THE EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HSLA-100 STEEL

by

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Tensile testing of hourglass shaped specimens was conducted at quasi-static strain rates. Individual tensile test temperatures ranged from 24 C to -196 C. True
stress, corrected for necking, and true plastic strain were monitored throughout the tests. This allowed a comparison to be made between the plastic strain behavior of HSLA-100 steel and a traditional constitutive equation used to describe the stress-strain behavior of metals.
The Effect of Temperature on the Tensile Properties of HSLA - 100 Steel

by

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ABSTRACT

High Strength Low Alloy (HSLA) steels have been shown to possess high strength and toughness. Additionally, these steels can be welded without the normal preheating required by comparable HY-series steels. HSLA - 100, 100 Ksi yield strength, contains increased amounts of copper, manganese and nickel over the currently certified HSLA - 80. However, prior to use in Naval ship construction knowledge of the steels toughness behavior is necessary. Existing fracture mechanics models are not applicable to HSLA - 100 because HSLA-100 has only 0.04% carbon and these models use carbides as the nucleation sites for cleavage fracture. This research is part of a program to investigate and model the micromechanics of deformation and fracture of HSLA-100.

Tensile testing of hourglass shaped specimens was conducted at quasi-static strain rates. Individual tensile test temperatures ranged from 24 C to -196 C. True stress, corrected for necking, and true plastic strain were monitored throughout the tests. This allowed a comparison to be made between the plastic strain behavior of HSLA - 100 steel and a traditional constitutive equation used to describe the stress-strain behavior of metals.
# TABLE OF CONTENTS

## I. INTRODUCTION

- A. DEVELOPMENT OF COPPER BEARING HSLA STEELS
- B. INFLUENCE OF ALLOYING ELEMENTS ON HSLA STEELS
- C. INFLUENCE OF HEAT TREATMENT ON HSLA STEEL PROPERTIES
  1. Temperature effect on precipitation hardening
  2. Time effect on precipitation hardening

## II. BACKGROUND

- A. STRESS - STRAIN RELATIONSHIPS
- B. INFLUENCE OF TEMPERATURE ON TENSILE PROPERTIES
- C. INFLUENCE OF STRAIN RATE ON TENSILE PROPERTIES
- D. SCOPE AND OBJECTIVES OF PRESENT WORK

## III. EXPERIMENTAL PROCEDURE

- A. MATERIAL
- B. TEST APPARATUS
- C. SAMPLE PREPARATION
- D. COLLECTION, REDUCTION AND DISPLAY OF THE OUTPUT DATA
- E. TEMPERATURE MEASUREMENT AND CONTROL
- F. MICROSCOPY
1. Light Microscopy ........................................... 38
2. Scanning Electron Microscopy ......................... 38
3. Transmission Electron Microscopy .................... 38

IV. RESULTS ............................................................... 41
A. MEASUREMENT OF TRUE STRESS ......................... 41
B. MEASUREMENT OF TRUE STRAIN ....................... 42
C. DETERMINATION OF THE MODULUS OF ELASTICITY .............. 44
D. TENSILE PROPERTIES OF HSLA - 100 STEEL ........... 49
E. CONSTITUTIVE EQUATION TESTING .................... 65
F. Fractography .................................................. 69

V. CONCLUSIONS AND RECOMMENDATIONS ..................... 73
A. CONCLUSIONS .................................................. 73
B. RECOMMENDATIONS ............................................ 73

APPENDIX A: INTERIM SPECIFICATION FOR TRIAL COMMERCIAL PRODUCTION OF HSLA - 100 STEEL PLATES ........ 74

APPENDIX B: CHECKLIST AND EXAMPLE SETTINGS .............. 78

APPENDIX C: BASIC COMPUTER PROGRAM FOR DATA COLLECTION -- 86
APPENDIX D: BASIC COMPUTER PROGRAM FOR DATA REDUCTION --- 93
APPENDIX E: BASIC COMPUTER PROGRAM FOR DATA DISPLAY ----- 98

APPENDIX F: BASIC COMPUTER PROGRAM FOR CONSTITUTIVE EQUATION TESTING .......................... 106

LIST OF REFERENCES .................................................. 111
INITIAL DISTRIBUTION LIST ........................................ 114
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I. INTRODUCTION

A. DEVELOPMENT OF COPPER BEARING HSLA STEELS

The problems associated with welding quenched and tempered high alloy and plain carbon steels are well documented [Refs. 1, 2]. The high cost of manufacturing and producing satisfactory critical welds in these conventional steels combined with the desire for higher strength weldable materials has led to the development of High Strength Low Alloy (HSLA) steels. These steels utilize small microalloying element additions while keeping carbon below 0.15% to develop the desired strength and toughness levels.

The variety of steels classified as high strength low alloy (HSLA) has expanded greatly over the past decade. Originally the classification applied strictly to carbon-manganese steels which were microalloyed with niobium, vanadium or titanium. The category of HSLA steels now includes acicular ferritic or low carbon bainitic steels, higher carbon more pearlitic steels, quenched and tempered steels, dual phase steels, and cold rolled and tempered steels. This paper will deal with acicular ferritic HSLA steels where copper is the primary strengthening microalloying constituent. When referring to HSLA steels herein this is the intent.
The ability of Cu additions to strengthen steels has been known since the 1930's; however, commercial development and production was slow to proceed until the late 1960's [Ref. 3]. The key reason for the slow progress in developing this type of HSLA steel was the deterioration of the hot working properties of Cu bearing steels [Refs. 4, 5]. Once the problem of "hot shortness" was overcome a rapid development of a variety of Cu bearing HSLA steels followed.

During the 1970's several Cu bearing low alloy steels with similar chemical compositions were developed and tested. Various trade names are: NICOP, IN-787, and NICUAGE TYPE I. High yield strength, above 70 KSI, improved weldability, toughness, ductility, and corrosion resistance over conventional steels has been reported for these new HSLA steels. [Refs. 6, 7, 8]

The military has certified a low alloy Copper - Nickel steel for structural uses, which is quite similar to the above mentioned commercial steels, designated HSLA - 80. The chemical composition of HSLA - 80 (MIL-S-24645) is listed in Table I of Appendix A which is taken in it's entirety from Reference 9.

B. INFLUENCE OF ALLOYING ELEMENTS ON HSLA STEELS

A portion of the Fe-Cu phase diagram is shown in Figure 1 [Ref. 10]. Wilson [Ref. 5: pp. 164-165] has verified that a sufficiently hardenable Fe-Cu alloy can be made to transform
from the austenite region to form martensite and supersaturated ferrite. As the solubility of copper in ferrite is less than in austenite some copper may precipitate in the ferrite however, the equilibrium solubility is not reached on cooling. Subsequent aging heat treatment then produces high strength levels by uniform precipitation of a copper rich epsilon phase which appears as rods or spheres. Quenching from elevated austenitizing temperatures causes significantly more copper to remain in solid solution than air cooling. The subsequent precipitation of epsilon copper particles in the ferrite by

Figure 1. Iron Rich End of the Fe-Cu Phase Diagram
Heat treating provides the primary strengthening mechanism of this type of HSLA steel. (Refs. 11, 12)

The microstructure of HSLA - 80 (Class 3 - quenched and aged) varies, depending on cooling rate from the austenitization temperature, from polygonal/acicular ferrite at high cooling rates (thin plates) to a polygonal ferrite matrix with dispersed groups of cementite particles for slower cooling rates (thicker plates) (Ref. 10: pp. 7-12). Steels with acicular ferrite microstructures exhibit much higher strength than those with polygonal ferrite microstructures (Ref. 13). Acicular ferrite, synonymous with bainitic ferrite, differs from polygonal ferrite in that acicular ferrite exhibits lath-like ferrite grains containing a high dislocation density. A key addition to HSLA - 100 is niobium. Its addition to these copper bearing steels is primarily for grain size refinement. This is accomplished in two ways, by the precipitation of niobium carbonitrides during the austenitization (Class 3 plates) process and by retarding austenite recrystallization during hot rolling (Ref. 12: pp. 556-659). Niobium also provides some precipitation hardening effect.

In these steels the potential problem of hot shortness, the formation of low melting point copper rich phases which can cause fissured surfaces during thermal mechanical processing, is prevented by nickel additions to copper bearing steels. However, the primary reason nickel is added
to these steels is its beneficial effect on toughness. As with niobium, a strength increase is also observed with nickel additions. Finally, since nickel remains with copper during remelting, scrap can be used in melts of other steels without the potential harmful effects of copper alone [Ref. 14].

Chromium and molybdenum are necessary to retard the epsilon copper precipitate nucleation and growth, during quenching from the austenitizing temperature, known as auto-aging. This enables closer control of the finished product and thus more consistency in mechanical properties. [Ref. 15]

Manganese, as with chromium and molybdenum helps to suppress polygonal ferrite formation, thus adding transformation substructure strengthening to these steels' overall strengthening components [Ref. 10: pp. 3-4]. Manganese increases the hardenability of HSLA steels as it does conventional steels.

Silicon is added as a deoxidizer and the aluminum present acts to enhance grain refinement. Impurity elements such as phosphorous and sulfur are kept to a minimum by direction in the military specification for HSLA - 80. The concern with phosphorous is embrittlement caused by the formation brittle iron and nickel phosphides [Ref. 1: p. 98]. Sulfur is kept as low as possible because a steel's susceptibility to lamellar tearing is proportional to the
sulfur content [Ref. 16]. This is accomplished by a low sulphur practice such as vacuum degassing and argon injection with CaSi or Mg for sulfide shape control, as specified in Appendix B.

