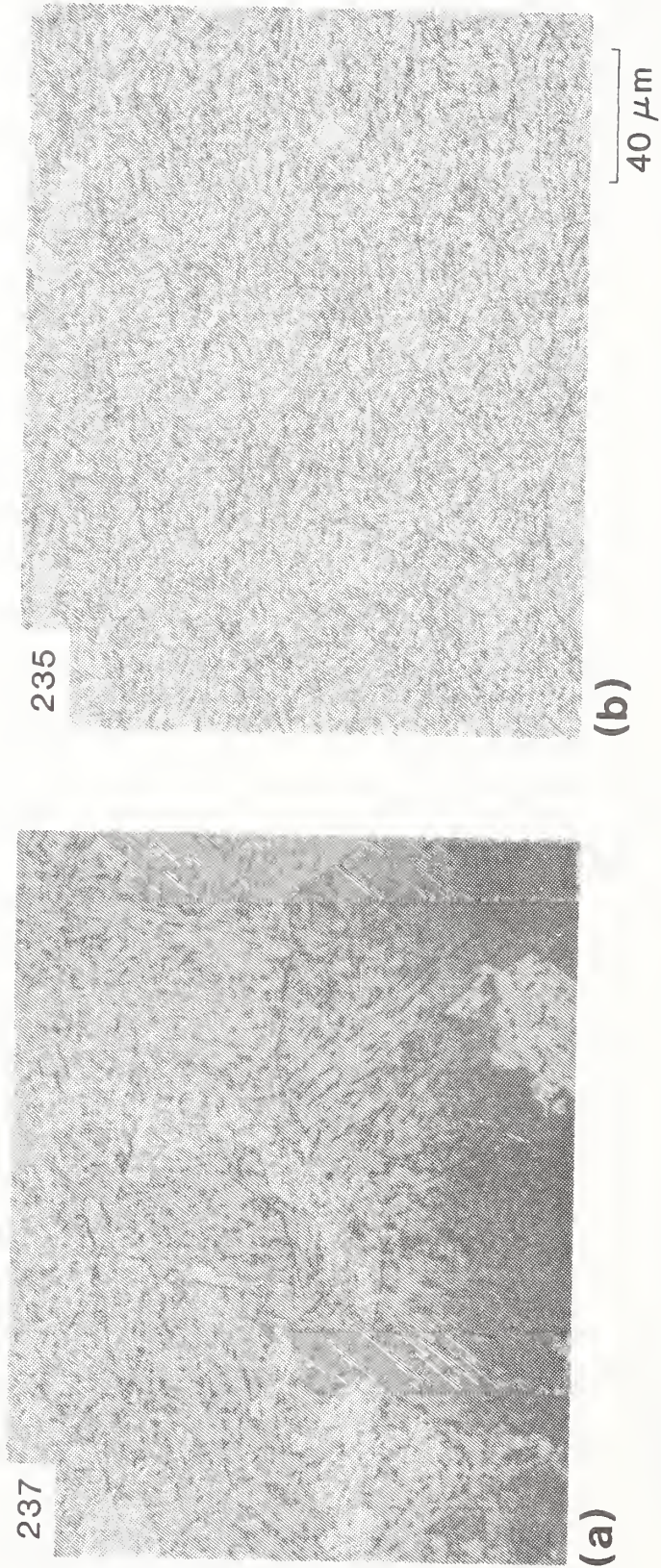
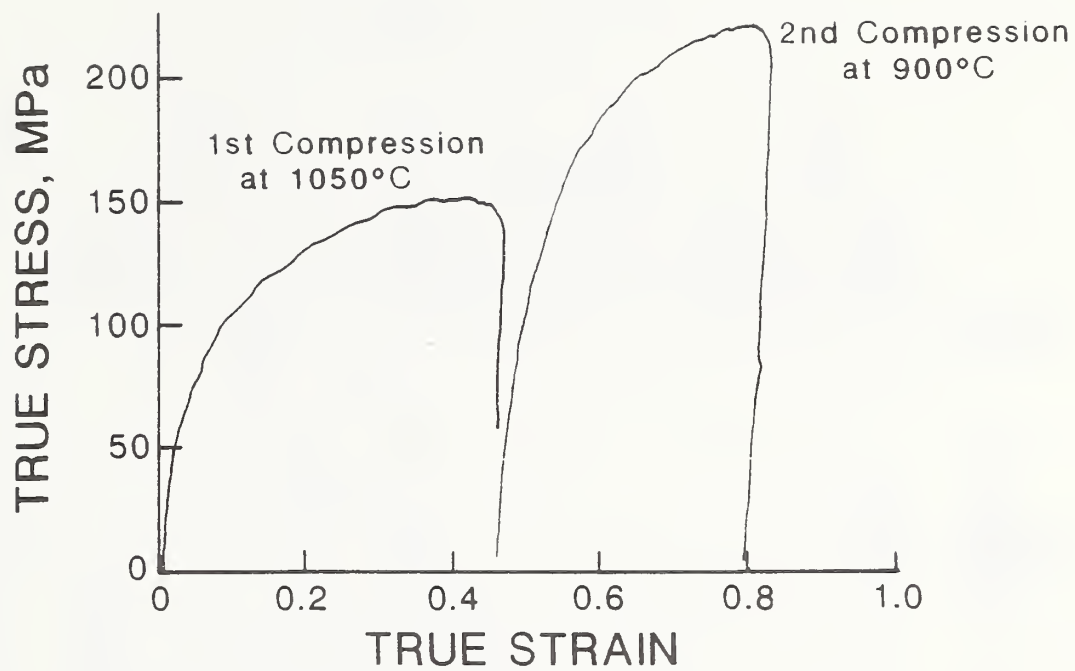
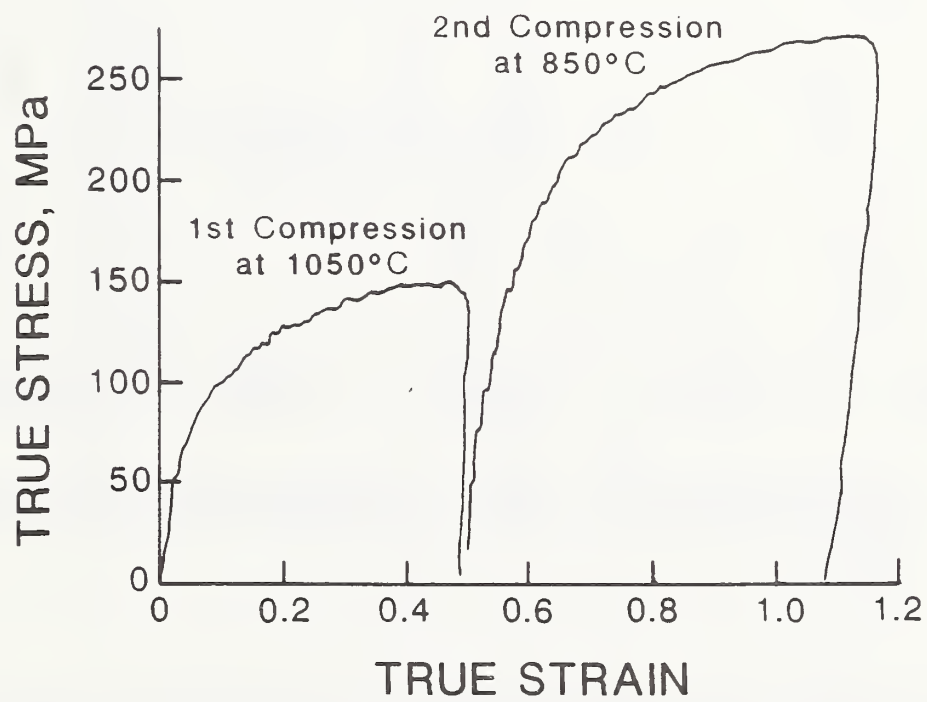


Figure 15. Variation of microstructures from (a) near the surface and (b) at the middle of the CR-DQ specimen.



(a)



(b)

Figure 16. True σ - ϵ curves obtained in simulated CR-DQ experiments (see Table 1); (a) treatment a in Table 1; (b) treatment c in Table 1.

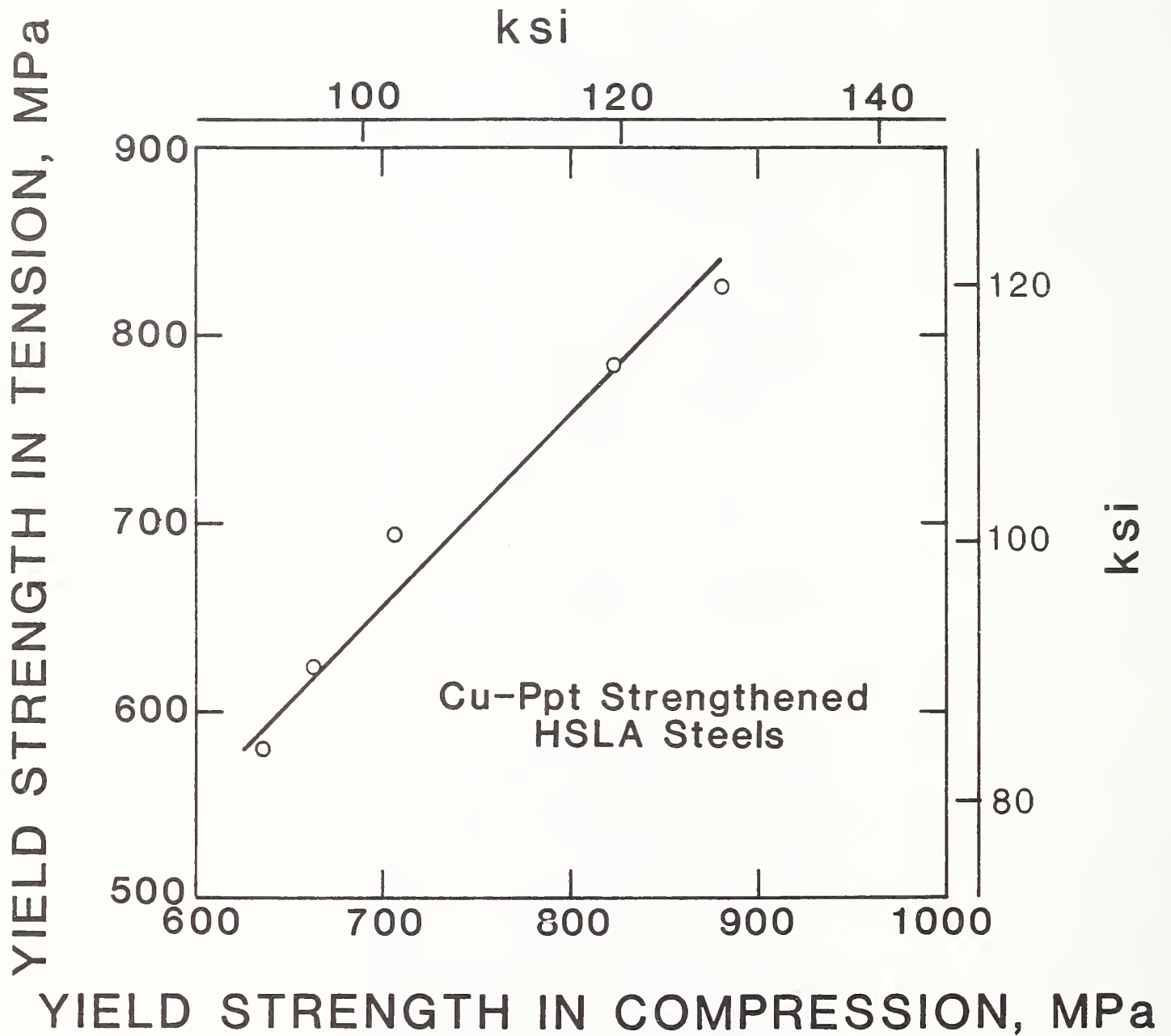


Figure 17. Correlation of yield strengths in tension and yield strengths in compression. Results of tension and compression at one strength level were obtained from the same steel plate.