C. INFLUENCE OF HEAT TREATMENT ON HSLA STEEL PROPERTIES

The ASTM heat treatment applicable to the copper bearing HSLA steels discussed herein is Class 3 (quenched and precipitation hardened). For HSLA - 80 the austenitizing temperature range is 870 to 970 °C (1600 to 1700 °F). After water quenching, approximately 450 MPa (65 Ksi) of the total expected 550 MPa (80 Ksi) yield strength is attained. Precipitation hardening at 540 to 665 °C (1000 to 1225 °F) supplies the remaining portion of the desired yield strength. This precipitation strengthening more than offsets any softening occurring at the precipitation heat treatment temperature. [Ref. 12:p. 656]

1. Temperature effect on precipitation hardening

In order to achieve the desired level of strength, toughness and weldability of the precipitation hardenable steels, various aging temperatures/times are used. There are three ASTM classifications for precipitation hardenable steels. Class 1 designated as-rolled plus precipitation hardened, yields the highest strength levels. Class 2 is normalized plus precipitation hardened, this produces a lower strength than Class 1 but improved toughness. Class 3
is quenched plus precipitation hardened, this Class provides the best overall level of toughness with strengths comparable to Class 1. As noted earlier a Class 3 precipitation heat treatment is required to provide the fine grained acicular ferrite microstructure. Jesseman and Murphy [Ref. 12:pp. 656] note that at this stage of production "the relatively soft as-rolled, as-normalized or as-quenched conditions have good ductility and moderate toughness. Cold forming at this stage is sometimes advantageous because lower press capacities are required." Then precipitation heat treating can ameliorate the effects of straining and aging on toughness. It is noteworthy that post weld precipitation hardening can serve as a simultaneous stress relief thus reducing overall fabrication costs [Ref. 3:pp. 445-449]. Since diffusion of copper in ferrite is involved in the strength determination of these steels, both the time and the temperature of the precipitation heat treatment is important. Jesseman and Murphy [Ref. 12:pp. 657-658] concluded that treating above 565 C (1050 F) produced a gradual softening. The rate of this softening was slow, due to the additions of molybdenum and chromium, and thus easily controllable. Additionally, raising the precipitation heat treatment temperature to 595 C (1100 F) or above markedly improved CVN impact energy in Class 2 and Class 3 plates.
2. **Time effect on precipitation hardening**

The mechanical properties of copper bearing HSLA steels are largely determined by the size and amount of the epsilon-copper precipitates. These in turn are governed by the aging treatment. The workers in Reference 17 report that overaging is desirable. Overaging promotes high toughness and it reduces the sensitivity of the steel to additional heating below the austenitizing temperature which could occur during welding or bending/shaping operations. Also, overaging was reported to lead to high toughness. Testing reported in Reference 12 revealed that the effect of time at aging temperature was notably less significant than the effect of temperature itself. Similar results were reported in Reference 17, where Class 3 steels only underwent a small change in properties when the aging time was varied thirty minutes at 899°C (1650°F). Several papers in the Conference Proceedings of International Conference on Technology and Applications of HSLA Steels 3-6 October 1983 Philadelphia, Pennsylvania noted that degraded mechanical properties were restorable by reaustenitization and aging treatment.
II. BACKGROUND

A. STRESS - STRAIN RELATIONSHIPS

Many mathematical formulations have been developed to relate stress and strain in metals. Historically the relations developed attempted to relate stress-strain behavior from the onset of loading to the point of fracture. No single relation has gained universal acceptance due to problems associated with describing elastic and plastic behavior in a single equation. As a result, although many expressions have been developed since Hooke's law was introduced in 1678, many are of limited utility (Ref. 18).

When a material has experienced plastic deformation the linear relationship between stress and strain, described by Hooke's law, is no longer applicable. Figure 2 depicts a general stress-strain diagram for a material without a pronounced yield point (Ref. 19). The figure depicts the elastic region and two regions of plastic deformation. In the elastic range stress is directly related to strain through a constant of proportionality. Hooke's law can be expressed as:

\[ S = E \varepsilon \]

Where \( S \) is the applied stress and \( \varepsilon \) the engineering strain is the change in specimen length divided by the original length. The constant of proportionality, \( E \), is a measure of
the material's stiffness and is referred to as Young's modulus or the modulus of elasticity. Once the yield stress, generally taken to be the stress necessary to produce 0.2% plastic strain, is exceeded the load necessary to produce further plastic deformation increases. The material is then undergoing strain hardening, by plastic deformation. In this region between the yield stress and the onset of specimen necking stress has been related to strain by expressions such as the Holloman equation [Ref. 20], as shown in Figure
2. The range of nonuniform plastic deformation begins when a localized neck develops in the weakest portion of the specimen. This neck causes a decrease in the specimen cross-sectional area; thus resulting in a decrease in load. The load reaches a maximum at the onset of necking, because the decrease in cross-sectional area offsets the strengthening produced by strain hardening. In this region of the curve the relation between stress and strain becomes more complicated to express mathematically. The development of the neck causes a triaxial stress state to exist instead of uniaxial tension that existed up to the point of necking. In describing the relation between stress and strain in this region the stress resulting from the triaxial stress state must be accounted for. (Ref. 19: pp. 4-21)

In recent years, attention has focused on the development of analytical expressions for stress and strain in the region between the yield stress and the point where necking commences (Ref. 21). A simple and commonly used expression relating stress and strain for a polycrystalline metal is the Holloman power function (Ref. 20: p. 374).

\[ \sigma = K \varepsilon^n \]

Where \( \sigma \) is the true stress and \( \varepsilon \) the true strain. \( K \) is a constant, representing the true stress at a true strain of unity, called the strength coefficient. When logarithms of
this power function are taken and true stress plotted versus true strain a straight line fit is predicted. The slope of the line has a value of $n$, the strain hardening exponent. Conway [Ref. 21: p. 156] notes that, although the equation calls for the use of true strain, "more consistency seems to be observed when true plastic strain is used". In this research the Holloman equation has been tested using the true plastic strain data obtained in testing HSLA-100.

B. INFLUENCE OF TEMPERATURE ON TENSILE PROPERTIES

The strain hardening exponent, $n$, is a function of the materials strength level, chemical composition, and microstructure [Ref. 21: p. 157]. A high yield strength is achieved when dislocation motion is impeded initially. Dislocation motion is impeded by obstacles to their movement such as precipitates, impurities and other dislocations. Precipitates and impurities distort an otherwise perfect lattice and set up stress fields on the atomic level. When these stress fields interact with the stress field surrounding a dislocation its motion is impeded. Solid solution and precipitation strengthening are examples of mechanisms which take advantage of these stress field interactions to pin dislocations and thus strengthen a material. In addition to the above mentioned obstacles to dislocation motion, there is an inherent resistance within a crystal lattice to dislocation motion. This resistance is
termed the Peierls force and it is strongly related to the directionality of bonding of the material. A moving dislocation causes bond angle distortions. Covalent and ionic materials are strongly directional in their bonding. The bond angle distortion necessary for dislocation motion in these materials is thus difficult to overcome. In these materials the Peierls force is the primary obstacle to dislocation motion even when lattice vibration energy is enhanced at high temperatures. Body centered cubic materials develop a directional bonding component at low temperatures. The movement of dislocations in body centered cubic materials is thus strongly inhibited at low temperatures by the Peierls force. This effect is nullified at high temperatures where thermally enhanced atomic vibration overcomes the effect of the Peierls force. It is therefore expected that yield strength of HSLA - 100, a body centered cubic material, will exhibit rapidly increasing yield strength with decreasing temperature. An increase in yield strength in this manner will influence the strain hardening exponent. Figure 3 [Ref. 19: p. 33] illustrates this effect for molybdenum a body centered cubic material. [Ref. 22]

C. INFLUENCE OF STRAIN RATE ON TENSILE PROPERTIES

Strain rate can markedly affect the relationship between stress and strain in a similar way to temperature. In general the strain hardening exponent increases with
increasing strain rate [Ref. 21: p. 157]. With conventional tensile testing machines, where a constant loading rate is imposed on specimen, the effect of necking is to increase the strain rate locally. The reduced cross-sectional area in the neck increases the strain and, as the loading is at a constant displacement rate, the strain rate increases. The rate of change of the strain rate continues to increase as the cross-sectional area decreases throughout the test. Tegart states that "the problems associated with necking are
accentuated at high testing speeds because adiabatic heating becomes localized in the necked region" [Ref. 19: pp. 37-38].

The experimental approach used in this research allows a tensile test to be conducted at constant strain rate. The rate of specimen diameter change, a direct measure of strain rate, is the controlling variable. Hourglass shaped specimens are used to ensure necking occurs at the minimum diameter. A diametral extensometer, fitted to the minimum diameter, continually follows the minimum specimen cross-section, providing feedback to the controlling system in order to maintain the constant rate of change of specimen diameter.

D. SCOPE AND OBJECTIVES OF PRESENT WORK

The nominal composition for HSLA - 100 steel is listed in Appendix A. Increased amounts of copper, nickel and manganese over that in the currently certified Navy steel HSLA - 80 provide the desired increase in yield strength, but before using this material in Naval ship construction, the resistance to brittle fracture must be evaluated and understood. Existing models for cleavage fracture of steels use the ever present iron carbides as crack initiation sites. However, the low carbon content (0.04%) of HSLA - 100 necessitates research to develop an applicable model. [Ref. 23]
Three regions of fracture behavior, ductile, transition and brittle, occur in steels [Ref. 23]. The terms ductile and brittle describe the amount of plastic deformation occurring at the tip of a crack propagating in a steel. Ductile behavior, resulting from the nucleation, growth and coalescence of microvoids, is characterized by significant levels of plastic deformation ahead of the crack tip. In a brittle fracture very little plastic deformation at the crack tip is evidenced. In the tensile testing of steels, ductile behavior is observed above a certain critical temperature, and cleavage, primarily a brittle process, is observed below the critical temperature. The critical temperature is termed the Ductile to Brittle Transition Temperature (DBTT). [Ref. 25]

The transition from ductile to brittle fracture behavior occurs over a range of temperature in which the fracture is neither completely ductile nor completely brittle. As a ductile failure is normally preceded by pronounced yielding it is desirable to have a low transition temperature. This precludes failure in a brittle manner, where cracks can propagate catastrophically. As strength levels in a metal are raised, by various means, there is a corresponding loss in the materials ductility. The loss of ductility leads to the fracture mode transition from ductile to brittle. Thus as strength increases, the DBTT for a given metal usually increases.
The DBTT for a particular steel is dependent on factors such as the chemical composition, microstructure, and crystal structure of the steel, as well as the temperature, state of stress, and strain rate at which it is tested. The chemical composition, effects of microalloying additions, and microstructure of HSLA - 100 are discussed with an emphasis on strengthening in the introduction to this work.

With respect to DBTT, the effects of individual alloying elements is difficult to evaluate. However, in general nickel is observed to improve toughness and lower DBTT in steels containing less than 0.40% carbon. Interstitial atoms such as carbon and nitrogen can pin dislocations thereby increasing yield strength. Increasing the amount of these atoms present produces a loss of ductility and an increase in DBTT. The effect of the Peierls force on the yield strength of body centered cubic materials as temperature is decreased is discussed above. The increased yield strength of body centered cubic metals at low temperatures causes ductile to brittle transition. When the stress necessary to cause dislocation motion exceeds that for cleavage, brittle fracture results. Similarly, increasing the strain rate promotes brittle fracture because materials which exhibit a strongly increasing yield strength with decreasing temperature also exhibit an increasing yield strength with increasing strain rate (Ref. 22:pp. 211-214).