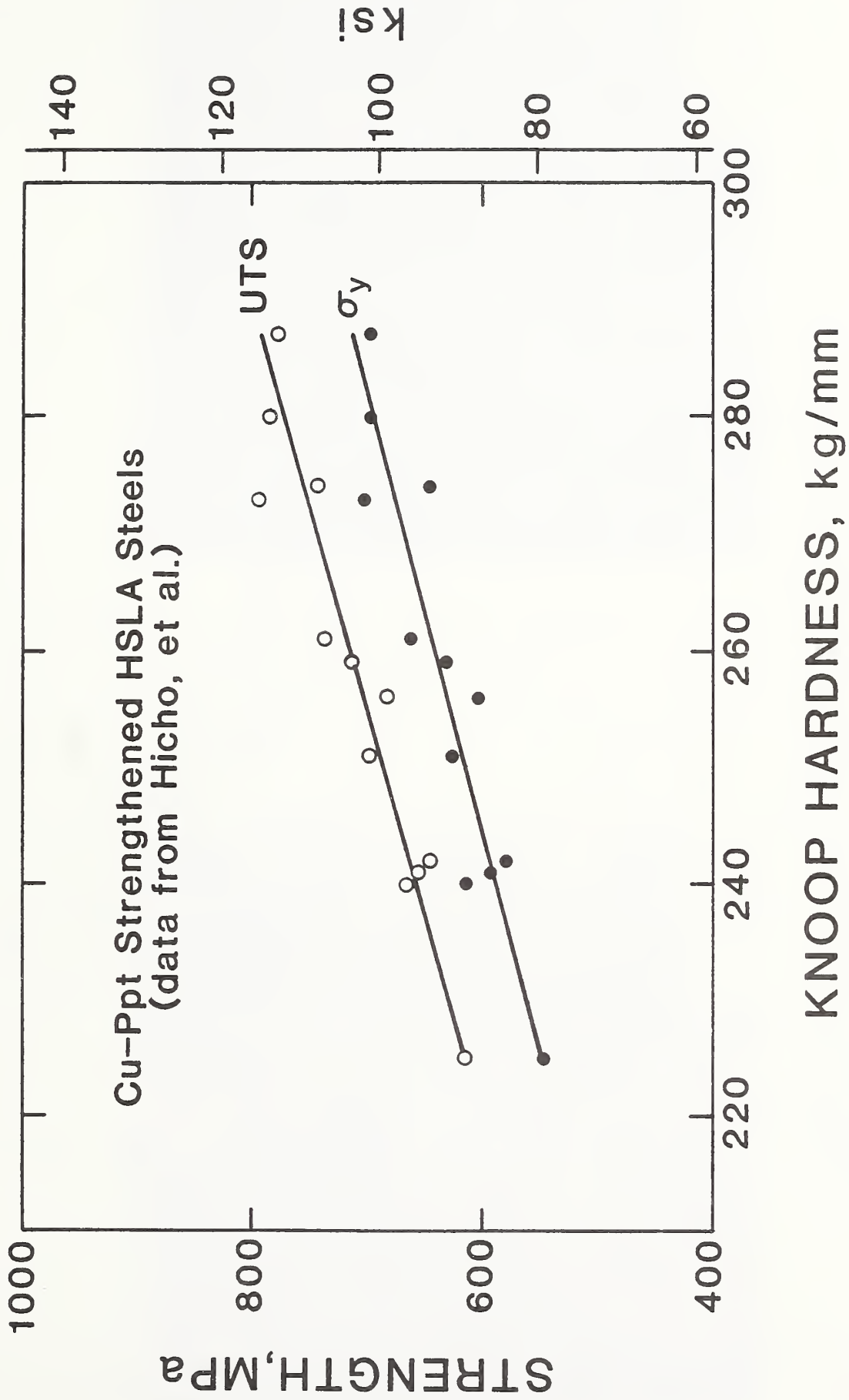


Figure 18. Correlation of tensile strengths with Knoop hardness numbers (numerical data taken from Ref. 27).

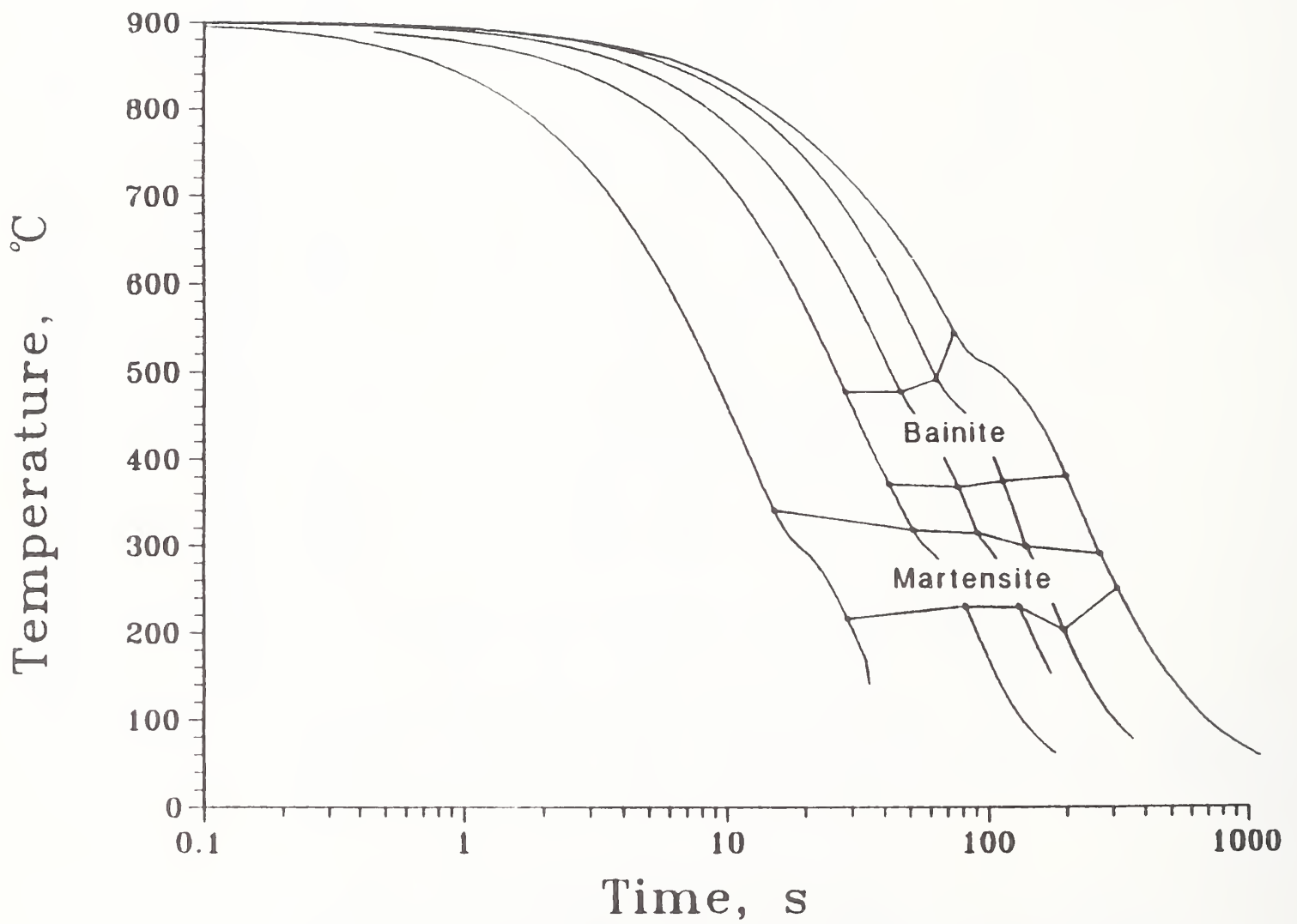


Figure 19. The CCT diagram of microalloyed 1522 forging steel.



(a)



(b)

Figure 20. Microstructures of 1522 microalloyed steel; (a) martensite after fast cooling; (b) bainite after slow cooling.

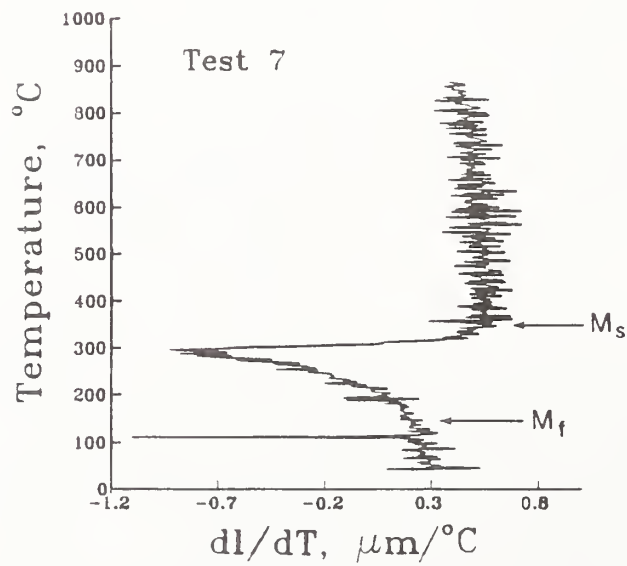
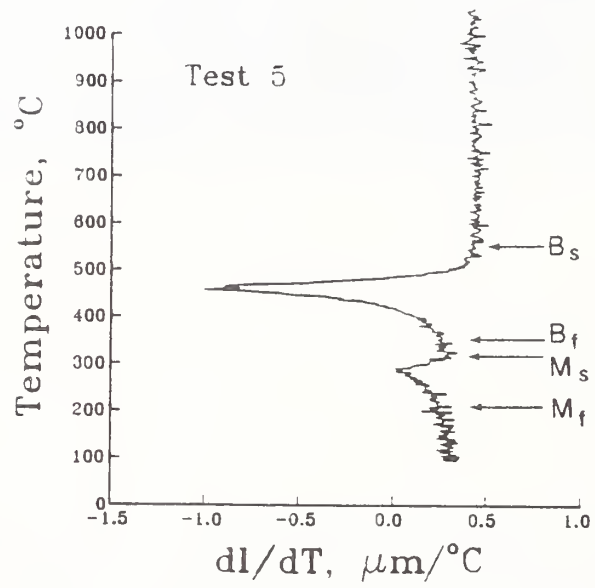
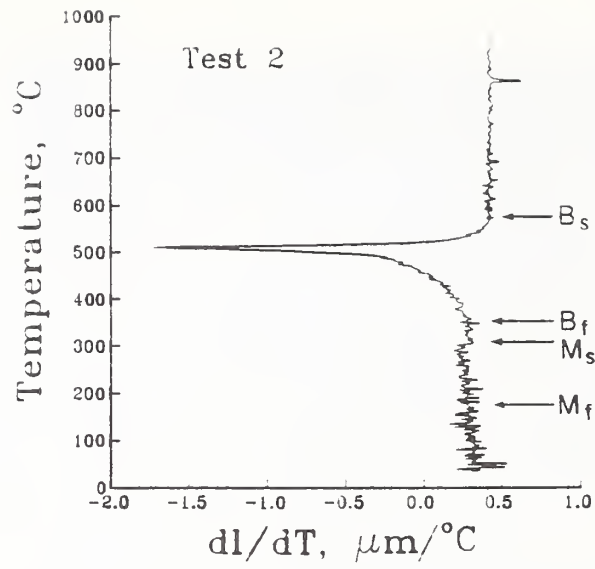


Figure 21. Determination of phase-transformation temperatures using the seven-point incremental polynomial technique. B_s : bainite starts; B_f : bainite finishes; M_s : martensite starts; M_f : martensite finishes.