In order to remove the effect of increasing strain rate on
DBTT, the tensile tests in this research were conducted at constant strain rates as discussed previously. [Ref. 26]

The first phase in the fracture model development is to examine the quasi-static fracture behavior of HSLA - 100 steel. The objective of the present work is to develop the true stress - true strain tensile curves as a function of temperature. This information will be later used in a finite element analysis of the crack tip fracture behavior of this material.
III. EXPERIMENTAL PROCEDURE

A. MATERIAL

Appendix A lists the interim material specifications for trial commercial production of HSLA - 100 steel plates. A 32mm (1-1/4 inch) thick plate of HSLA - 100 steel (Plate # 5644-16B) meeting these specifications was prepared by the supplier. The plate was provided to the Naval Postgraduate School for examination by David Taylor Naval Ship Research and Development Center. The plate was heat treated by the supplier by austenitizing at 949 C (1650 F) for 70 minutes and water quenched; and subsequently aged at 615 C (1050 F) for 70 minutes and water quenched. This resulted in the strength properties reported in Table I, according to the supplier.

### TABLE I

STRENGTH PROPERTIES OF PLATE # 5644-16B (AS REPORTED BY THE SUPPLIER)

<table>
<thead>
<tr>
<th></th>
<th>Yield Strength (Ksi)</th>
<th>Ultimate Tensile Strength (Ksi)</th>
<th>% Elongation</th>
<th>% Reduction in area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>Transverse</td>
<td>101</td>
<td>147</td>
<td>22</td>
</tr>
<tr>
<td>Bottom</td>
<td>Transverse</td>
<td>106</td>
<td>139</td>
<td>23</td>
</tr>
</tbody>
</table>
B. TEST APPARATUS

In this research tensile tests were conducted with a Material Test System (MTS) 810 apparatus. On this system the loading is provided via a hydraulic actuator and grip assembly to a threaded specimen receptacle. A diametral extensometer was used to measure diametral displacement which was used as the test controlling variable. Load cell and extensometer output voltages were monitored by a digital voltmeter. The output voltages are converted to load and diametral displacement by a computer program. The computer program for collection of output data is listed in Appendix C. The frequency of sampling the output voltages by the digital voltmeter is determined by the collection program. If the user selects no additional delay between samplings the voltmeter is triggered by the computer to sample the output voltages from the MTS 810 at approximately 4 samplings per second. Thus when monitoring load, diametral displacement and hydraulic actuator piston stroke, all three channels from the MTS 810 can be sampled at least once a second. The program allows the flexibility to input an additional delay between samplings. In the testing conducted for this research no additional delay was requested for the first 50 samplings on all tests. In the intervals between 51 to 200, 201 to 400, and 410 to 500 nominal sampling delays were zero, 1 and 5 seconds respectively. The equipment used to conduct the tensile tests, collect, reduce and display
the output data are as follows:

1. **MTS Closed-loop Electrohydraulic Testing System**
   - a) MTS Model 312.41 Load Frame
   - b) MTS Model 681.21A -O3 Load Cell (25 Kip)
   - c) MTS Model 410.31 Function Generator
   - d) MTS Model 506.20 Hydraulic Power Supply

2. **MTS Model 651.1XA Environmental Chamber (Modified)**
   - a) MTS Model 409 Temperature Controller
   - b) MTS Diametral Extensometer Model 632.19B-21 (Modified)
   - c) MTS Extensometer Model 613.20B

3. **Hewlitt-Packard Data Acquisition System**
   - a) 9826 Computer
   - b) 3497A Data Acquisition Control Unit (DVM)
   - c) 3437A System Voltmeter
   - d) 2617G Printer
   - e) 7225B Plotter

Figures 4a and 4b, are photographs of the testing system and Figure 5 is a photograph of the acquisition and reduction system used in this research. Figure 6 illustrates the environmental chamber as modified. The environmental chamber was modified to allow either liquid carbon-dioxide or liquid nitrogen to be used as the cooling medium. An operators checklist and a detailed operational sequence to conduct constant strain rate tensile test are listed in Appendix B.

C. SAMPLE PREPARATION

The plate, once received at the Naval Postgraduate School was cut and machined into tensile test specimens. Two uniform gage-length specimens were made in accordance with
Figure 4. Experimental Test Equipment (a). Environmental Chamber Mounted on Load Frame, with an hourglass Specimen Installed in Hydraulic Actuator Grips (b). MTS 810 Electronic Equipment Console
Figure 7. Twelve hourglass shaped specimens were made in accordance with Figure 8. The samples were cut from the plate parallel to the rolling (longitudinal) direction in all cases to ensure the consistency of the results. The hourglass specimen design was selected to ensure that fracture occurred at the minimum specimen diameter where the strain is measured continuously from test start to fracture by using a diametral extensometer. The data thus obtained could then be used to determine the appropriate constitutive equation for this material as a function of temperature.
1 - 25 KIP Load Cell
2 - Load Cell Extension
3 - Actuator Extension
4 - Thermal Hydraulic Grip
5 - Diametral Extensometer
6 - Extensometer Mount
7 - Extensometer Electrical Hook-up
8 - Thermal Couple Junction Box
9 - Seal
10 - Spiral Washers
11 - Actuator
12 - Hourglass Specimen

Figure 6. Environmental Chamber, as Modified
NOTES: 1. All dimensions in inches.
2. Tolerances as per ASTM tensile specimen standards.
3. Specimen gage length to be parallel to plate as rolled direction.
4. Gage length shall be 32 cms.
5. Mark with applicable specimen number on both ends.

![Diagram of uniform gage-length tensile specimen dimensions]

Figure 7. Uniform Gage-length Tensile Specimen Dimensions
NOTES:
1. All dimensions in inches.
2. Tolerances: As per ASTM tensile specimen standards.
3. Specimen gage length to be parallel to plate as rolled direction.
4. Reduced section area of specimen shall be polished in a manner parallel to specimen longitudinal axis to 32 rms.
5. Mark with applicable specimen number on both ends, vibrating type engraving tool is permissible.

Figure 8. Hourglass Tensile Specimen Dimensions
D. COLLECTION, REDUCTION AND DISPLAY OF THE OUTPUT DATA

During a test, data is collected by the acquisition system using the program "JHCOLLECT". Appendix C lists this program. Upon completion of a tensile test the program allows the renaming of data files. The data files are generic in nature and are renamed after each test run with an appropriate specimen number, i.e. lodi, Dial etc. Appendix D lists the data reduction program "JHREDUCE". Running this program computes true strain/strain, log true stress/log true strain, corrected true stress/strain, plastic strain, log corrected true stress/true plastic strain and stores these values in arrays. The array names match the specimen numbers i.e. Stressi, Straini. Appendix E lists the plotting program "JHPlot". Running this program allows graphs of the array values stored by "JHCOLLECT" and "JHREDUCE". Appendix F lists the program "POWERFIT". Running this program plots the log corrected true stress vs the log plastic true strain from the stored array values. Additionally, the strength coefficient, K, and strain hardening exponent, n, for the Hollomon power function are determined (Ref. 20:pp. 374-375). Using the computed values of slope n and intercept log K a line is plotted between true plastic strain values of .001 and 1.0. A correlation coefficient, R, for the power function is determined by the powerfit program using a least squares approximation. The correlation coefficient compares the fit between the log
corrected true stress versus log true plastic strain plot and the line generated using the power law coefficients determined.

E. TEMPERATURE MEASUREMENT AND CONTROL

Temperature measurement in this research was accomplished using chromel/alumel thermocouples. Chromel/alumel thermocouples are useful over the temperature range -200 to 1300 C. Their uncalibrated accuracy is + 3 C in the range 0 to 400 C [Ref. 27]. Many thermocouples normally used for high temperature monitoring show a decreasing temperature sensitivity with decreasing temperature. For chromel/alumel thermocouples below approximately -130 C the temperature/voltage relation displays this decreasing sensitivity [Ref. 28]. The use of a known fixed temperature reference junction, near the measured temperature, is used to improve accuracy. Several thermocouples were tested in an ice water bath, zero degrees centigrade, and all indicated 0 C, this verified the calibration of the Newport temperature monitoring device. Additionally, the thermocouples were calibrated at -196 C using liquid nitrogen.

Two chromel/alumel thermocouples per test sample were used in the sub zero tensile tests conducted in this research. The samples were spot welded to the hourglass specimen, Figure 8, approximately 0.35 inches on each side of the specimen minimum diameter.
Low temperature tests were initially carried out using the MTS model 409 temperature controller. The controller activated a solenoid to either admit or stop the flow of liquid nitrogen to the environmental chamber. The controller uses a thermocouple to compare sensed temperature with a manually adjustable setpoint. The coolant flow entered through the back of the chamber, by plastic tubing, and was then directed either on the specimen or the actuator grips. This arrangement was satisfactory for tests in which the lowest temperature achievable was desired. Once the specimen thermocouples were stable, at essentially liquid nitrogen temperature, the tensile tests were conducted while maintaining the flow of coolant to the chamber. This method of cooling the samples was not used for test temperatures between room temperature and liquid nitrogen temperature. In this range the on/off action of the solenoid/controller caused the temperature to vary as the coolant flow pulsed on and off. Additionally, the pulsing of coolant flow on the diametral extensometer produced an error signal from the extensometer which prevented starting the hydraulic system. This is a result of the difference in temperature of the extensometer and that of the liquid nitrogen. To conduct the tensile tests at temperatures below room temperature and above liquid nitrogen temperature the coolant flow system was modified. Figure 9 is a photograph of the inside of the environmental chamber with the modified coolant system in
Figure 9. Environmental Chamber Interior, Showing Modified Coolant System
place. Liquid nitrogen is directed by tubing to machined paths in the actuator grips. Thus, without coolant flow directly on the specimen, the sample is cooled by conduction from the grips to the desired test temperature. Once the temperature has stabilized, the flow of liquid nitrogen to the grips can be stopped and the grips provide a heat sink to maintain the sample at the desired test temperature. The thermocouples were monitored throughout each tensile test; and the average is reported as the test temperature.

F. MICROSCOPY

1. **Optical Microscopy**

   A polished and etched (2% nital) HSLA - 100 sample was photographed using a light microscope. Figure 10 (a) and Figure 10 (b) are representative of the microstructures observed. The microstructure is predominantly bainitic and was uniform throughout the thickness of the plate, except for regions of increased grain size near the plate edges.

2. **Scanning Electron Microscopy**

   The scanning electron microscope (SEM) was used to examine the HSLA - 100 tensile specimen fracture surfaces after testing. A discussion of the typical fracture surface and micrographs is presented in the results section.

3. **Transmission Electron Microscopy**

   Figure 11 is a representative thin foil micrograph of the HSLA - 100 steel used in this research. The
Figure 10. Light Micrographs of HSLA - 100 Steel (a). Microstructure at 500X (b). Microstructure at 1000X
Figure 11. Thin Foil Transmission Electron Micrograph of HSLA - 100 Microstructure

Microstructure is characterized by elongated parallel laths, less than 1 micron in width, containing a very high dislocation density. In addition, a uniform distribution of very fine niobium carbonitrides was also observed.
IV. RESULTS AND DISCUSSION

A. MEASUREMENT OF TRUE STRESS

Once a tensile test specimen begins to neck a triaxial stress state exists at the minimum cross-section, Figure 2. In order to obtain the true stress in the specimen a correction for this must be applied to the measured stress. Tegart discusses various expressions for the stress state in the neck but comments that the Bridgman correction most accurately estimates the degree of stress concentration [Ref. 19: pp. 21]. The Bridgman correction can be expressed as [Ref. 29]:

\[ \sigma = \frac{\sigma_{av}}{(1 + 2R/r_n) \ln(1 + r_n/2R)} \]

where the measured average stress \( \sigma_{av} \) is reduced to a corrected value \( \sigma \). \( R \) is the radius of curvature of the neck and \( r_n \) is the radius of the cross-section at the neck.