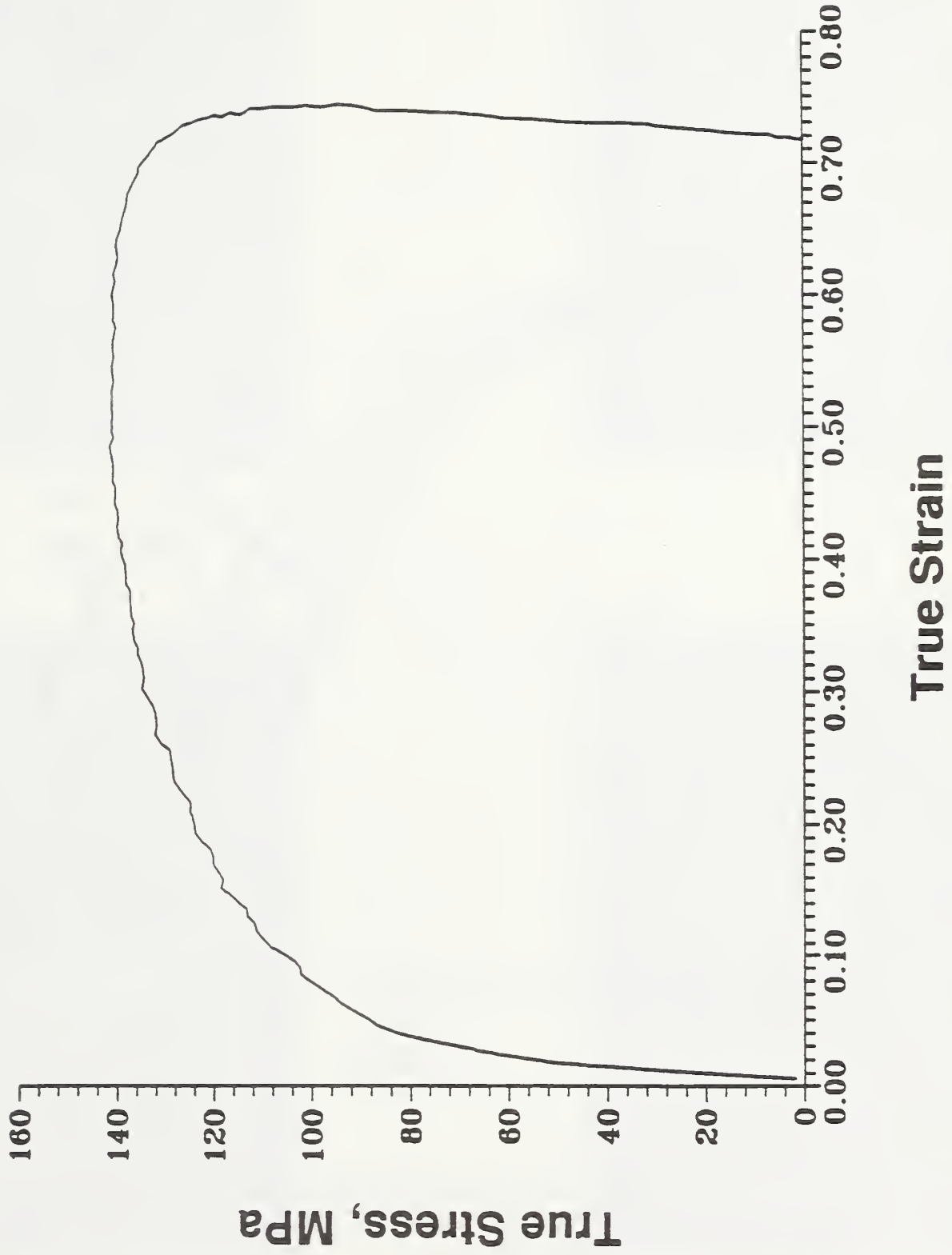


Figure 22. True σ - ϵ characteristic of 1522 microalloyed steel at 1093°C with a compressive strain rate of 10 s^{-1} .

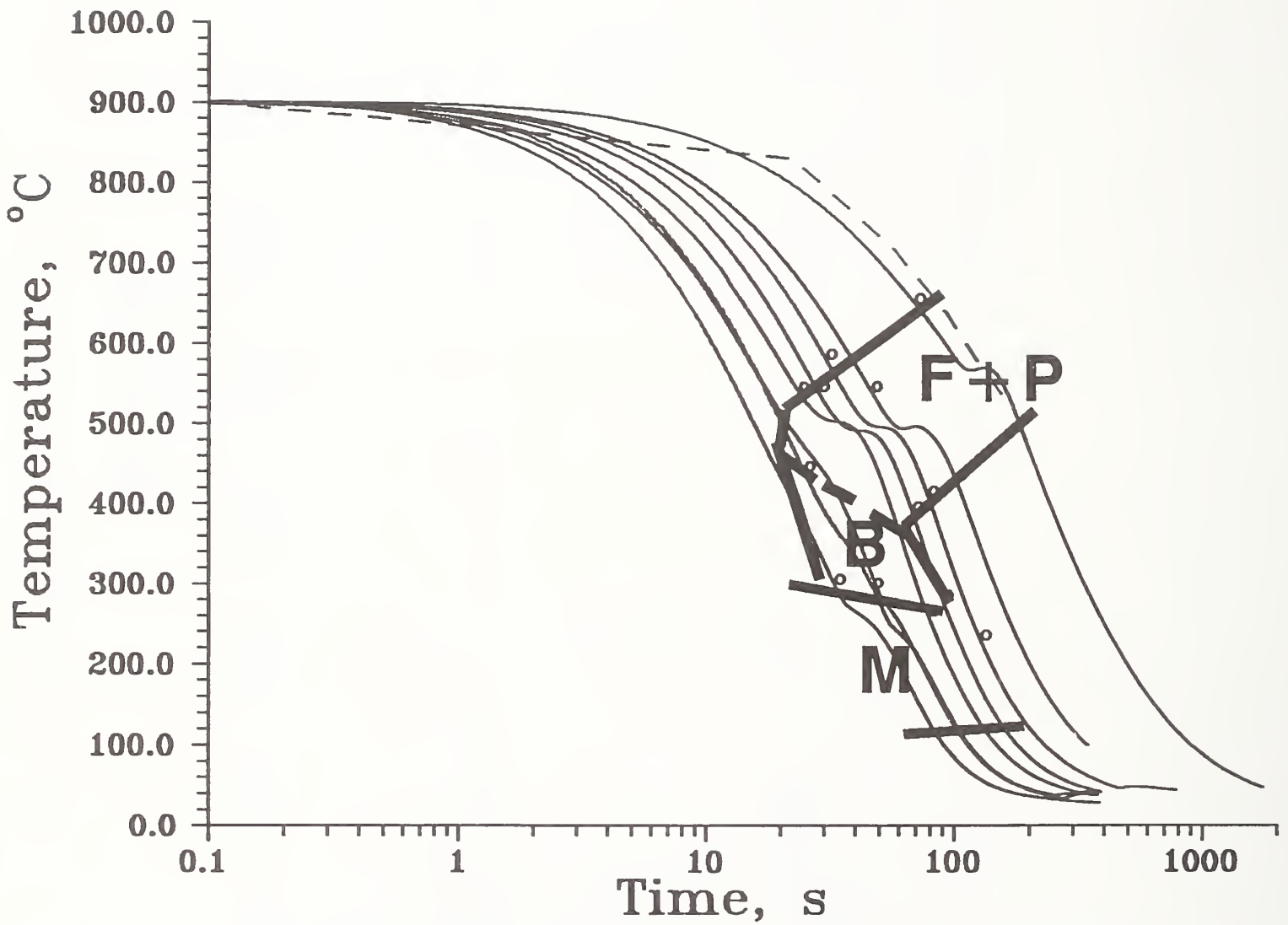


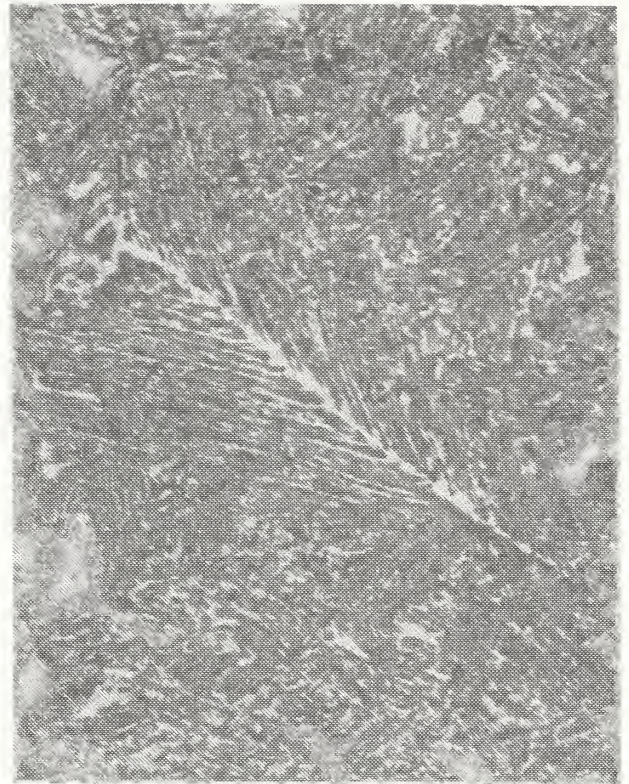
Figure 23. The CCT diagram of the 1141 microalloyed forging steel. Dashed line is the typical cooling rate found in a forging without forced cooling (Ref. 31).

20 Rc



(a)

29 Rc



(b)

50 Rc



(c)

42 Rc



(d)

20 μm

Figure 24. Microstructures of the microalloyed 1141 steel with different cooling rates. (a) ferrite plus pearlite; (b) pearlite-ferrite (Widmanstätten) plus small portion of bainite; (c) bainite plus small portion of martensite; (d) martensite plus small portion of bainite.

APPENDIX 1. Computer Program Listing for System Control and Data Acquisition

```

\*****
\
\          SYSTEM CONTROL AND DATA ACQUISITION PROGRAM
\
\*****

```

```

65280 SYSTEM.BUFFER.SIZE
DIM[ 10 , 50 ] STRING.ARRAY SCOPE.BACK
14 GPIB.DEVICE SCOPE SCOPE.BACK "GPIB.BUFFER
REAL DIM[ 50 ] ARRAY [ ]DATA.WAVETEK
2 GPIB.DEVICE WAVETEK [ ]DATA.WAVETEK [ ]GPIB.BUFFER
SEND.INTERFACE.CLEAR
REMOTE.ENABLE.ON
4000 TIMEOUT
REAL SCALAR TOTALtime
SCALAR DELAY
SCALAR EPStotal
SCALAR STRKFACTOR          \ Conversion factor (stroke): V to mm
SCALAR PFACTOR             \ Conversion factor (load): V to kN
SCALAR ACTUorGAGE          \ Checking if actuator or gage is used for strain
SCALAR VFACTOR             \ Starting point in displacement curve
                           \ on oscilloscope.
SCALAR AA
SCALAR VALVEfactor
SCALAR TEMP                \ Temperature inputs
SCALAR VTEMPmean           \ 20-point average for temperature determination
                           \ in mV
SCALAR VTEMP               \ Average mV for temperature checking
SCALAR 1stTEMP             \ 1st compression temperature
SCALAR TT                  \ Test temperature
INTEGER SCALAR NMAX
SCALAR ASCDIM
SCALAR ASCDIM1
40 STRING FILENAME
40 STRING FILENAME1
20 STRING SPECIMEN.NAME
20 STRING MATERIAL
64 STRING TREATMENT
15 STRING TEST.DATE

```

```

20 STRING OPERATOR
64 STRING TEMPERATURE
64 STRING TEST.TYPE
64 STRING RESERVED
RAEL DIM[ 1000 ] ARRAY TTRANS
REAL DIM[ 1000 ] ARRAY DTRANS
REAL DIM[ 200 ] ARRAY VOLTOUT
REAL DIM[ 200 ] ARRAY TIMEI
REAL DIM[ 50 ] ARRAY PARAM
REAL DIM[ 1500 ] ARRAY PLOAD
REAL DIM[ 1500 ] ARRAY DISPL.
REAL DIM[ 1500 ] ARRAY STRESS
REAL DIM[ 1500 ] ARRAY STRAIN
REAL DIM[ 1500 ] ARRAY SIGMA
REAL DIM[ 1500 ] ARRAY EPSILON
REAL DIM[ 1500 ] ARRAY EPLAST
REAL DIM[ 1500 ] ARRAY L           \ Instantaneous gage length
REAL DIM[ 1500 ] ARRAY STS
REAL DIM[ 1500 ] ARRAY STN
REAL DIM[ 9 ] ARRAY deltaH
REAL DIM[ 9 ] ARRAY tTEMP
0. PARAM :=
0. PLOAD :=
0. DISPL. :=
0. STRESS :=
0. STRAIN :=
0. SIGMA :=
0. EPSILON :=
0. EPLAST :=
0. L :=
0. VOLTOUT :=
0. TIMEI :=
0. tTEMP :=
0. deltaH :=
0. STN :=
0. STS :=

```



```

0. TTRANS :=
0. DTRANS :=
DT2820
0 0 D/A.TEMPLATE DT0A
1 1 D/A.TEMPLATE DT0A1
3 3 A/D.TEMPLATE T
1 1 A/D.TEMPLATE G
." INPUT.PARAMETERS "
: INPUT.PARAMETERS \ *****
0. PARAM :=
CR CR
." Enter the specimen name (8 CHARACTERS EXACTLY !!!!!) " "INPUT
SPECIMEN.NAME " :=
CR CR ." Enter the material (20 CHARACTERS) " "INPUT .
MATERIAL " :=
CR CR ." Enter the thermal treatment (64 CHARACTERS) " "INPUT
TREATMENT " :=
CR CR ." Enter the test date (MM/DD/YY) " "INPUT
TEST.DATE " :=
CR CR ." Enter the operator's name (20 CHARACTERS) " "INPUT
OPERATOR " :=
CR CR
." Enter the test temperatures for future record (64 CHARACTERS) " "INPUT
TEMPERATURE " :=
CR CR
." Enter the test type (Tension/Compression with/without ext. etc.,(64 CHAR.) "
"INPUT
TEST.TYPE " :=
CR CR ." Enter any additional data (64 CHAR.) " "INPUT
RESERVED " :=
CR CR ." Hit 0 for TENSION or 1 for COMPRESSION " #INPUT
PARAM [ 2 ] := \ Tension/Compression
CR CR ." Enter the initial height of the stroke (mm) " #INPUT
PARAM [ 4 ] :=
CR CR ." Enter gage length Lo/Ho (mm) " #INPUT
PARAM [ 5 ] := \ Total initial length (Lo)

```

```

CR CR ." Enter specimen's area Ao (sq. mm) " #INPUT
PARAM [ 6 ] :=
                \ Initial area (Ao)
                \ PARAM [ 16 ] is reserved for NMAX
CR CR ." Enter FILE NAME for data saving (20 CHAR.) " #INPUT
FILENAME " :=
SCREEN.CLEAR
CR CR ." How many hits do you want? (up to 10) " #INPUT
PARAM [ 1 ] :=
CR CR ." Enter how-many-N per 1 V (Newtons) " #INPUT
PFACTOR :=
CR CR ." Enter how-many-V (stroke) per 1 mm (volts) " #INPUT
STRKFACTOR :=
PFACTOR PARAM [ 3 ] :=
CR CR ." Enter 1 for ACTUATOR, 0 for GAGE " #INPUT
ACTUorGAGE :=
ACTUorGAGE PARAM [ 7 ] :=
CR CR ." Enter the desired true strain rate (1/s) " #INPUT
PARAM [ 19 ] :=
CR CR ." Enter the COOLING-RATE (0.= 0 V equivalent to valve close;
    5.= 5 V equivalent to valve fully open) " #INPUT
VALVEfactor :=
VALVEfactor PARAM [ 17 ] :=
CR CR ." Enter the desired FINAL height after the 1st HIT (mm) " #INPUT
PARAM [ 21 ] :=
CR CR ." Enter the temperature (deg. C) for the 1st Hit " #INPUT
1stTEMP :=
1stTEMP PARAM [ 18 ] :=
CR CR
NORMAL.DISPLAY
PARAM [ 1 ] 1 > IF
PARAM [ 1 ] 1 DO
." Enter Delta-Height (mm) for hit No - " I 1 + . ." #INPUT
deltaH [ I ] :=
CR CR
LOOP
deltaH [ 1 ] PARAM [ 8 ] :=
                \ 2nd hit

```

```

deltaH [ 2 ] PARAM [ 9 ] :=          \ 3rd hit
deltaH [ 3 ] PARAM [ 10 ] :=         \ 4th hit
deltaH [ 4 ] PARAM [ 11 ] :=         \ 5th hit
deltaH [ 5 ] PARAM [ 12 ] :=         \ 6th hit
deltaH [ 6 ] PARAM [ 13 ] :=         \ 7th hit
deltaH [ 7 ] PARAM [ 14 ] :=         \ 8th hit
deltaH [ 8 ] PARAM [ 15 ] :=         \ 9th hit
NORMAL.DISPLAY
PARAM [ 1 ] 1 DO
." Enter the temperature (deg. C) for hit No " I 1 + . . " #INPUT
tTEMP [ I ] :=
CR CR
LOOP
tTEMP [ 1 ] PARAM [ 20 ] :=          \ 2nd hit temperature
tTEMP [ 2 ] PARAM [ 22 ] :=          \ 3rd
tTEMP [ 3 ] PARAM [ 42 ] :=          \ 4th
tTEMP [ 4 ] PARAM [ 43 ] :=          \ 5th
tTEMP [ 5 ] PARAM [ 50 ] :=          \ 6th
THEN
SCREEN.CLEAR
CR ."          " INVERSE.ON ." Important !!!! " INVERSE.OFF
CR CR CR CR
." After you return to the main menu type S to exit and enter a value for the
time INTERVAL (ms between dilation-temperature data points during cooling); "
CR CR ." For example: "
CR CR CR ." 300. INTERVAL := "
CR CR CR ." Then, type NAR to return to the main menu and start the test "
CR CR CR CR ." Hit <RET> to continue..... " #INPUT
;
." SAVE.PARAMETERS "
: SAVE.PARAMETERS \ *****
FILE.TEMPLATE
9 COMMENTS
REAL DIM[ 50 ] SUBFILE
REAL DIM[ 1500 ] SUBFILE
3 TIMES

```

```

REAL DIM[ 9 ] SUBFILE
2 TIMES
END
FILENAME DEFER> FILE.CREATE FILENAME DEFER> FILE.OPEN
FILENAME          1  >COMMENT
SPECIMEN.NAME     2  >COMMENT
MATERIAL          3  >COMMENT
TREATMENT         4  >COMMENT
TEST.DATE         5  >COMMENT
OPERATOR          6  >COMMENT
TEMPERATURE       7  >COMMENT
TEST.TYPE         8  >COMMENT
RESERVED          9  >COMMENT
1 SUBFILE PARAM ARRAY>FILE
2 SUBFILE PLOAD ARRAY>FILE
3 SUBFILE DISPL. ARRAY>FILE
4 SUBFILE L ARRAY>FILE
5 SUBFILE tTEMP ARRAY>FILE
6 SUBFILE deltaH ARRAY>FILE
FILE.CLOSE
;
." INITIALIZE.SYSTEM "
: INITIALIZE.SYSTEM \ *****
0. PLOAD :=
0. DISPL. :=
0. STRESS :=
0. STRAIN :=
0. SIGMA :=
0. EPSILON :=
0. EPLAST :=
0. VOLTOUT :=
0. TIMEI :=
0. AA :=
0. STN :=
0. STS :=
DT2820 DtoA D/A.INIT 2048. D/A.OUT

```

DtoA1 D/A.INIT 2048. D/A.OUT

```
;
: CHECK.TEMP \ *****
NORMAL.DISPLAY
CR CR CR CR CR
INVERSE.ON
." Waiting for the correct test temperature ! " INVERSE.OFF
BEGIN
0. VTEMPmean :=
T A/D.INIT
21 1 DO
A/D.IN VTEMPmean + VTEMPmean :=
LOOP
VTEMPmean 20. / 2048. - 2048. / 100. * VTEMP :=
VTEMP 130.268 * -3.8403 VTEMP 2. ** * + 0.104154
VTEMP 3. ** * + 11.7469 + TEMP :=
TEMP TT <=
UNTIL
;
: READ.TEMP.AND.DILATION \ Acquire dilation-temperature data during
                           cooling
SCREEN.CLEAR
CR CR CR CR CR
INVERSE.ON
." Reading temperature and dilation data ..... " INVERSE.OFF
1001 1 DO
T A/D.INIT A/D.IN TTRANS [ I ] :=
G A/D.INIT A/D.IN DTRANS [ I ] :=
INTERVAL MSEC.DELAY
LOOP
TTRANS 2048. TTRANS :=
TTRANS 2048. / TTRANS :=
TTRANS 100. * TTRANS :=
1001 1 DO
TTRANS [ I ] 3. ** 0.104154 * TTRANS [ I ] 2. ** -3.8403 * + TTRANS [ I ]
130.268 * + 11.7469 + TTRANS [ I ] :=
LOOP
```

```

DTRANS 2048. - 2048. / -928.8878 * DTRANS :=
STACK.CLEAR
;
: COMMUNICATE \ ***** Initializing GPIB *****
SCOPE.BACK "GPIB.BUFFER
ME TALKER SCOPE LISTENER OAH EOS.CHARACTER EOI.OFF EOS.ON
" C,4,1,44 " GPIB.WRITE 10 ASCII" GPIB.WRITE
ME LISTENER SCOPE TALKER
BUFFER.LISTEN
;
: COMPUTER.CONTROL
ME TALKER SCOPE LISTENER OAH EOS.CHARACTER EOI.OFF EOS.ON
" Z1 " GPIB.WRITE 10 ASCII" GPIB.WRITE
ME LISTENER SCOPE TALKER
BUFFER.LISTEN
;
: TRIGGER.SCOPE.RIGHT
ME TALKER SCOPE LISTENER OAH EOS.CHARACTER EOI.OFF EOS.ON
" H,1,2 " GPIB.WRITE 10 ASCII" GPIB.WRITE
ME LISTENER SCOPE TALKER
BUFFER.LISTEN
;
: TRIGGER.SCOPE.LEFT
ME TALKER SCOPE LISTENER OAH EOS.CHARACTER EOI.OFF EOS.ON
" H,1,1 " GPIB.WRITE 10 ASCII" GPIB.WRITE
ME LISTENER SCOPE TALKER
BUFFER.LISTEN
;
: RECORD.SIGNAL
ME TALKER SCOPE LISTENER OAH EOS.CHARACTER EOI.OFF EOS.ON
" S,0,0,0 " GPIB.WRITE 10 ASCII" GPIB.WRITE
ME LISTENER SCOPE TALKER
BUFFER.LISTEN
;
: CONTROL.BACK.TO.SCOPE
ME TALKER SCOPE LISTENER OAH EOS.CHARACTER EOI.OFF EOS.ON

```

```

" ZO " GPIB.WRITE 10 ASCII" GPIB.WRITE
ME LISTENER SCOPE TALKER
BUFFER.LISTEN
;
." GET.DATA "          \ Get data through A/D channel
: GET.DATA
DToA D/A.INIT
PARAM [ 4 ] PARAM [ 21 ] / LN EPStotal :=
EPStotal PARAM [ 19 ] / TOTALtime :=
TOTALtime 5.0251 * DELAY :=
201 1 DO
I 200. / TOTALtime * TIMEI [ I ] :=
TIMEI [ I ] PARAM [ 19 ] * -1. * EXP 0.5 * PARAM [ 4 ] * 2.5 /
VOLTOUT [ I ] :=
LOOP
VOLTOUT VOLTOUT [ 1 ] - AA + VOLTOUT :=
VOLTOUT [ 200 ] AA :=
VOLTOUT -10 10 D/A.SCALE VOLTOUT :=
DELAY SYNC.PERIOD
SYNC.ERROR.OFF
SCOPE.BACK "GPIB.BUFFER
COMMUNICATE
COMPUTER.CONTROL
TRIGGER.SCOPE.RIGHT
100 MSEC.DELAY
201 1 DO          \ Operating the stroke
SYNCHRONIZE
VOLTOUT [ I ]
D/A.OUT
LOOP
RECORD.SIGNAL
CONTROL.BACK.TO.SCOPE
;
: READ.ASCII \ ***** ASCII TO ASYST *****
CR CR CR ." Enter the name of the ASCII LOAD file....      - " "INPUT
DEFER> BASIC.OPEN