The initial radius of curvature of the hourglass section of the specimen used in this study is 1.1 in.; this results in an initial correction of 0.972 \( \sigma_{av} \). The objective of this research was to measure true stress and true strain from the onset of loading to the point of fracture. Thus this initial correction has been applied to the true stress up to the onset of necking. Once a test was completed the final radius of curvature was measured by first fitting the specimen.
back together and magnifying the necked region with an overhead projector. Then comparing the fit of various circular templates to the projected image produced the final radius of curvature (when divided by the magnification factor). This value along with the measured final cross-section radius allowed determination of a final correction factor for each test specimen. In order to gradually change the magnitude of the Bridgman correction from the onset of necking to fracture, a linear relation was developed between the value at the onset of necking and the fracture point for each specimen. This relation was then applied to the measured true stress values after the maximum load was reached. The justification for using a linearly changing correction factor derived from the fact that the tests were conducted with a constant diametral displacement rate. The computation of the linear relation for the correction factor and its application to individual points is accomplished by the data reduction program, Appendix D.

B. MEASUREMENT OF TRUE STRAIN

The true strain was determined using an MTS model 632.19B-21 diametral extensometer. Figure 12 shows a typical series 632.19B adjustable diametral extensometer and lists the operating characteristics based on specific model number. The extensometer contacts, shown more clearly in Figures 13 and 14, were not capable of following the
**Figure 12. Model 632.19B Diametral Extensometer and a Table of Specific Model Operating Characteristics**

diametral displacement once necking produced a radius of curvature below .5 inches. The contacts were modified to allow the measurement of strain up to the minimum radius of the neck which preceded fracture. Figure 15 is a photograph of the extensometer contacts after modification. The limited range of accurate unmodified extensometer travel is

---

**Table: Model 632.19B Diametral Extensometer Operating Characteristics**

<table>
<thead>
<tr>
<th>Model</th>
<th>632.198.20</th>
<th>632.198.21</th>
<th>632.198.23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gage Diameter Adjustment</td>
<td>3.6 mm to 13 mm</td>
<td>3.6 mm to 13 mm</td>
<td>3.6 mm to 13 mm</td>
</tr>
<tr>
<td>Minimum Range (Diametral)</td>
<td>0.000 in. to 0.000 in.</td>
<td>0.000 in. to 0.000 in.</td>
<td>0.000 in. to 0.000 in.</td>
</tr>
<tr>
<td>Linearity**</td>
<td>0.01% of range</td>
<td>0.01% of range</td>
<td>0.01% of range</td>
</tr>
<tr>
<td>Maximum Hysteresis</td>
<td>0.01% of range</td>
<td>0.01% of range</td>
<td>0.01% of range</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-110°F to +250°F</td>
<td>-110°F to +250°F</td>
<td>-110°F to +250°F</td>
</tr>
<tr>
<td>Maximum Deflection</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Maximum Operating Frequency</td>
<td>100 Hz</td>
<td>100 Hz</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Effective Deformation Range</td>
<td>45 grams</td>
<td>45 grams</td>
<td>45 grams</td>
</tr>
<tr>
<td>Apparent Clamping Force on Specimen</td>
<td>150 grams max</td>
<td>150 grams max</td>
<td>150 grams max</td>
</tr>
<tr>
<td>Recommended Clamping Range (Outer/Inner)</td>
<td>0.030 in./0.010 in.</td>
<td>0.030 in./0.010 in.</td>
<td>0.030 in./0.010 in.</td>
</tr>
</tbody>
</table>

*All models include case, instruction manual, and mating connector (American 181-14).

**When calibrating over a range from tension to compression, linearity is somewhat degraded. However, this is electronically compensated to the stated value by the recommended MTS Transducer Conditioners.

###Immerzable in most fluids used for specimen heating and cooling, including alcohol, acetone and silicone oils.

###Recommended Transducer Conditioners: 440.11, 445.41, 446.21, 446.22. Other conditioners may be used; maximum excitation is 12 V output is approximately 3 mV/µV.

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Figure 13. Typical Series 632 Adjustable Diametral Extensometer - Attachment to Specimen

reflected in Figure 16, the load vs. diametral displacement curve for hourglass specimen number 4. Figure 17, the load displacement curve for hourglass specimen number 5, illustrates the improved range of measuring diametral displacement once the extensometer was modified.
C. DETERMINATION OF THE MODULUS OF ELASTICITY

The value of the modulus of elasticity or Young's modulus for the HSLA - 100 steel tested in this research was determined experimentally. The test of hourglass specimen number 4, Figure 16, indicated yielding occurred for loads above approximately 5.5 Kips. A uniform gage-length specimen equipped with an axial extensometer was loaded to 4 Kips in load control at a rate of \(4 \times 10^{-3}\) Kip/sec. The specimen was loaded to 4 Kips then returned to zero load at the same rate. This was done twice and the value of Young's modulus determined by the slope of the stress-strain curve generated by an X-Y recorder. The average value of Young's modulus for the two tests is \(2.414 \times 10^6\) psi. This value was
SCALE IN INCHES

unmodified contact arms

modified contact arms

Figure 15. Model 632.19B-21 Diametral Extensometer Contacts (Unmodified and Modified)
HSLA-100 HOURGLASS
SPECIMEN NO. 4

Figure 16. Load - Diametral Displacement Curve for Hourglass Specimen No. 4, Tested at Room Temperature.
then used along with the corrected true stress in the determination of the true plastic strain, as follows:

\[ \varepsilon_p = \varepsilon_t - \frac{\sigma}{E} \]

where \( \varepsilon_p \) is the true plastic strain, \( \varepsilon_t \) the total true strain, \( \sigma \) the corrected true stress and \( E \) is Young's modulus.

D. TENSILE PROPERTIES OF HSLA - 100 STEEL

Table II summarizes the mechanical properties for HSLA - 100 resulting from this research. The test temperature for hourglass specimen no. 6 was taken as the average of the test start and test complete temperatures. There was a 36 C change in temperature from test start to specimen failure as the coolant supply exhausted prior to starting the test and prior to the actuator grips/extensions equilibrating at the desired test temperature. In all other tests the test temperature, taken as the start/finish average, varied less than \( \pm 10 \) C from the start to finish.

In comparing the results reported by the plate manufacturer listed in Table II with those obtained in this study Table I, an obvious difference exists. The uniform gage-length samples from this study exhibited comparable values for percent reduction in area (\( \% \) R/A) and ultimate tensile strengths (UTS) to those reported by the supplier. However, the .2\% offset yield strength values are much
higher and the % elongation is much lower than reported by the supplier. The unexpectedly high yield strength results, of the room temperature tensile tests were reported to the project liaison at David Taylor Research and Development Center, Mr. M. Vassilaros. Subsequent conversation with Mr. Vassilaros revealed that the plate received at the Naval Postgraduate School had not been heat treated properly and

### TABLE II

**STRENGTH PROPERTIES OF HSLA - 100 PLATE # 5544-16B (AS DETERMINED IN THIS RESEARCH) - HOURGLASS SPECIMEN**

<table>
<thead>
<tr>
<th>No.</th>
<th>Average Test Temperature (deg C)</th>
<th>Yield Strength (ksi)</th>
<th>Ultimate Tensile Strength (ksi)</th>
<th>Elongation in 1 inch (%)</th>
<th>Reduction in Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
<td>a</td>
<td>a</td>
<td>N/A</td>
<td>63.0</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>127.0</td>
<td>156.9</td>
<td>N/A</td>
<td>b</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>a</td>
<td>a</td>
<td>N/A</td>
<td>62.7</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>126.0</td>
<td>156.7</td>
<td>N/A</td>
<td>59.6</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>130.6</td>
<td>156.1</td>
<td>N/A</td>
<td>63.7</td>
</tr>
<tr>
<td>6</td>
<td>-109</td>
<td>159.0</td>
<td>177.2</td>
<td>N/A</td>
<td>#48.8</td>
</tr>
<tr>
<td>7</td>
<td>-175</td>
<td>164.2</td>
<td>201.2</td>
<td>N/A</td>
<td>27.0</td>
</tr>
<tr>
<td>8</td>
<td>-198</td>
<td>a</td>
<td>a</td>
<td>N/A</td>
<td>27.0</td>
</tr>
<tr>
<td>9</td>
<td>-72</td>
<td>146.8</td>
<td>164.1</td>
<td>N/A</td>
<td>62.3</td>
</tr>
<tr>
<td>10</td>
<td>-27</td>
<td>137.2</td>
<td>159.3</td>
<td>N/A</td>
<td>64.7</td>
</tr>
<tr>
<td>11</td>
<td>-150</td>
<td>167.7</td>
<td>184.2</td>
<td>N/A</td>
<td>#54.5</td>
</tr>
<tr>
<td>12</td>
<td>-129</td>
<td>155.7</td>
<td>177.0</td>
<td>N/A</td>
<td>#55.9</td>
</tr>
</tbody>
</table>

**UNIFORM GAGE-LENGTH SPECIMEN**

<table>
<thead>
<tr>
<th>No.</th>
<th>Average Test Temperature (deg C)</th>
<th>Yield Strength (ksi)</th>
<th>Ultimate Tensile Strength (ksi)</th>
<th>Elongation in 1 inch (%)</th>
<th>Reduction in Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23</td>
<td>132.7</td>
<td>142.6</td>
<td>12.3</td>
<td>68.6</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>130.4</td>
<td>142.6</td>
<td>16.4</td>
<td>68.6</td>
</tr>
</tbody>
</table>

a - no data collected.

b - specimen not tested to the point of fracture.

* - specimen did not fail at the minimum diameter. The % R/A in the table is based on the specimen minimum diameter and is therefore a conservative (low) value.
that yield strengths above those in the interim HSLA - 100 specification should be expected.

In addition to the load versus diametral displacement curves, as shown in Figures 16 and 17, the reduction and plotting programs, Appendices D and E respectively, allow other useful curves to be generated. The next several figures will provide a sample of the various plots and serve to compare the results at room temperature to a test at -176 C.