```

```

BASIC.READ DROP
BEGIN
BASIC.READ DROP
CATENATE
?BASIC.EOF
UNTIL
BASIC.CLOSE
[ ]SIZE ASCDIM :=
SUB[ 1 , ASCDIM ] -1. * PLOAD SUB[ 1 , ASCDIM ] :=
CR CR CR ." Enter the name of the ASCII DISPLACEMENT file .. - " "INPUT
DEFER> BASIC.OPEN
BASIC.READ DROP
BEGIN
BASIC.READ DROP
CATENATE
?BASIC.EOF
UNTIL
BASIC.CLOSE
SUB[ 1 , ASCDIM ] -1. * DISPL. SUB[ 1 , ASCDIM ] :=
CR CR CR
INVERSE.ON
." Enter V factor for the displacement starting point (on oscilloscope,
negative V) "
CR CR #INPUT
VFACTOR := INVERSE.OFF
DISPL. VFACTOR + DISPL. :=
PLOAD PARAM [ 3 ] * PLOAD := \ Convert V to N(ewtons)
PARAM [ 7 ] 0 > IF
DISPL. STRKFACTOR * DISPL. := \ Convert V (actuator) to mm
ELSE
DISPL. 0.1011 * DISPL. := \ Convert V (displacement gage) to mm;
1 V = 0.1011 mm
THEN
PARAM [ 5 ] L [ 1 ] :=
ASCDIM 1 + 2 DO
L [ 1 ] DISPL. [ I ] - L [ I ] :=
LOOP

```



```

ASCDIM PARAM [ 16 ] :=
NORMAL.DISPLAY
;
." SAVE.DATA "
: SAVE.DATA \ ****
." SAVE.DATA "
FILE.TEMPLATE
9 COMMENTS
REAL DIM[ 50 ] SUBFILE
REAL DIM[ 1500 ] SUBFILE
3 TIMES
REAL DIM[ 9 ] SUBFILE
2 TIMES
END
FILENAME DEFER> FILE.CREATE FILENAME DEFER> FILE.OPEN
FILENAME          1 >COMMENT
SPECIMEN.NAME     2 >COMMENT
MATERIAL          3 >COMMENT
TREATMENT         4 >COMMENT
TEST.DATE         5 >COMMENT
OPERATOR          6 >COMMENT
TEMPERATURE       7 >COMMENT
TEST.TYPE         8 >COMMENT
RESERVED          9 >COMMENT
1 SUBFILE PARAM ARRAY>FILE
2 SUBFILE PLOAD ARRAY>FILE
3 SUBFILE DISPL. ARRAY>FILE
4 SUBFILE L ARRAY>FILE
5 SUBFILE tTEMP ARRAY>FILE
6 SUBFILE deltaH ARRAY>FILE
FILE.CLOSE
;
." SAVE.DATA1 "
: SAVE.DATA1 \ ****
." SAVE.DATA1 "
FILE.TEMPLATE

```

```

9 COMMENTS
REAL DIM[ 50 ] SUBFILE
REAL DIM[ 1500 ] SUBFILE
3 TIMES
REAL DIM[ 9 ] SUBFILE
2 TIMES
END
FILENAME1 DEFER> FILE.CREATE FILENAME1 DEFER> FILE.OPEN
FILENAME1          1 >COMMENT
SPECIMEN.NAME     2 >COMMENT
MATERIAL          3 >COMMENT
TREATMENT         4 >COMMENT
TEST.DATE         5 >COMMENT
OPERATOR          6 >COMMENT
TEMPERATURE       7 >COMMENT
TEST.TYPE         8 >COMMENT
RESERVED          9 >COMMENT
1 SUBFILE PARAM ARRAY>FILE
2 SUBFILE PLOAD ARRAY>FILE
3 SUBFILE DISPL. ARRAY>FILE
4 SUBFILE L ARRAY>FILE
5 SUBFILE tTEMP ARRAY>FILE
6 SUBFILE deltaH ARRAY>FILE
FILE.CLOSE
;
." REPEATED.HITS "
: REPEATED.HITS \ *****
PARAM [ 18 ] TT :=
CHECK.TEMP
GET.DATA
PARAM [ 1 ] 1 > IF
PARAM [ 1 ] 1 DO
PARAM [ 21 ] PARAM [ 4 ] :=
PARAM [ 21 ] deltaH [ I ] - PARAM [ 21 ] :=
tTEMP [ I ] TT :=
CHECK.TEMP

```

```

GET.DATA
FILENAME I "." 32 "COMPRESS "CAT FILENAME1 " :=
SAVE.DATA1
LOOP
THEN
50. MSEC.DELAY
DTOA D/A.INIT 40.96 5. * VOLTOUT [ 200 ] + D/A.OUT
;
." READ.FILE "
: READ.FILE \ ****
CR ." Enter name of file you want to load " "INPUT
DEFER> FILE.OPEN
1 COMMENT> FILENAME :=
2 COMMENT> SPECIMEN.NAME :=
3 COMMENT> MATERIAL :=
4 COMMENT> TREATMENT :=
5 COMMENT> TEST.DATE :=
6 COMMENT> OPERATOR :=
7 COMMENT> TEMPERATURE :=
8 COMMENT> TEST.TYPE :=
9 COMMENT> RESERVED :=
1 SUBFILE PARAM FILE>ARRAY
2 SUBFILE PLOAD FILE>ARRAY
3 SUBFILE DISPL. FILE>ARRAY
4 SUBFILE L FILE>ARRAY
5 SUBFILE tTEMP FILE>ARRAY
6 SUBFILE deltaH FILE>ARRAY
FILE.CLOSE
DT2820 DtOA1 D/A.INIT 2048. D/A.OUT
      DtoA D/A.INIT 2048. D/A.OUT
;
." SEE FILE "
: SEE.FILE \ ****
CR ." FILENAME - " FILENAME "TYPE
CR ." SPECIMEN.NAME - " SPECIMEN.NAME "TYPE
CR ." MATERIAL - " MATERIAL "TYPE

```

```

CR ." TREATMENT - " TREATMENT "TYPE
CR ." TEST.DATE - " TEST.DATE "TYPE
CR ." OPERATOR - " OPERATOR "TYPE
CR ." TEMPERATURE - " TEMPERATURE "TYPE
CR ." TEST.TYPE - " TEST.TYPE "TYPE
CR ." RESERVED - " RESERVED "TYPE
CR CR ." THE CURRENT VALUES ARE :      I          PARAM[I] "
51 1 DO PARAM [ I ] I
CR ."          " . ."          " .
PAUSE LOOP
CR CR ." THE DATA VALUES ARE:  I          LOAD          DISPL. "
CR
1501 1 DO DISPL. [ I ] PLOAD [ I ] I
CR ."          " . ."          " . ."          " .
PAUSE ?KEY IF KEY DROP LEAVE THEN LOOP
;
." DEFINE.PARAMETERS "
: DEFINE.PARAMETERS \ *****
CR ." Those are the names of the string parameters "
CR ." SPECIMEN.NAME      FILENAME      MATERIAL      TREATMENT      TEST.DATE      "
CR ." TEMPERATURE      TEST.TYPE      RESERVED      OPERATOR      "
CR ." Those are the meanings of the items in the PARAM array "
CR ." PARAM [ 1 ] - No of hits "
CR ."      2      - Tension/Compression ( 0 = Tension ) "
CR ."      3      - Load calibration factor (N per 1 V) "
CR ."      4      - The initial height of the stroke above the lower anvil "
CR ."      5      - Gage length (Lo/Ho) "
CR ."      6      - Initial area (Ao) "
CR ."      7      - Actuator (param [7] = 1) or Displacement Gage (= 0) "
CR ."      8      - DELTA H in hit No 2 "
CR ."      9      - DELTA H in hit No 3 "
CR ."     10      - DELTA H in hit No 4 "
CR ."     11      - DELTA H in hit No 5 "
CR ."     12      - DELTA H in hit No 6 "
CR ."     13      - DELTA H in hit No 7 "
CR ."     14      - DELTA H in hit No 8 "

```

```

CR ."      15  - DELTA H in HIT No 9 "
CR ."      16  - No. of data points (NMAX) "
CR ."      17  - Cooling valve opening (V) "
CR ."      18  - 1st hit temperature "
CR ."      19  - Strain rate (1/s) "
CR ."      20  - 2nd hit temperature "
CR ."      21  - HEIGHT after hit No. 1 "
CR ."      22  - 3rd hit temperature "
CR ."      23  - Stress at 0.01% "
CR ."      24  - Stress at 0.05% "
CR ."      25  - Stress at 0.1% "
CR ."      26  - Stress at 0.2% "
CR ."      27  - Ultimate stress "
CR ."      28  - Ultimate strain "
CR ."      29  - Fracture stress "
CR ."      30  - Fracture strain "
CR ."      31  - Young's Modulus "
CR ."      32  - Proportional limit "
CR ."      33  - No. of point in P.L. "
CR ."      34  - K1 "
CR ."      35  - K2 "
CR ."      36  - K3 "
CR ."      37  - N1 "
CR ."      38  - N2 "
CR ."      39  - N3 "
CR ."      40  - SLOPE "
CR ."      41  - INTERCEPT "
CR ."      42  - 4th hit temperature "
CR ."      43  - 5th hit temperature "
CR ."      44 - 49  - Limits for N/K calculations "
CR ."      50  - 6th hit temperature "
CR ." To change a parameter, do (for example): 5 PARAM [ 6 ] := "
CR
." To change a string parameter, do (for example): ' ' CHENG ' ' OPERATOR ' ':="
;
." CHANGE.PARAMETERS "

```

```

: CHANGE.PARAMETERS \ ****
CR ." After hitting a key you will return to the system. "
CR ." Change any parameters you want and type NAR to return to menu "
;
." CALCULATE.STRESS.STRAIN "
: CALCULATE.STRESS.STRAIN \ ****
INVERSE.ON ." Please wait, I am THINKING " INVERSE.OFF
1501 1 DO
PLOAD [ I ] PARAM [ 6 ] / STRESS [ I ] :=
DISPL. [ I ] PARAM [ 5 ] / 100. * STRAIN [ I ] :=
LOOP
;
." SEE.CURVE "
: SEE.CURVE \ ****
AXIS.DEFAULTS
STRAIN SUB[ 2 , PARAM [ 16 ] 1 - ]
STRESS SUB[ 2 , PARAM [ 16 ] 1 - ] XY.AUTO.PLOT
NORMAL.COORDS
0.5 0.05 POSITION " Strain, % " LABEL
90 LABEL.DIR
90 CHAR.DIR
0.015 0.3 POSITION CURSOR.OFF " Stress, Mpa " LABEL
0 LABEL.DIR
0 CHAR.DIR
WORLD.COORDS
CR ." Hit any key to continue "
KEY DROP
NORMAL.DISPLAY
;
: CONVERT.TO.ASCII \ ****
NORMAL.DISPLAY INVERSE.ON
CR CR CR ." An ASCII file named *****.DAT will be created. "
CR CR CR CR CR ." Hit any No key and <RET> to start data-conversion " #INPUT
INVERSE.OFF DROP
CR CR CR
STRESS SUB[ 1 , PARAM [ 16 ] 1 - 3 / , 3 ] [ ]SIZE ASCDIM1 :=

```

```

STRESS SUB[ 1 , PARAM [ 16 ] 1 - 3 / , 3 ] STS SUB[ 1 , ASCDIM1 ] :=
STRAIN SUB[ 1 , PARAM [ 16 ] 1 - 3 / , 3 ] STN SUB[ 1 , ASCDIM1 ] :=
SCREEN.CLEAR
CR CR CR CR CR CR
." Enter a name for the ASCII output file      (8 chars.DAT) "
CONSOLE.OFF "INPUT
DEFER> OUT>FILE
ASCDIM1 1 + 1 DO
STN [ I ] . ." , " STS [ I ] . CR
LOOP
OUT>FILE.CLOSE
;
." GO.ON "
: GO.ON \ *****
CR CR ." Hit any key to continue "
KEY DROP
;
: SEND.WAVETEK.SIGNAL \ Shut-off the induction generator
ME TALKER WAVETEK LISTENER
" P1F0.5A5DOB101COIJ " GPIB.WRITE
;
: OPEN.VALVE \ ***** Start forced cooling *****
DtoA1 D/A.INIT
2048. 10. / PARAM [ 17 ] * 2048. + D/A.OUT
;
." NAR "
: NAR \ ***** Program starting word *****
NORMAL.DISPLAY
1501 1 DO
SCREEN.CLEAR INTEN.ON INVERSE.ON
." F&D Dv.: THERMOMECHANICAL PROCESSING GROUP-INTERACTIVE TESTING PROGRAM "
CR CR
INTEN.OFF INVERSE.OFF
." Enter parameters for a new test ..... HIT 1 "
CR CR ." Start test ..... HIT 2 "
CR CR ." View S/e (engineering) curve ..... HIT 3 "

```

```

CR CR ." Parameters definition ..... HIT 4 "
CR CR ." Load file ..... HIT 5 "
CR CR ." Change file ..... HIT 6 "
CR CR ." See file ..... HIT 7 "
CR CR ." Save file ..... HIT 8 "
CR CR ." Convert ASCII data (*****.AD file) to ASYST, HIT 9 "
CR CR ." Convert ASYST data-file to ASCII (create ****.DAT file), HIT 0 "
CR CR ." QUIT ..... HIT S "

```

CR CR

KEY

CASE

49 OF INPUT.PARAMETERS SAVE.PARAMETERS INITIALIZE.SYSTEM ENDOF

50 OF INITIALIZE.SYSTEM

COMMUNICATE

COMPUTER.CONTROL

TRIGGER.SCOPE.RIGHT

REPEATED.HITS

RECORD.SIGNAL

CONTROL.BACK.TO.SCOPE

COMMUNICATE

COMPUTER.CONTROL

SEND.WAVETEK.SIGNAL

TRIGGER.SCOPE.LEFT

CONTROL.BACK.TO.SCOPE

OPEN.VALVE

READ.TEMP.AND.DILATION

ENDOF

51 OF CALCULATE.STRESS.STRAIN SEE.CURVE ENDOF

52 OF DEFINE.PARAMETERS GO.ON ENDOF

53 OF READ.FILE GO.ON ENDOF

54 OF CHANGE.PARAMETERS GO.ON LEAVE ENDOF

55 OF SEE.FILE GO.ON ENDOF

56 OF SAVE.DATA ENDOF

57 OF READ.ASCII SAVE.DATA ENDOF

48 OF READ.FILE CALCULATE.STRESS.STRAIN CONVERT.TO.ASCII ENDOF

83 OF LEAVE ENDOF

115 OF LEAVE ENDOF

NOF

ENDCASE

LOOP

;

APPENDIX 2. Computer Program Listing for Post-Test Data Analysis

```

\ *****
\          DATA ANALYSIS AND SUMMARIZING REPORT PRODUCTION PROGRAM
\ *****

```

```

REAL SCALAR I1
    SCALAR INDEX
    SCALAR SLOPE
    SCALAR INTERCEPT
    SCALAR RIGHT
    SCALAR LEFT
    SCALAR LEFT1
    SCALAR RANGE
    SCALAR K1
    SCALAR N
DIM[ 25 , 20 ] STRING.ARRAY FILENAMES
REAL DIM[ 1500 ] ARRAY E
REAL DIM[ 1500 ] ARRAY S
REAL DIM[ 1500 ] ARRAY YLEAST
REAL DIM[ 1500 ] ARRAY XLEAST
REAL DIM[ 2 ] ARRAY XYLEAST
REAL DIM[ 4 ] ARRAY CURSOR.POSITION
REAL DIM[ 25 ] ARRAY STATIS
REAL DIM[ 25 ] ARRAY STATIS1
REAL DIM[ 25 ] ARRAY MEANS
REAL DIM[ 25 ] ARRAY SDEV
REAL DIM[ 25 , 10 ] ARRAY TABLE4
REAL DIM[ 25 , 12 ] ARRAY TABLE5
O. YLEAST :=
O. XLEAST :=
O. XYLEAST :=
O. STATIS :=
O. STATIS1 :=
O. MEANS :=
O. SDEV :=
O. TABLE4 :=
O. E :=

```

```

0. S :=
VUPORT VU1
0 0.21 VUPORT.ORIG
1 0.79 VUPORT.SIZE
20 0 25 80 WINDOW VU2
." GO.ON1 "
: GO.ON1 \ ****
CR ." Enter 1 to continue :
BEGIN
#INPUT 1 = IF EXIT THEN
AGAIN
;
." A "
: A \ ***** EPLAST, SIGMA, EPSILON Calculations *****
INVERSE.ON ." Please wait " INVERSE.OFF
PARAM [ 33 ] 1 DO
0. EPLAST [ I ] :=
LOOP
PARAM [ 16 ] 1 + PARAM [ 33 ] DO
STRESS [ I ] 0. > IF
STRAIN [ I ] 100. / STRESS [ I ] PARAM [ 41 ] - PARAM [ 31 ] / - EPLAST [ I ]
:=
THEN
LOOP
PARAM [ 2 ] 0 >
IF
1. EPLAST -
STRESS * SIGMA :=
PARAM [ 16 ] 1 + 2 DO
L [ I 1 - ] L [ I ] - L [ I ] / EPSILON [ I 1 - ] :=
LOOP
EPSILON ^SUM EPSILON :=
ELSE
1. EPLAST +
STRESS * SIGMA :=
PARAM [ 16 ] 1 + 2 do

```

```

L [ I ] L [ I 1 - ] - L [ I 1 - ] / EPSILON [ I 1 - ] :=
LOOP
EPSILON ^SUM EPSILON :=
THEN
;
." NKTABLE "
: NKTABLE \ *****
CR CR
." Specimen          N1          K1          N2          K2          N3          K3  "
CR
." name              MPA              MPA              MPA  "
CR
." ----- "
CR
DUP
1 + 1 DO
CR
FILENAMES "[ I ] "TYPE
12 3 FIX.FORMAT
TABLE5 [ I , 1 ] .
10 0 FIX.FORMAT
TABLE5 [ I , 2 ] .
10 3 FIX.FORMAT
TABLE5 [ I , 3 ] .
10 0 FIX.FORMAT
TABLE5 [ I , 4 ] .
10 3 FIX.FORMAT
TABLE5 [ I , 5 ] .
10 0 FIX.FORMAT
TABLE5 [ I , 6 ] .
LOOP
CR
." ----- "
-1 4 FIX.FORMAT
1 + 1 DO
CR

```

```

I . TABLE5 [ I , 7 ] . TABLE5 [ I , 10 ] . ." "
TABLE5 [ I , 8 ] . TABLE5 [ I , 11 ] . ." "
TABLE5 [ I , 9 ] . TABLE5 [ I , 12 ] . ." "
LOOP
;
." SEE.CURVE1 "
: SEE.CURVE1 \ ****
LOAD.OVERLAY MATFIT.SOV
VERTICAL LINEAR
HORIZONTAL LINEAR
STACK.CLEAR
-1 4 FIX.FORMAT
GRAPHICS.DISPLAY VU1 VU2
CR ." Hit 1 to calculate Young's modulus, 2 to calculate UTS "
#INPUT
1 = IF
BEGIN
STRAIN SUB[ 2 , PARAM [ 16 ] 1 - ]
STRESS SUB[ 2 , PARAM [ 16 ] 1 - ] XY.AUTO.PLOT
NORMAL.COORDS
0.5 0.05 POSITION " Strain, % " LABEL
90 LABEL.DIR
90 CHAR.DIR
0.015 0.3 POSITION CURSOR.OFF " Stress, Mpa " LABEL
0 LABEL.DIR
0 CHAR.DIR
WORLD.COORDS
ARRAY.READOUT
CR ." Place left cursor to define a zone for magnification "
GO.ON1
READOUT.INDICES
1 + RIGHT :=
1 + LEFT1 :=
BEGIN
STRAIN SUB[ 2 , LEFT1 ] STRESS SUB[ 2 , LEFT1 ] XY.AUTO.PLOT
NORMAL.COORDS

```

```

0.5 0.05 POSITION " Strain, % " LABEL
90 LABEL.DIR
90 CHAR.DIR
0.015 0.3 POSITION CURSOR.OFF " Stress, Mpa " LABEL
0 LABEL.DIR
0 CHAR.DIR
WORLD.COORDS
ARRAY.READOUT
SCREEN.CLEAR CR ." Define a line for Y.M. and " GO.ON1
READOUT.INDICES
1 + RIGHT :=
1 + LEFT :=
LEFT 1 = IF 2 LEFT := THEN
RIGHT LEFT - RANGE :=
XLEAST [ ]RAMP
WITHOUT.WEIGHTS
STRAIN SUB[ LEFT , RANGE ]
STRESS SUB[ LEFT , RANGE ] 1 LEASTSQ.POLY.FIT
XYLEAST :=
XYLEAST [ 1 ] SLOPE :=
SLOPE PARAM [ 40 ] :=
XYLEAST [ 2 ] INTERCEPT :=
INTERCEPT PARAM [ 41 ] :=
XLEAST XLEAST [ RIGHT ] / STRAIN [ RIGHT ] * XLEAST :=
XLEAST SLOPE * INTERCEPT + YLEAST :=
LEFT1 LEFT - RANGE :=
RANGE PARAM [ 16 ] > IF PARAM [ 16 ] LEFT - RANGE := THEN
XLEAST SUB[ LEFT , RANGE ] YLEAST SUB[ LEFT , RANGE ] XY.AUTO.PLOT
NORMAL.COORDS
0.5 0.05 POSITION " Strain, % " LABEL
90 LABEL.DIR
90 CHAR.DIR
0.015 0.3 POSITION CURSOR.OFF " Stress, Mpa " LABEL
0 LABEL.DIR
0 CHAR.DIR
WORLD.COORDS

```

```

STRAIN SUB[ LEFT , RANGE ] STRESS SUB[ LEFT , RANGE ] XY.DATA.PLOT
NORMAL.COORDS
0.5 0.05 POSITION " Strain, % " LABEL
90 LABEL.DIR
90 CHAR.DIR
0.015 0.3 POSITION CURSOR.OFF " Stress, Mpa " LABEL
0 LABEL.DIR
0 CHAR.DIR
WORLD.COORDS
SLOPE 100. * PARAM [ 31 ] :=
SCREEN.CLEAR
CR ." Y. Module = " PARAM [ 31 ] .
CR ." Hit 1 to recalculate "
CR ." Hit 2 to continue (P.L.) "
#INPUT
2 = UNTIL
ARRAY.READOUT
SCREEN.CLEAR
CR ." Mark P.L. with right cursor and "
GO.ON1
READOUT.INDICES
LEFT + PARAM [ 33 ] :=
LEFT + LEFT :=
STRESS [ PARAM [ 33 ] ] DUP PARAM [ 32 ] :=
CR ." P.L. = " .
CR ." Hit 1 to recalculate "
CR ." Hit 2 to continue (UTS) "
#INPUT
2 = UNTIL
THEN
STRAIN SUB[ 2 , PARAM [ 16 ] 1 - ]
STRESS SUB[ 2 , PARAM [ 16 ] 1 - ] XY.AUTO.PLOT
NORMAL.COORDS
0.5 0.05 POSITION " Strain, % " LABEL
90 LABEL.DIR
90 CHAR.DIR