The true stress - true strain curves at room temperature and -176 C are shown in Figures 18 and 19 respectively. Note the marked increase in true stress and corresponding decrease in ductility in the -176 C temperature test. As expected, the strength is higher and ductility lower at -176 C than at room temperature. Figure 20, applies the linearly varying Bridgman corrected true stress to the results shown in Figure 18. The maximum correction to the true stress for the triaxial stresses in the necked region of this sample is 0.955. The maximum travel (0.072) of the diametral extensometer was too small to follow the deformation process to the fracture point, the fracture point is plotted as an asterisk. The decrease in ductility at low temperatures, Figure 21, allowed the extensometer to follow the deformation process to the fracture point. The log true stress-log true strain curves for room temperature and -176 C are shown in Figures 22 and 23. When the true stress is
Figure 18. True Stress - True Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature
Figure 20. True Stress (Corrected for Necking) - True Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature, * Indicates Fracture Point
Figure 21. True Stress (Corrected for Necking) - True Strain Curve for Hourglass Specimen No. 7, Tested at -176 C, * Indicates Fracture Point
Figure 23. Log True Stress - Log True Strain Curve for Hourglass Specimen No. 7, Tested at -176 C, * Indicates Fracture Point
corrected for initial specimen geometry and the triaxiality associated with necking the resulting curves, Figures 24 and 25, reflect a lowering of the log true stress values. The reduction in corrected log true stress values over the uncorrected values increases with increasing strain due to the decreasing radius of curvature in the necked area. The log true strain values in Figures 22 through 25 are total true strain. By subtracting the elastic strain from the total true strain an approximately linear true stress - true plastic strain results when plotted logarithmically, Figures 26 and 27; the Holloman power function appears to closely describe the stress - strain behavior of this material.

Figure 28 presents the yield strength of HSLA - 100 as a function of temperature. The rapidly increasing strength with decreasing temperature is a result of the increasing Peierls force with decreasing temperature for this body centered cubic steel. The percent reduction in area undergoes a rapid decrease at temperatures below -150 C, Figure 29. The three results between -100 C and -150 C represent the minimum percent reduction in areas, since the specimens actually failed outside the minimum diameter. These results indicate that HSLA - 100 steel experiences little loss in ductility at temperatures above -150 C. The fact that specimens 6, 11, and 12 failed outside the minimum diameter is most remarkable. In all three cases significant necking, based on % R/A, preceded specimen failure. The
Figure 24. Log True Stress (Corrected for Necking) - Log True Strain Curve for Hourglass Specimen No. 5, Tested at Room Temperature. * Indicates Fracture Point
HSLA-100 HOURGLASS SPECIMEN NO. 7

Test Temperature -176 deg C

Figure 25. Log True Stress (Corrected for necking) - Log True Strain Curve for Hourglass Specimen No. 7, Tested at -176 C, * Indicates Fracture Point
HSLA-100 HOURGLASS SPECIMEN NO. 5

Figure 26. Log True Stress (Corrected for Necking) - Log True Plastic Strain Curve for Hourglass Specimen No. 5. Tested at Room Temperature, * indicates fracture point.
Figure 27. Log True Stress (Corrected for Necking) - Log True Plastic Strain Curve for Hourglass Specimen No. 7, Tested at -176 C, * Indicates Fracture Point
HSLA-100 STEEL
YIELD STRENGTH VS. TEMPERATURE

Figure 26. Yield Strength vs. Temperature for the Hourglass Specimens
HSLA - 100 STEEL
% R/A VS. TEMPERATURE

Three specimens did not fail at the minimum diameter.

Error bars indicate variance of test temperature from start to finish.

Figure 29. % R/A vs. Temperature for the Hourglass Specimens
diametral extensometer remained in the necked region, following the deformation process throughout these three tensile tests. The fracture surfaces of specimens 6, 11 and 12, revealed a mixture of ductile and cleavage behavior. All three experienced axial cracking (parallel to the specimen axis). A discussion on the cracks, known as delaminations or separations, is contained in the section titled microscopy observations.

E. CONSTITUTIVE EQUATION TESTING

In this research the Holloman power function, described earlier, was tested for applicability as a constitutive equation to describe the stress-strain behavior of HSLA-100 steel. Table III is a tabulation of power law fit constants determined for each test specimen. The constants were determined using a least squares approximation (as discussed in the experimental section [Ref. 30]) to the log true corrected stress-log true plastic strain behavior of the material.

A value of R equal to one is a perfect fit of the straight line; a correlation above .98 is considered a good fit. The calculations necessary to produce the results listed in Table III are preformed by the program in Appendix F. The wide variation in the strength coefficient, and strain hardening exponent and the low values of the
correlation coefficient indicate that the Holloman power law is not very applicable to HSLA - 100 Steel.

TABLE III

CONSTANTS FOR POWER LAW FIT (HOURGLASS SPECIMEN)

<table>
<thead>
<tr>
<th>No.</th>
<th>Temperature (deg C)</th>
<th>Strain Rate x10/sec</th>
<th>Strain Hardening Exponent -4</th>
<th>Strength (ksi)</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>20</td>
<td>9.30</td>
<td>0.0464</td>
<td>183.0</td>
<td>.981</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>9.26</td>
<td>0.0779</td>
<td>204.2</td>
<td>.972</td>
</tr>
<tr>
<td>6</td>
<td>-109</td>
<td>9.30</td>
<td>0.0721</td>
<td>225.7</td>
<td>.962</td>
</tr>
<tr>
<td>7</td>
<td>-176</td>
<td>9.26</td>
<td>0.0585</td>
<td>255.9</td>
<td>.911</td>
</tr>
<tr>
<td>8</td>
<td>-196</td>
<td>9.35</td>
<td>a</td>
<td>213.3</td>
<td>.980</td>
</tr>
<tr>
<td>9</td>
<td>-72</td>
<td>9.26</td>
<td>0.0660</td>
<td>213.3</td>
<td>.980</td>
</tr>
<tr>
<td>10</td>
<td>-27</td>
<td>9.26</td>
<td>0.0610</td>
<td>204.9</td>
<td>.989</td>
</tr>
<tr>
<td>11</td>
<td>-150</td>
<td>9.35</td>
<td>0.0600</td>
<td>237.0</td>
<td>.971</td>
</tr>
<tr>
<td>12</td>
<td>-129</td>
<td>9.30</td>
<td>0.0783</td>
<td>240.3</td>
<td>.975</td>
</tr>
</tbody>
</table>

UNIFORM GAGE-LENGTH SPECIMEN

<table>
<thead>
<tr>
<th>No.</th>
<th>Temperature (deg C)</th>
<th>Strain Rate x10/sec</th>
<th>Strain Hardening Exponent -4</th>
<th>Strength (ksi)</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>4.34</td>
<td>0.0465</td>
<td>173.6</td>
<td>.989</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>9.28</td>
<td>0.0402</td>
<td>184.7</td>
<td>.969</td>
</tr>
</tbody>
</table>

a - no data collected.

The apparent good fit illustrated in Figures 26 and 27 is lost when the corrected log true stress scale is expanded. An expanded corrected log true stress versus log plastic true strain plot is shown for specimens 9 and 10, whose correlation coefficients were high (above .980), in Figures 30 and 31. The data follows a flattened "S" shape instead of the straight line as predicted by the Holloman power law. This flattened "S" shape was observed in the corrected log true stress - log plastic true strain plots.
Figure 30. Log True Stress (Corrected for Necking) - Log True Plastic Strain Curve for Hourglass Specimen No. 9, Tested at -72°C. * Indicates Fracture Point.
Figure 31. Log True Stress (Corrected for Necking) - Log True Plastic Strain Curve for Hourglass Specimen No. 10, Tested at -27 C, * Indicates Fracture Point
for all the specimens tested. Closer scrutiny of Figures 26 and 27, for specimens 5 and 7, reveals a flattened "S" shaped curve even on the broad corrected log true stress scale.

Conway [Ref. 21:pp. 163-169] discusses an alternative stress - strain relation when the use of the power law is precluded. When the log true stress - log true strain curve results in a flattened "S" shape, see Figures 24 and 25, the power law is not applicable. The alternative stress - strain relation, purported to accurately describe the type of behavior reported herein, is the Voce relation [Ref. 18]. The Voce relation is expressed as follows:

\[ S = S_\infty - (S_0 - S) e^{-e/k} \]

Where \( S \) is the true stress, \( S_\infty \) the final constant stress attained at very large strains, \( S_0 \) is the initial stress corresponding roughly with the 0.1% yield stress, \( S \) is the true strain, \( k \) is a constant and \( e \) represents the natural logarithm function. A development of the Voce relation is presented by Conway [Ref. 21:pp. 160-174]. Although the Voce relation will not discussed further herein, a logical follow on to this work would be to test its applicability.

F. FRACTOGRAPHY

With the exception of the samples tested below -150°C, the fracture surfaces were characterized by delamin
which occurred as cracks running parallel to the rolling direction. The specimens tested between -100 C and -150 C did not fail at the minimum diameter. In these specimens the actual fracture surface occurred between .125 in. and .150 in. from the minimum diameter. Two of these failures occurred above the minimum diameter and one occurred below the minimum diameter.

Figure 32 is a photograph of the specimen tested at -109 C and is typical of the specimens which did not fail at the minimum diameter. In Figure 32 the delamination, running parallel to the specimen longitudinal axis is quite evident. The fracture surface of this specimen is characterized by a mixed ductile-brittle fracture mode, Figure 33. Near the delamination very fine microvoids, characteristic of ductile failure, are evident. While further from the delamination cleavage facets prevailed. These failure modes, ductile and brittle can be seen more clearly in Figures 34 (a) and 34 (b), respectively. The origin of the delaminations, which are planes of weakness parallel to the deformation direction, is still controversial. One possible explanation is that an aligned microstructure, due to the deformation, coupled with inclusions and/or grain boundary carbides provide the weak interfaces which allow the delamination to occur [Ref. 31]. However, other authors have reported that this is not the sole mechanism contributing to this behavior; but that crystallographic texture is also important [Refs. 32, 33].

70
Figure 32. Hourglass Specimen No. 6

Figure 33. Fracture Surface of Hourglass Specimen No. 6
Figure 34. Fracture Surface of Specimen No. 6 (a) Adjacent to the Delamination (b) Adjacent to the area in (a), away from the Delamination
V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The HSLA - 100 steel tested in this research has excellent ductility above -150 C. Rapidly increasing yield strength is observed as temperature decreases.

The Hollomon power function should not be used as the constitutive equation for HSLA - 100 steel as it does not satisfactorily describe the stress - strain response of this steel.

B. RECOMMENDATIONS

The effect of temperature on the tensile properties of properly heat treated HSLA - 100 steel plate should be determined.

The Voce relation should be tested for applicability as a constitutive equation to describe the stress - strain response of HSLA - 100 steel.

Tensile testing at higher strain rates should be conducted to determine the effect of strain rate, in addition to the effect of temperature, on the toughness behavior of HSLA - 100 steel.
APPENDIX A

INTERIM SPECIFICATION FOR TRIAL COMMERCIAL PRODUCTION OF HSLA-100 STEEL PLATES

Melting, Refining and Casting

The heat shall be fully killed and produced to fine grain practice. It shall be made with a low sulfur practice, vacuum degassed and argon injected with CaSi or Mg for sulfide shape control. The heat shall be ingot cast with bottom-pour molds to ensure good surface.

Chemical Composition

The chemical composition shall be as shown in Table I.

Table I - Chemical Composition (Heat and Product Analysis)

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>TARGET for Max. % by Weight Unless a Range is Indicated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.04</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.90</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>ALAP</td>
</tr>
<tr>
<td>Sulfur</td>
<td>ALAP</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.25</td>
</tr>
<tr>
<td>Nickel</td>
<td>3.50</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.60</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.60</td>
</tr>
<tr>
<td>Copper</td>
<td>1.60</td>
</tr>
<tr>
<td>Columbiun</td>
<td>0.025</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.030</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.010</td>
</tr>
</tbody>
</table>

* As low as possible
Hot Rolling

Plates 1/4, 3/4, 1-1/4, and 2 in. thick shall be rolled. Extra care shall be taken to minimize rolled-in scale that could later interfere with achieving an adequate cooling rate during quenching from the solution treating temperature. The plates shall be roller leveled while still warm after rolling.

Heat Treatment

All of the plates shall be solution heat treated for one hour at 1650 F (934 C) and platen quenched with high pressure water jets from above and beneath the plate. The quench water shall not exceed 100 F to ensure an efficient quench.

The plates shall be given an age hardening treatment using temperatures and times determined for each plate by preliminary tensile testing of samples from coupons aged at various conditions. Aging conditions for the plates shall be chosen so as to give the tensile properties listed in Table II.

Mechanical Properties

The heat treated material shall meet the tensile property requirements specified in Table II and the impact property requirements specified in Table III.
Table II - Tensile Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>&lt;0.75 in.</th>
<th>&gt;0.75 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength, psi</td>
<td>100,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Yield Strength, 0.2% Offset, psi</td>
<td>120,000</td>
<td>115,000</td>
</tr>
<tr>
<td>Min. Elongation in 2 in., %</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>Min. Reduction Area, Round Specimen, %</td>
<td>--</td>
<td>45</td>
</tr>
</tbody>
</table>

The tensile properties shall be determined as the average value of duplicate specimens from each plate tested in accordance with ASTM method of testing E8. Full thickness flat specimens shall be tested for the 1/4 - in. thick plate and standard round specimens 0.505 in. in diameter shall be tested for the plates 3/4 in. thick and thicker. All specimens shall be taken transverse to the primary rolling direction.

Table III - Impact Properties

<table>
<thead>
<tr>
<th>Test Thickness, in.</th>
<th>Specimen Size</th>
<th>Test Temp., F</th>
<th>CVN Energy, ft-lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>5mm x 10mm</td>
<td>0 + 3</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-120 + 3</td>
<td>15</td>
</tr>
<tr>
<td>Charpy V-Notch</td>
<td>0.75, 1.25,</td>
<td>10mm x 10mm</td>
<td></td>
</tr>
<tr>
<td>Transverse</td>
<td>2.00</td>
<td>0 + 3</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-120 + 3</td>
<td>30</td>
</tr>
</tbody>
</table>

** Avg. of three tests, minimum.
The Charpy impact properties shall be determined in accordance with ASTM method E23. Three tests transverse to the final rolling direction of the plate shall be conducted. No single value shall fall below the minimum average specified in Table III by more than 5 ft-lb for standard specimens and 2-1/2 ft-lb for half size specimens.
APPENDIX B

CHECKLIST AND EXAMPLE SETTINGS

The purpose of this appendix is to provide a detailed checklist for conducting tensile tests on a Materials Testing System (MTS) 810 series system. The form of this appendix is that of an operators checklist followed by an operational sequence for conducting the constant strain rate tensile test. It provides a sequence of operations and references to information in the system technical manuals.

Nominal testing parameters are as follows:

2. Total diametral displacement range = 0.072 in.
3. A tensile test will be set up herein using a dual slope, hold at breakpoint, ramp and invert function generator set up to allow full extensometer travel.
4. The initial diameter of the specimen will be 0.25 in. and the initial specimen gage length will be 1.00 in. as in Figure 8 for a hourglass shaped specimen.
5. Note: Safe operation of MTS equipment is contingent upon knowledge contained in the introductory section of the system operating manual.
<table>
<thead>
<tr>
<th>CHECK PROCEDURE</th>
<th>RECORD ADJUSTMENT</th>
<th>MANUAL REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONSOLE TURN ON</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Turn CONSOLE POWER on

PRELIMINARY ADJUSTMENT

2. If the load cell, Extensometer, clip-on gage, or LVDT is changed, ensure that the proper range card is installed in the appropriate transducer conditioner. NOTE: CRYOGENIC DIAMETRAL EXTENSOMETER model No. 632.19B-21

PROGRAMMING

3. Select desired controlled \( X \) LOAD \( X \) STRAIN \( X \) STROKE variable. Control panel interlock must be open (RESET lit).

4. Select desired operating range. LOAD \( \pm \text{ FS} \) RANGE \( \pm \text{ FS} \) 440.21 OP, FULL SCALE \( \pm 20 \) KIP page 3

<table>
<thead>
<tr>
<th>LOAD ( \pm \text{ FS} )</th>
<th>RANGE ( \pm \text{ FS} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STRAIN ( \pm \text{ FS} )</th>
<th>RANGE ( \pm \text{ FS} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STROKE ( \pm \text{ FS} )</th>
<th>RANGE ( \pm \text{ FS} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

---

79
_5. Adjust Digital Function Generator

CONTROL MODE
- REMOTE  X
- LOCAL  
- SINGLE CYCLE

OUTPUT
- RAMP  X
- SINE
- HAVERSINE
- HAVERSQUARE
- INVERT

BREAKPOINT
- REMOTE
- NORMAL  X
- REVERSE

LOCAL
- NORMAL  X
- REVERSE

- 90
  PERCENT

- DUAL SLOPE
- HOLD AT BRKPT  X
- RAMP THRU ZERO
- MANUAL BRKPT (OVERRIDE)

- 360
  RATE 1

- 1000
  RATE 2

_6. Adjust SPAN 1 for desired Digital Function Generator signal amplitude.

- SPAN 1

_7. Adjust Digital Display INPUT SELECT

80
**CHECK**

**PROCEDURE**

| indicator. |

**RECORD**

**ADJUSTMENT**

| page 2 |

---

1 (LOAD)  
2 (STRAIN)  
3 (STROKE)  
4 (INPUT options 4-6 are available).

**FAILSAFE ADJUSTMENTS**

8. Adjust Limit Detectors, XDCR 1 (LOAD)  
   if applicable.

| 440.41 OP, page 4 |

**NOTE:**
This step may be performed after test has started. See  
440.41 OP, page 5

---

**UPPER**

| X (+) |
| (-) |

---

**LOWER**

| (+) |
| (-) |

**INTERLOCK**

| INDICATE |

**UPPER**

| X (+) |
| (-) |

---

**LOWER**

| (+) |
| (-) |

**INTERLOCK**

| INDICATE |

| 81 |
CHECK PROCEDURE

RECORD ADJUSTMENT

MANUAL REFERENCE

XDCR 3 (STROKE) 440.41 OP, page 4
100 UP

(+)
(-)

100 LOWER

(+)
(-)

X INTERLOCK

INDICATE

...... PRELIMINARY ADJUSTMENTS AND HYDRAULIC TURN ON .......

_9. Monitor DC ERROR on the Controller meter. 440.13 OP, page 8
_10. Null the meter using the SET POINT control. 440.13 OP, page 3
_11. Push RESET on the Control Panel if it is lit. 413.05 OP, page 2

NOTE: If at any time
RESET will not extinguish,
look for an abnormal condition as described on
the last page of this checklist under IN CASE OF SYSTEM SHUTDOWN.

_12. Set AUTO RESET switch to OUT. 440.14/.14A OP, page 2

If at any time an emergency occurs, push EMERGENCY STOP

.................. INSTALLING THE SPECIMEN ....................

82
14. Lower Hydraulic Actuator
   SET POINT CONTROL full CCW
to bottom stop; then turn
off hydraulic pressure.

15. Install specimen in the upper grip.
   Tighten collar with spanner wrench.
   Plug thermocouple(s) into receptacles.

16. Push reset on Control Panel
    and select low pressure. By
    adjusting the SET POINT control
    CCW slowly raise the actuator up to
    the specimen. Thread the locking collar
    into the lower grip, as the actuator
    moves upward, using the spanner wrench.

17. Check that LOAD is zeroed. Adjust
    if necessary. See Technical
    Manual—TRANSDUCERS

18. The extensometer is clamped to the
    specimen with a spring-loaded arm on
    one side and an adjustable station-
    ary arm on the other. The adjustable
    arm contact can be changed to the
    desired gage length by loosening the
    contact hold-down screws, moving the
    contact to the desired gage length,
    and the retightening the hold-down
    screws. To obtain 0.072 in. of diametral
    travel preset extensometer to near -9.0
    volts then adjust to -9.000 volts using the
    zero adjust.

19. Once the extensometer is attached
    to the specimen, its electrical
    output may be adjusted to desired
    voltage using the zero adjust on
    the strain transducer conditioner.
RUNNING A TENSILE TEST

20. Turn console power on
21. Select desired test temperature on the temperature controller. Attach thermocouple to desired locale for controlling the temperature.
22. With the environmental chamber door closed turn the temperature controller to cool. Open the liquid output valve on the cooling medium container.
23. Bring specimen to the desired test temperature. Ensure that temperature has equilibrated on the specimen by monitoring thermocouple temperatures for the two thermocouples attached to the specimen.
24. Press return to zero on the function generator.
25. Press MTS 440.37 process controller clear D/A button.
26. Select strain control.
27. Zero controller meter using set point potentiometer.
28. Press interlock resets on MTS 445 and then MTS 413.
29. Set rate 1 on the function generator to 10 sec. and rate 2 to 1 sec.
30. Turn on the Tektronics oscilloscope.
31. Press start on the function generator. When, in 10 sec., the oscilloscope sweep reaches -9 volts press function generator hold button.
32. Set function generator rate to 360 sec. and rate 2 to 1000 sec.
33. Zero the controller meter using the set point potentiometer.
34. Clear interlock resets on MTS 445 then MTS 413.
35. Turn on hydraulics in low then switch to high pressure.
36. Turn on the 9828 Hewlett Packard computer, DVM, printer and plotter.
37. Boot up data collection program "JHCOLLECT". Press run and input the requested values.
38. Set the MTS 445 controller recorder dials to Y1 : load, Y2 : strain and X : stroke, this sends these values to channels 1-3 on the DVM.
39. Set the MTS 445 controller oscilloscope dials to Y1 : load, Y2 : off, and X : strain. Then run leads to the chart recorder. The abscissa is strain and the ordinate is load. Set chart recorder at 1 volt/in.
40. To start the test, press the computer soft Key labeled start and release the function generator hold button.
41. If full extensometer travel is reached prior to the specimen fracturing, stop hydraulics and pause the data collection program.
42. Set function generator rate 2 to one sec. and press return to zero.
43. Select stroke control on the MTS 445 controller and zero the meter using the set point potentiometer.
44. Change the controller oscilloscope X dial to stroke.
45. Press interlock resets on the MTS 445 and then the MTS 413.
46. Turn on hydraulics in low pressure then switch to high.
47. Press continue on the data collection program.
48. While observing the chart recorder plot SLOWLY load the specimen to the point of fracture. This is done by manually adjusting the set point control in the clockwise direction.
49. When the specimen fractures press stop hydraulics on the MTS 413 master control panel.
50. Press test stop on the data collection program.
51. Secure the flow of the cooling medium to the environmental chamber.
52. Turn off console power. When the environmental chamber is at room temperature the specimen can be removed.
APPENDIX C