```



```

0.015 0.3 POSITION CURSOR.OFF " Stress, Mpa " LABEL
0 LABEL.DIR
0 CHAR.DIR
WORLD.COORDS
ARRAY.READOUT
SCREEN.CLEAR
CR ." Define a zone for UTS, use INS and "
GO.ON1
GRAPHICS.READOUT
CURSOR.POSITION
READOUT>ARRAY
SCREEN.CLEAR
CR ." Type *** HOME *** and "
GO.ON1
CURSOR.POSITION [ 2 ] PARAM [ 27 ] :=
CURSOR.POSITION [ 1 ] 100 / PARAM [ 27 ] PARAM [ 41 ] -
PARAM [ 31 ] / - 100 * PARAM [ 28 ] :=
SCREEN.CLEAR
PARAM [ 27 ] CR ." Ultimate stress = " .
PARAM [ 28 ] CR ." Ultimate strain = " .
GO.ON1
STRAIN SUB[ 2 , PARAM [ 16 ] 1 - ]
STRESS SUB[ 2 , PARAM [ 16 ] 1 - ] XY.AUTO.PLOT
NORMAL.COORDS
0.5 0.05 POSITION " Strain, % " LABEL
90 LABEL.DIR
90 CHAR.DIR
0.015 0.3 POSITION CURSOR.OFF " Stress, Mpa " LABEL
0 LABEL.DIR
0 CHAR.DIR
WORLD.COORDS
ARRAY.READOUT
SCREEN.CLEAR
CR ." Define a zone for FRACTURE, use INS and "
GO.ON1
GRAPHICS.READOUT

```

```

CURSOR.POSITION
READOUT>ARRAY
SCREEN.CLEAR
CR ." Type *** HOME *** and "
GO.ON1
CURSOR.POSITION [ 2 ] PARAM [ 29 ] :=
CURSOR.POSITION [ 1 ] 100 / PARAM [ 29 ] PARAM [ 41 ] -
PARAM [ 31 ] / - 100 * PARAM [ 30 ] :=
SCREEN.CLEAR
PARAM [ 29 ] CR ." Fracture stress = " .
PARAM [ 30 ] CR ." Fracture strain = " .
GO.ON1
NORMAL.DISPLAY PREVIOUS.WINDOW DEF.VUPOINT
A
SCREEN.CLEAR
CR ." Hit 1 for N/K calculations, 2 to QUIT "
#INPUT
1 = IF
4 1 DO
BEGIN
GRAPHICS.DISPLAY VU1 VU2
PARAM [ 16 ] 1 + 1 DO
EPSILON [ I ] 0. <= IF I INDEX := THEN
LOOP
PARAM [ 16 ] INDEX - 4 - 1 INDEX + DO
EPSILON [ I ] LOG E [ I ] :=
SIGMA [ I ] LOG S [ I ] :=
LOOP
E S XY.AUTO.PLOT
NORMAL.COORDS
0.5 0.05 POSITION " Log true strain " LABEL
90 LABEL.DIR
90 CHAR.DIR
0.015 0.3 POSITION CURSOR.OFF " Log true stress " LABEL
0 LABEL.DIR
0 CHAR.DIR

```

```

WORLD.COORDS
ARRAY.READOUT
SCREEN.CLEAR
." Mark an area for fitting "
GO.ON1
READOUT.INDICES
RIGHT :=
1 INDEX + RIGHT + RIGHT :=
LEFT1 :=
1 INDEX + LEFT1 + LEFT1 :=
RIGHT LEFT1 - RANGE :=
WITHOUT.WEIGHTS
EPSILON SUB[ LEFT1 , RANGE ] LOG
SIGMA SUB[ LEFT1 , RANGE ] LOG 1 LEASTSQ.POLY.FIT
XYLEAST :=
XYLEAST [ 1 ] N :=
10 XYLEAST [ 2 ] ** K1 :=
SCREEN.CLEAR ." N = " N . ." K = " K1 . ." E1 = " EPSILON [ RIGHT ] .
." E2 = " EPSILON [ LEFT1 ] .
CR ." Hit 1 to save values, 2 to recalculate "
#INPUT
1. = UNTIL
EPSILON [ LEFT1 ] PARAM [ 43 I + ] :=
EPSILON [ RIGHT ] PARAM [ 46 I + ] :=
K1 PARAM [ 33 I + ] :=
N PARAM [ 36 I + ] :=
CR ." Hit 3 to EXIT N/K calculations "
#INPUT
3 = IF LEAVE THEN
LOOP
THEN
VERTICAL LINEAR
HORIZONTAL LINEAR
;
." SPECIAL.POINTS1 "
: SPECIAL.POINTS1 \ *****

```

```

PARAM [ 16 ] 1 + 1 DO DUP EPLAST [ I ] < IF LEAVE THEN I I1 := LOOP I1 PARAM [
16 ] = IF DROP 0. THEN
EPLAST [ I1 1 - ] - EPLAST [ I1 ] EPLAST [ I1 1 - ] - - /
STRESS [ I1 ] STRESS [ I1 1 - ] - * STRESS [ I1 1 - ] +
;
." SPECIAL.POINTS "
: SPECIAL.POINTS \ *****
100. EPLAST * EPLAST := \ Changing EPLAST to percents
0 PARAM [ 23 ] :=
0 PARAM [ 24 ] :=
0 PARAM [ 25 ] :=
0 PARAM [ 26 ] :=
0.01 SPECIAL.POINTS1 PARAM [ 23 ] :=
0.05 SPECIAL.POINTS1 PARAM [ 24 ] :=
0.1 SPECIAL.POINTS1 PARAM [ 25 ] :=
0.2 SPECIAL.POINTS1 PARAM [ 26 ] :=
;
." TABLE1 "
: TABLE1 \ *****
SCREEN.CLEAR
." Specimen Y. Modulus P.L. | Plastic Yield | S.U. E.U. S.F. "
." E.F "
CR
." name MPA MPA |.01% .05% 0.1% 0.2%| MPA % MPA "
." % "
CR
." ----- "
." ---- "
CR ;
." TABLE2 "
: TABLE2 \ *****
1 + 1 DO
CR
FILENAMES "[ I ] "TYPE
12 0 FIX.FORMAT
TABLE4 [ I , 1 ] .

```

```

6 0 FIX.FORMAT
TABLE4 [ I , 2 ] .
7 0 FIX.FORMAT
TABLE4 [ I , 3 ] .
6 0 FIX.FORMAT
TABLE4 [ I , 4 ] .
6 0 FIX.FORMAT
TABLE4 [ I , 5 ] .
7 0 FIX.FORMAT
TABLE4 [ I , 6 ] .
6 0 FIX.FORMAT
TABLE4 [ I , 7 ] .
6 1 FIX.FORMAT
TABLE4 [ I , 8 ] .
7 0 FIX.FORMAT
TABLE4 [ I , 9 ] .
6 1 FIX.FORMAT
TABLE4 [ I , 10 ] .
-1 4 FIX.FORMAT
LOOP
CR
;
." STATS "
: STATS \ ****
STATIS1 :=
0. INDEX :=
11 1 DO
STATIS1 [ I ] 0. >
IF INDEX 1 + INDEX := STATIS1 [ I ] STATIS [ INDEX ] := ELSE THEN LOOP
;
." TABLE3 "
: TABLE3 \ ****
0. TABLE4 :=
0. TABLE5 :=
CR ." How many specimens for table? "
#INPUT DUP DUP

```

```

1 + 1 DO
READ.FILE
SPECIMEN.NAME FILENAMES "[ I ] " :=
PARAM [ 31 ] TABLE4 [ I , 1 ] :=
PARAM [ 32 ] TABLE4 [ I , 2 ] :=
PARAM [ 23 ] TABLE4 [ I , 3 ] :=
PARAM [ 24 ] TABLE4 [ I , 4 ] :=
PARAM [ 25 ] TABLE4 [ I , 5 ] :=
PARAM [ 26 ] TABLE4 [ I , 6 ] :=
PARAM [ 27 ] TABLE4 [ I , 7 ] :=
PARAM [ 28 ] TABLE4 [ I , 8 ] :=
PARAM [ 29 ] TABLE4 [ I , 9 ] :=
PARAM [ 30 ] TABLE4 [ I , 10 ] :=
PARAM [ 37 ] TABLE5 [ I , 1 ] :=
PARAM [ 34 ] TABLE5 [ I , 2 ] :=
PARAM [ 38 ] TABLE5 [ I , 3 ] :=
PARAM [ 35 ] TABLE5 [ I , 4 ] :=
PARAM [ 39 ] TABLE5 [ I , 5 ] :=
PARAM [ 36 ] TABLE5 [ I , 6 ] :=
PARAM [ 44 ] TABLE5 [ I , 7 ] :=
PARAM [ 45 ] TABLE5 [ I , 8 ] :=
PARAM [ 46 ] TABLE5 [ I , 9 ] :=
PARAM [ 47 ] TABLE5 [ I , 10 ] :=
PARAM [ 48 ] TABLE5 [ I , 11 ] :=
PARAM [ 49 ] TABLE5 [ I , 12 ] :=
LOOP
CR ." Arrange paper and hit 1 to print on printer "
#INPUT 1 = IF OUT>PRINTER THEN
TABLE1
TABLE2
CR
." ----- "
." ---- "
11 1 DO
TABLE4 XSECT[ ! , I ] STATS
STATIS SUB[ 1 , INDEX ] MEAN MEANS [ I ] :=

```

```

INDEX 2 < IF 0. SDEV [ I ] := ELSE
STATIS SUB[ 1 , INDEX ] SAMPLE.VARIANCE SQRT SDEV [ I ] := THEN LOOP
CR ." AVERAGE "
12 0 FIX.FORMAT
MEANS [ 1 ] .
6 0 FIX.FORMAT
MEANS [ 2 ] .
7 0 FIX.FORMAT
MEANS [ 3 ] .
6 0 FIX.FORMAT
MEANS [ 4 ] .
6 0 FIX.FORMAT
MEANS [ 5 ] .
7 0 FIX.FORMAT
MEANS [ 6 ] .
6 0 FIX.FORMAT
MEANS [ 7 ] .
6 1 FIX.FORMAT
MEANS [ 8 ] .
7 0 FIX.FORMAT
MEANS [ 9 ] .
6 1 FIX.FORMAT
MEANS [ 10 ] .
CR ." S. DEV. "
12 0 FIX.FORMAT
SDEV [ 1 ] .
7 1 FIX.FORMAT
SDEV [ 2 ] .
SDEV [ 3 ] .
6 1 FIX.FORMAT
SDEV [ 4 ] .
SDEV [ 5 ] .
7 1 FIX.FORMAT
SDEV [ 6 ] .
6 1 FIX.FORMAT
SDEV [ 7 ] .