BASIC COMPUTER PROGRAM FOR DATA COLLECTION

111 'PROGRAM STORED AS 'JICOLLECT'.
130 'ILLUSTRATES CHARACTERISTICS VS TEMP HSLA 100.
150 'THE PURPOSE OF THE PROGRAM IS TO COLLECT
170 'THE FOLLOWING FOUR PARAMETERS DURING
190 'CONSTANT STRAIN RATE TENSILE TESTS AT
210 'VARIOUS TEMPERATURES: THE DATA IS STORED
230 'IN ARRAYS FOR SUBSEQUENT MANIPULATION AND-
250 'PLOTTING. THE PROGRAM ALSO ALLOWS PLOT-
270 'IN OF THE LOAD VS. DIAMETRAL DISPLACEMENT
290 'DATA OBTAINED HEREIN.
310 'PARAMETERS
330 'Load = LOAD
350 'Dia = DIAMETRAL DISPLACEMENT
370 'Stk = MACHINE ACTUATOR STROKE
390 'Time = TIME OF TEST RUN
410
430 'DIMENSION THE ARRAYS FOR STORING DATA
450 DIM Load(500), Stk(500), Dia(500), Time(500)
470 PRINTER IS ON
490 Select: ! CREATE DATA FILES
510 PRINT "Select program using softkeys."
530 OFF KEY
550 ON KEY 6 LABEL "CREATE DATA" GOTO 0_form
570 ON KEY 4 LABEL "RENAME DATA FILE" GOTO R_name
590 ON KEY 9 LABEL "RUN TEST" GOTO 1_test
610 START_IDLE: (GOTO Start_idle
630 Load_test=0 for test in prog 1 for test stopped
650 Dim_@H=9 ^ ADRESS OF HP3497A
670 CLEAR Ovw "INITIALIZES HP3497A"
690 S et up: "INITIALIZE HIS TEST SET UP"
710 Printer is 1
730 PRINT USING "a,*"
750 OFF KEY
770 PRINT "ENTER LOAD TRANSDUCER RANGE 1-4"""
790 PRINT "OK PRESS KEY 1 FOR CANNED DATA"
810 Icond= 1 TRANSDUCER CONDITIONER #1
830 GSUB Range_set
850 PRINT "ENTER STRAIN TRANSDUCER RANGE 1-4"
870 Icond=2 TRANSDUCER CONDITIONER #2
890 GSUB Range_set
910 PRINT "CHOOSE EXTENSOMETER TYPE", Extensom, "THEN CONTINUE"
930 Strain.go: OFF KEY
950 ON KEY 0 LABEL "DIAMETRAL" GOTO Dia
970 ON KEY 4 LABEL "LONGITUDINAL" GOTO Long
990 ON KEY 9 LABEL "CONTINUE" GOTO Aze
1010 Strain_wait: GOTO Strain_wait
1030 AXE:!
1050 PRINT "EXTENSOMETER TYPE IS ", Extensom
1070 BEEP 300...
1090 PRINT "ENSURE PROPER DISPLACEMENT IS ENTERED WHEN REQUESTED"
1110 Icond=3 TRANSDUCER CONDITIONER #3
1130 GSUB Range_set
1150 OFF KEY
1170 Init_st=0 THIS IS THE STARTING POINT FOR ACTUATOR STROKE
1190 Init_tr = 0 THIS IS THE STARTING POINT FOR THE EXTENSOMETER
610 BEEP 500.3
620 PRINTER IS 1
630 PRINT USING "@.e"
640 PRINT "TURN ON THE DVM!!!!!!!"
650 PRINT
660 PRINT "CHANGE THE DISC??????????"
670 PRINT "ENSURE NTS HYDRAULICS IN HIGH PRESSURE AT THIS POINT"
680 PRINT "PRESS 'CONTINUE' TO RESUME "
690 PAUSE
700 OUTPUT Dvm:"VRS AF1 AL3"!SETS CHANNELS 1-3 TO AUTO RANGE
710 OUTPUT Dvm:"AI3 VT1"!READS PRESENT STROKE
720 ENTER Dvm:St
730 OUTPUT Dvm:"AI2 VT1"!READS PRESENT STRAIN
740 ENTER Dvm:Str
750 PRINT "INITIAL STROKE PER DVM:";St
760 PRINT "INITIAL STRAIN PER DVM:";Str
770 Bstroke=Initstr-Istroke=St!BSTROKE SET BY INITIAL CONDITIONS
780 INPUT "Specify maximum strain transducer output, V";Max_str
790 INPUT "Specify displacement at this voltage, inches";Max_disp
800 ! THE FOLLOWING ACCOUNTS FOR TRANSDUCER RANGE SETTINGS
810 Istrain=Initstr-(Max_disp/Max_str)
820 Bstrain=Initstr-Istrain-Str!BSTRAIN SET BY INITIAL CONDITIONS
830 GOTO G_1
840 Long:
850 Extensos="Longitudinal"
860 GOTO Strain_go
870 Diam:
880 Extensive="Diametral"
890 GOTO Strain_go
900 G_1:INPUT "Gauge length, inches?";Gage
910 INPUT "Initial diameter, inches?";D_0
920 A_0=(PI/4)*(D_0^2)
930 GOTO Begin
940 Range_set:
950 ! SUBROUTINE TO INPUT RANGES AND TO CONVERT VOLTAGES TO ENGINEERING UNITS
960 OFF KEY
970 ON KEY 0 LABEL "TEST DATA" GOTO Test_dat
980 ON KEY 1 LABEL "RANGE 1 = 100%" GOTO R_1
990 ON KEY 2 LABEL "RANGE 2 = 50%" GOTO R_2
1000 ON KEY 3 LABEL "RANGE 3 = 20%" GOTO R_3
1010 ON KEY 4 LABEL "RANGE 4 = 10%" GOTO R_4
1020 R_4: GOTO R_5
1030 R_1: PRINT "Range 1 selected."
1040 IF Icond=1 THEN Iload=2.0
1050 IF Icond=2 THEN Istrain=1.0
1060 IF Icond=3 THEN Istroke=.50
1070 RETURN
1080 R_2:PRINT "Range 2 selected."
1090 IF Icond=1 THEN Iload=.0
1100 IF Icond=2 THEN Istrain=.5
1110 IF Icond=3 THEN Istroke=.25
1120 RETURN
1130 R_3:PRINT "Range 3 selected."
1140 IF Icond=1 THEN Iload=.4
1150 IF Icond=2 THEN Istrain=.2
1160 IF Icond=3 THEN Istroke=.10
1170 RETURN
1180 R_4:PRINT "Range 4 selected."
1190 IF Icond=1 THEN Iload=.2
1200 IF Icond=2 THEN Istrain=.8
1210 IF Icond=3 THEN Istroke=.0
Q1t0