```

```

5 1 FIX.FORMAT
SDEV [ 8 ] .
8 1 FIX.FORMAT
SDEV [ 9 ] .
5 1 FIX.FORMAT
SDEV [ 10 ] .
-1 4 FIX.FORMAT
CR
." ----- "
." ---- "
NKTABLE
CONSOLE
;
." PLOTTER1 "
: PLOTTER1 \ ****
LOAD.OVERLAY HPPLOTR.SOV
HP7475
PLOTTER.DEFAULTS
7 10 PLOTTER.SIZE
1 COLOR
NORMAL.COORDS
30. SLANT 0.35 0.99 POSITION " TMP group " LABEL 0. SLANT
0.85 0.99 POSITION FILENAME LABEL
WORLD.COORDS
;
." PLOTTER5 " \ ****
: PLOTTER5
NORMAL.COORDS
0.88 0.05 POSITION " e (%) " LABEL
0.18 0.99 POSITION " S (MPA) " LABEL
WORLD.COORDS
;
." PLOTTER6 " \ ****
: PLOTTER6
NORMAL.COORDS
0.83 0.08 POSITION " Log Epsilon " LABEL

```



```

0.17 0.99 POSITION " Log Sigma " LABEL
WORLD.COORDS
;
." PLOTTER16 " \ *****
: PLOTTER16
NORMAL.COORDS
0.85 0.08 POSITION " Epsilon " LABEL
0.17 0.99 POSITION " Sigma " LABEL
WORLD.COORDS
;
." PLOTTER2 "
: PLOTTER2 \ *****
STRAIN SUB[ 2 , PARAM [ 16 ] 1 - ]
STRESS SUB[ 2 , PARAM [ 16 ] 1 - ] XY.AUTO.PLOT
;
." PLOTTER3 "
: PLOTTER3 \ *****
STRAIN SUB[ 2 , LEFT1 ] STRESS SUB[ 2 , LEFT1 ] XY.AUTO.PLOT
;
." PLOTTER7 "
: PLOTTER7 \ *****
EPSILON SUB[ 1 INDEX + , PARAM [ 16 ] INDEX - 5 - ] LOG
SIGMA SUB[ 1 INDEX + , PARAM [ 16 ] INDEX - 5 - ] LOG XY.AUTO.PLOT
;
." PLOTTER17 "
: PLOTTER17 \ *****
EPSILON SUB[ 1 INDEX + , PARAM [ 16 ] INDEX - 5 - ]
SIGMA SUB[ 1 INDEX + , PARAM [ 16 ] INDEX - 5 - ] XY.AUTO.PLOT ;
." RETURN.PEN "
: RETURN.PEN \ *****
" SP; " GRAPH.COMMAND GRAPHICS.DISPLAY
;
." PLOTTER4 "
: PLOTTER4 \ *****
2 COLOR
0 XLEAST :=

```

```

0 YLEAST :=
XLEAST [ ]RAMP
XLEAST XLEAST [ PARAM [ 33 ] 20 + ] / STRAIN [ PARAM [ 33 ] 20 + ] * XLEAST :=
XLEAST PARAM [ 40 ] * PARAM [ 41 ] + YLEAST :=
501 1 DO YLEAST [ I ] 0. > IF LEAVE THEN I INDEX := LOOP
XLEAST SUB[ INDEX , PARAM [ 33 ] INDEX - 5 + ] YLEAST
SUB[ INDEX , PARAM [ 33 ] INDEX - 5 + ] XY.DATA.PLOT
;
." PLOT.DATA "
: PLOT.DATA \ *****
BEGIN
GRAPHICS.DISPLAY
VERTICAL GRID.OFF HORIZONTAL GRID.OFF
STRAIN SUB[ 2 , PARAM [ 16 ] 1 - ]
STRESS SUB[ 2 , PARAM [ 16 ] 1 - ] XY.AUTO.PLOT
NORMAL.COORDS
0.5 0.05 POSITION " Strain, % " LABEL
90 LABEL.DIR
90 CHAR.DIR
0.015 0.3 POSITION CURSOR.OFF " Stress, Mpa " LABEL
0 LABEL.DIR
0 CHAR.DIR
WORLD.COORDS
SCREEN.CLEAR CR ." Hit 1 to plot on PLOTTER, 2 to continue "
#INPUT 1 = IF
PLOTTER1 PLOTTER5 PLOTTER2 PLOTTER4 RETURN.PEN
THEN
STRAIN SUB[ 2 , PARAM [ 16 ] 1 - ]
STRESS SUB[ 2 , PARAM [ 16 ] 1 - ] XY.AUTO.PLOT
NORMAL.COORDS
0.5 0.05 POSITION " Strain, % " LABEL
90 LABEL.DIR
90 CHAR.DIR
0.015 0.3 POSITION CURSOR.OFF " Stress, Mpa " LABEL
0 LABEL.DIR
0 CHAR.DIR

```

```

WORLD.COORDS
ARRAY.READOUT
SCREEN.CLEAR CR GO.ON1
READOUT.INDICES
1 + RIGHT :=
1 + LEFT1 :=
STRAIN SUB[ 2 , LEFT1 ] STRESS SUB[ 2 , LEFT1 ] XY.AUTO.PLOT
NORMAL.COORDS
0.5 0.05 POSITION " Strain, % " LABEL
90 LABEL.DIR
90 CHAR.DIR
0.015 0.3 POSITION CURSOR.OFF " Stress, Mpa " LABEL
0 LABEL.DIR
0 CHAR.DIR
WORLD.COORDS
SCREEN.CLEAR CR
." Hit 1 to plot on PLOTTER, 2 to continue "
#INPUT 1 = IF
PLOTTER1 PLOTTER5 PLOTTER3 PLOTTER4 RETURN.PEN
THEN
SCREEN.CLEAR CR
." Hit 1 to PLOT again, 2 to STOP "
#INPUT 2 = UNTIL
AXIS.DEFAULTS
;
." PLOT.DATA11 "
: PLOT.DATA11 \ *****
BEGIN
GRAPHICS.DISPLAY
VERTICAL GRID.OFF HORIZONTAL GRID.OFF
PARAM [ 16 ] 1 + 1 DO
EPSILON [ I ] 0. <= IF I INDEX := THEN
LOOP
PARAM [ 16 ] INDEX - 4 - 1 INDEX + DO
EPSILON [ I ] LOG E [ I ] :=
SIGMA [ I ] LOG S [ I ] :=

```

```

LOOP
E S XY.AUTO.PLOT
NORMAL.COORDS
0.5 0.05 POSITION " True strain (LOG) " LABEL
90 LABEL.DIR
90 CHAR.DIR
0.015 0.3 POSITION CURSOR.OFF " True stress, Mpa (LOG) " LABEL 0 LABEL.DIR
0 CHAR.DIR
WORLD.COORDS
SCREEN.CLEAR CR ." Hit 1 to plot on PLOTTER, 2 to continue "
#INPUT 1 = IF
PLOTTER1 PLOTTER6 PLOTTER7 RETURN.PEN
THEN
SCREEN.CLEAR CR
." Hit 1 to PLOT again, 2 to STOP "
#INPUT 2 = UNTIL
AXIS.DEFAULTS
;
." PLOT.DATA12 "
: PLOT.DATA12 \ *****
BEGIN
GRAPHICS.DISPLAY
VERTICAL GRID.OFF HORIZONTAL GRID.OFF
PARAM [ 16 ] 1 + 1 DO
EPSILON [ I ] 0. <= IF I INDEX := THEN
LOOP
EPSILON SUB[ 1 INDEX + , PARAM [ 16 ] INDEX - 5 - ]
SIGMA SUB[ 1 INDEX + , PARAM [ 16 ] INDEX - 5 - ] XY.AUTO.PLOT NORMAL.COORDS
0.5 0.05 POSITION " True strain " LABEL
90 LABEL.DIR
90 CHAR.DIR
0.015 0.3 POSITION CURSOR.OFF " True stress, Mpa " LABEL
0 LABEL.DIR
0 CHAR.DIR
WORLD.COORDS
SCREEN.CLEAR CR ." Hit 1 to plot on PLOTTER, 2 to continue "

```

```

#INPUT 1 = IF
PLOTTER1 PLOTTER16 PLOTTER17 RETURN.PEN
THEN
SCREEN.CLEAR CR
." Hit 1 to PLOT again, 2 to STOP "
#INPUT 2 = UNTIL
AXIS.DEFAULTS
;
." PLOT.DATA1 " \ *****
: PLOT.DATA1
SCREEN.CLEAR
." Hit 1 to get Sigma/Epsilon plots "
#INPUT
1 = IF PLOT.DATA12 THEN
." Hit 1 to get LOG Sigma / LOG Epsilon plots "
#INPUT
1 = IF PLOT.DATA11 THEN
;
: CONVERT.TO.ASCII1 \ *****
NORMAL.DISPLAY INVERSE.ON
CR CR CR ." An ASCII file named *****.DAT will be created. "
CR CR CR CR CR ." Hit any No key and <RET> to start data-conversion "
#INPUT INVERSE.OFF DROP
CR CR CR
SIGMA SUB[ 1 , PARAM [ 16 ] 1 - 3 / , 3 ] [ ]SIZE ASCDIM1 :=
SIGMA SUB[ 1 , PARAM [ 16 ] 1 - 3 / , 3 ] STS SUB[ 1 , ASCDIM1 ] :=
EPSILON SUB[ 1 , PARAM [ 16 ] 1 - 3 / , 3 ] STN SUB[ 1 , ASCDIM1 ] :=
SCREEN.CLEAR CR CR CR CR CR CR CR CR
." Enter a name for the ASCII output file (8 chars.DAT) "
CONSOLE.OFF
"INPUT DEFER> OUT>FILE
ASCDIM1 1 + 1 DO
STN [ I ] . ." , " STS [ I ] . CR
LOOP
OUT>FILE.CLOSE
;

```

```

." YNG "
: YNG \ ***** Program starting word *****
1501 1 DO
AXIS.DEFAULTS NORMAL.DISPLAY SCREEN.CLEAR INTEN.ON INVERSE.ON
."          T-M-P Group - Interactive Analysis Program "
INTEN.OFF INVERSE.OFF
CR CR
." Analyse file (Engineering S - e).....HIT 1 "
CR CR
." Produce table.....HIT 2 "
CR CR
." Plot data (Engineering S - e).....HIT 3 "
CR CR
." Plot data (True Sigma -Epsilon).....HIT 4 "
CR CR
." Acquisition (NAR).....HIT 5 "
CR CR
." Convert ASYST data file to ASCII (create *****.DAT)HIT 0 "
CR CR
." QUIT.....HIT S "
CR CR KEY
CASE
  49 OF READ.FILE CALCULATE.STRESS.STRAIN SEE.CURVE1
    SPECIAL.POINTS SAVE.DATA ENDOF
  50 OF TABLE3 GO.ON ENDOF
  51 OF READ.FILE CALCULATE.STRESS.STRAIN PLOT.DATA ENDOF
  52 OF READ.FILE CALCULATE.STRESS.STRAIN A PLOT.DATA1 ENDOF
  53 OF NAR ENDOF
  48 OF READ.FILE CALCULATE.STRESS.STRAIN A CONVERT.TO.ASCII1      ENDOF
  83 OF LEAVE ENDOF
  115 OF LEAVE ENDOF
  NOP
ENDCASE
LOOP
;
```

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TITLE AND SUBTITLE

DEVELOPMENT OF A COMPUTER-CONTROLLED HOT-DEFORMATION APPARATUS AT NIST

AUTHOR(S)

Yi-Wen Cheng, Yair Rosenthal, Harry I. McHenry

PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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SUPPLEMENTARY NOTES

DOCUMENT DESCRIBES A COMPUTER PROGRAM; SF-185, FIPS SOFTWARE SUMMARY, IS ATTACHED.

ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

This report describes a computer-controlled hot-deformation apparatus suitable for thermomechanical-processing (TMP) simulation of forging and steel plates. The apparatus was designed and built at the National Institute of Standards and Technology, and has the following main features: a servohydraulic load frame with a 250 kN capacity in tension or compression; a variable-actuator traveling speed up to 55 mm-s⁻¹; a multiple-strike capability with controllable displacements and strain rates; a maximum heating rate of 50°C-s⁻¹ with a 10 kW induction heater (for a cylindrical steel specimen 9 mm in diameter and 18 mm in height); a maximum cooling rate of 25°C-s⁻¹ with helium-gas cooling; and vacuum to 1.33 x 10⁻³ Pa (1 x 10⁻⁵ Torr) within 25 min. Source codes of the computer programs that perform system control, data acquisition, and data analysis are included in this report. The apparatus has been used to perform the direct-quenching simulation of the ASTM A710 plate steel, and forging simulation of the directly cooled microalloyed ISI 1522 and 1141 steels. Results of these studies are presented.

KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

computer control; continuous-cooling transformation; controlled rolling; direct quenching; forging; high-strength low-alloy steels; hot-deformation apparatus; microalloyed steels; physical simulation; thermomechanical processing.

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