IF Icond-2 THEN Istra~n-.10
1220 IF Icond-3 THEN Istroke-.050
1230 RETURN
1240 Begin!:still setting up
1250 I-1
1260 INPUT "HOW MANY READINGS PER TEST 500 MAX?":Rdg
1270 PRINT Rdg;" readings selected."
1280 PRINT "THE INTERNAL TRIGGERING OF THE DVM"
1290 PRINT "ALLOWS APPROXIMATELY 2 READINGS OF THE"
1300 PRINT "FOUR VARIABLES PER SECOND WITH NO ADDITIONAL DELAY"
1310 INPUT "ADDITIONAL SECONDS BETWEEN READINGS 1 AND 50":Delay
1320 INPUT "ADDITIONAL SECONDS BETWEEN READINGS 51 AND 200":Delay1
1330 INPUT "ADDITIONAL SECONDS BETWEEN READINGS 201 AND 400":Delay2
1340 INPUT "ADDITIONAL SECONDS BETWEEN READINGS 401 AND 500":Delay3
1350 Cal x;
1360 OFF KEY
1370 PRINT
1380 PRINT "TEST SET UP AS FOLLOWS:"
1390 PRINT "FOR Icond-1, I VOLT = ";Iread;"K*p"
1400 PRINT "FOR Icond-2, I VOLT = ";IstraLn;"IN"
1410 PRINT "FOR Icond-3, I VOLT = ";Istroke;"IN"
1420 PRINT
1430 PRINT "TYPE EXTENSOMETER IS ";ExtensoS
1440 PRINT "NUMBER OF READINGS = ";Rdg
1450 PRINT "DELAY BETWEEN READINGS 0-50":Delay;"SECONDS"
1460 PRINT "DELAY BETWEEN READINGS 51-200":Delay1;"SECONDS"
1470 PRINT "DELAY BETWEEN READINGS 201-400":Delay2;"SECONDS"
1480 PRINT "DELAY BETWEEN READINGS 401-500":Delay3;"SECONDS"
1490 PRINT "Press softkey to start or to change set up.",
1500 BEEP 1000."
1510 ON KEY 0 LABEL "Start" GOTO Starter
1520 ON KEY 2 LABEL "Fix G.L." GOTO G1
1530 ON KEY 4 LABEL "Change" GOTO Set
1540 Begin_idle; GOTO Begin_idle
1550 Starter:!
1560 PRINT "Data Acquiring"
1570 OFF KEY
1580 Starter2:This interrupts data acc & restarts when "CONTINUE" is pressed
1590 ON KEY 1 LABEL "pause" GOTO Test_pause
1600 ON KEY 4 LABEL "STOP" GOTO Test_complete
1610 IF I<50 THEN WAIT Delay
1620 IF I>50 AND I<200 THEN WAIT Delay1
1630 IF I>200 AND I<400 THEN WAIT Delay2
1640 IF I>400 THEN WAIT Delay3
1650 Data_acc: 'DATA ACQUISITION ROUTINE
1660 IF I=1 THEN T=0-TIMEDATE
1670 OUTPUT Dvm:"VRS AFO AL3"; 'SETS CHANNELS 1-3 TO AUTO RANGE
1680 OUTPUT Dvm:"At1 VT1"; 'READS LOAD
1690 ENTER Dvm:Load;
1700 OUTPUT Dvm:"At2 VT1"; 'READS STRAIN
1710 ENTER Dvm:Strain;
1720 OUTPUT Dvm:"At3 VT1"; 'READS STROKE
1730 ENTER Dvm:Stk;
1740 Itime(I)=TIMEDATE-T
1750 I-1
1760 Ld(I):+'LAST READING COUNTER FOR STOPPING TEST
1770 IF Rdg OR I>499 THEN Stopper
1780 GOTO Starter
1790 Stopper:!
1800 PRINT "ACQUISITION COMPLETE"
1810 Count_out*1 ! COUNTING AND SORTING VARIABLE
1820 Conv=gs; !
1830 !CONVERT VOLTAGE DATA TO ENG UNITS LOAD, TEMP, STROKE, DISPL
1840 Lrdg=Lrdg-1
1850 FOR M=1 TO Lrdg
1860 Lod(H)=Lod(M) X load
1870 Stk(H)=Stk(M) X stroke X bstroke
1880 Dia(H)=Dia(M) X strain X bstrain
1890 NEXT H
1900 STORE DATA AS CONVERTED TO BDAT FILES
1910 OFF KEY
1920 Dat_out=!!
1930 PRINTER IS 1
1940 PRINT USING "*.a"
1950 PRINT "Data is being stored. Sorry for the delay......"
1960 PRINT "Assigning to Load, etc."
1970 ASSIGN #Path1 TO "Lod"
1980 ASSIGN #Path2 TO "Dia"
1990 ASSIGN #Path3 TO "Stk"
2000 ASSIGN #Path4 TO "Itime"
2010 FOR I=1 TO Lrdg
2020 OUTPUT #Path1:Lod(I)
2030 OUTPUT #Path2:Dia(I)
2040 OUTPUT #Path3:Stk(I)
2050 OUTPUT #Path4:Itime(I)
2060 NEXT I
2070 FOR I=1 TO Lrdg
2080 ASSIGN #Path1 TO *
2090 ASSIGN #Path2 TO *
2100 ASSIGN #Path3 TO *
2110 ASSIGN #Path4 TO *
2120 NEXT I
2130 !OUTPUT THE DATA
2140 PRINT USING "*.a"
2150 PRINT "SELECT HARD OR SOFT COPY"
2160 PRINT "LOAD/DISP"
2170 OFF KEY
2180 ON KEY 0 LABEL "HARD COPY" GOTO Har
2190 ON KEY 4 LABEL "NO HARD COPY" GOTO Sof
2200 Stop_idle: GOTO Stop_idle
2210 Har: PRINTER IS 706
2220 Sof: !
2230 OFF KEY
2240 PRINT "I LOAD DISPL STROKE TIME"
2250 PRINT "(kip) (in) (in) (sec)"
2260 FOR I=1 TO Lrdg
2270 PRINT USING Fmt':I,Lod(I),Dia(I),Stk(I),Itime(I)
2280 NEXT I
2290 Fmt':IMAGE 000,5X.44!X.SD.DDE
2300 OFF KEY
2310 Plot: !
2320 DEC: !
2330 OFF KEY
2340 PRINT "Choose whether or not to plot"
2350 ON KEY 4 LABEL "NO PLOT" GOTO N_p
2360 ON KEY 0 LABEL "YES PLOT" GOTO Y_p
2370 GOTO 2370
2380 Y_p: !PLOT ROUTINE
2390 OFF KEY
2400 GCLEAR
2410 GINIT
2420 GRAPHICS ON
2430 PLOTTER IS 705,"HPGL"
2440 VIEWPORT 13.5,133.0,10.5,95.0
2450 PEN 1
2460 VIEWPORT 25.110.30.85
2470 IF Count_out=1 THEN
2480 max_x=05
2490 max_y=8
2500 T step=8
2510 END IF
2520 WINDOW 0, max_x,0, Max_y
2530 AXES Max_x/10, Max_y/10,0,0
2540 CSIZE 2,0
2550 VIEWPORT 13.5,133.10.5,95
2560 LORG 4
2570 FOR I=0 TO Max_x STEP Max_x/10
2580 MOVE I-.Max_y/20
2590 LABEL USING "K";I
2600 NEXT I
2610 CSIZE 3
2620 MOVE Max_x/2, Max_y/10
2630 IF Count_out=1 THEN LABEL USING "K";"Displacement in"
2640 LORG 8
2650 CSIZE 2
2660 FOR I=0 TO Max_y STEP Max_y/Y_step
2670 MOVE -Max_y/10,1
2680 LABEL USING "K";I
2690 NEXT I
2700 CSIZE 3
2710 LDIR 90
2720 LORG 6
2730 MOVE -Max_x/8,Max_y/2
2740 IF Count_out=1 THEN LABEL USING "K";"Load, kip"
2750 LDIR 9
2760 LORG 5
2770 CSIZE 1.5
2780 MOVE 0,0
2790 FOR J=1 TO Lrdg
2800 DRAW Dia(J),Lod(J)
2810 NEXT J
2820 N_p:1
2830 Count_out=Count_out+1
2840 IF Count_out=2 THEN Conv=.ss
2850 I=1
2860 PRINT "Run another test? Press soft key"
2870 FOR Q=0 TO 3
2880 ON KEY Q LABEL "Run again" GOTO 2450
2890 ON KEY Q=5 LABEL "New set up" GOTO 2450
2900 NEXT Q
2910 ON KEY 6 LABEL "Stop" GOTO S-10
2920 ON KEY 9 LABEL "Stop" GOTO S-10
2930 S-10:STOP
2940 S-10:STOP
2950 Test halted!
2960 Dia=Dia(J)+1strain=Bstrain
2970 Strx=Strx(J)+1stroke=Bstroke
2980 Lod=Lod(J)+1load=Blod
2990 PRINT "test halted at:"
3000 PRINT "dia of":Dia;"in"
3010 PRINT "stroke of ":Strk:" in"
3020 PRINT "load of ":Lode:" lbs"
3030 BEEP
3040 GOTO Cal_x
3050 Test_pause: !
3060 OFF KEY
3070 PRINT "TEST PAUSE HIT CONTINUE TO RESUME"
3080 PAUSE
3090 GOTO Data_acq
3100 Test_complete: ! STOPS DATA COLLECTION AND STORES THAT COLLECTED
3110 OFF KEY
3120 GOTO Stopper
3130 Test_dat: !SAMPLE DATA FOR VERIFYING PROGRAM
3140 ! Istroke=1
3150 ! Istrain=.001 ! FOR DIAM. EXTENS. RANGE
3160 ! Istrain=.010 ! FOR LONG. EXTENS. RANGE
3170 ! load=1
3180 ! Bstrain=.040 ! FOR DIAM. EXTENS. RANGE
3190 ! Bstrain=0 ! FOR LONG. EXTENS.
3200 D_o=.25
3210 A_o=.049
3220 T_0=TIMEDATE
3230 Lrep=10
3240 FOR I=1 TO 11
3250 ! Lod(I)=I/2
3260 ! Stk(I)=I/5
3270 ! Dia(I)=2*I-12 !FOR DIAM. EXTENS. 0-10v
3280 ! Dia(I)=I !FOR LONG. EXTENS. 0-10v
3290 ! time(I)=TIMEDATE-T_0
3300 NEXT I
3310 GOTO Stopper
3320 R_nam: !
3330 BEEP 500,.2
3340 BEEP 1000,.2
3350 PRINT "Put in data disc!!!!!!!!!!!!!!!"
3360 PRINT "Hit continue key when ready"
3370 PAUSE
3380 OFF KEY
3390 PRINT "Select old file name using soft keys"
3400 ON KEY 0 LABEL "Lod" GOTO R_nam_1
3410 ON KEY 1 LABEL "Dia" GOTO R_nam_2
3420 ON KEY 2 LABEL "Stk" GOTO R_nam_3
3430 ON KEY 4 LABEL "time" GOTO R_nam_5
3440 R_nam_0: GOTO R_nam_0
3450 R_nam_1:Old_file$="Lod"
3460 GOTO R_nam_0
3470 R_nam_2:Old_file$="Dia"
3480 GOTO R_nam_0
3490 R_nam_3:Old_file$="Stk"
3500 GOTO R_nam_0
3510 R_nam_5:Old_file$="time"
3520 GOTO R_nam_0
3530 R_nam_8: !
3540 OFF KEY
3550 INPUT "What is new file name?":New_file$
3560 RENAME Old_file$ TO New_file$
3570 PRINT USING ".
3580 PRINT "Any more files to rename?"
3590 ON KEY 0 LABEL "MORE FILES" GOTO R_nam
3600 ON KEY 4 LABEL "quit" GOTO Select_
Rna.dle: GOTO R_nan_idle

OFF KEY

ON ERROR GOTO Error_check

PRINTER IS 1

PRINT USING "9,9,9"

PRINT "Put in data disc!!!!!!!!!!"

PRINT "Then hit continue key."

BEEP 100,2

BEEP 350,2

BEEP 1000,2

PAUSE

PRINT "Creating Lod file"

CREATE BDAT "Lod",501,8

PRINT "Creating Dia file"

CREATE BDAT "Dia",501,8

PRINT "Creating Stk file"

CREATE BDAT "Stk",501,8

PRINT "Creating Itime file"

CREATE BDAT "Itime",501,8

GOTO Select

Error_check:

IF ERR=54 THEN GOTO Select

PRINT "Error...ERRN is":ERR

GOTO D_form

END
APPENDIX D

BASIC COMPUTER PROGRAM FOR DATA REDUCTION

10 "PROGRAM STORED AS "JHREDUCE"
20 "PROGRAM TO CALCULATE STRESS/STRAIN ...
30 "FROM THE DATA COLLECTED IN "JHCOLLECT"
40 "THEN STORE CALCULATED VALUES IN ARRAYS FOR ...
50 "SUBSEQUENT PLOTTING AND CURVE FITTING"
60 "KEY VARIABLES USED:
70 "Lod = Load
80 "Dia. = Diametral displacement
90 "Stress = True Stress
100 "Strain = True Strain
110 "Lstress = Log of True Stress
120 "Lstrain = Log of True Strain
130 "Cstress = Bridgeman corrected True Stress
140 "Cstrain = Log Bridgeman Stress
150 "Strainp = Plastic true Strain
160 "Lstrainp = Log Plastic true Strain
170 "Lstress = Log Bridgeman Corrected True Stress
180 "Lstrainp = Log Plastic true Strain
190 "DIMENSION ARRAYS
200 DIM Lod(500),Stk(500),Dia(500),Itimo(500)
210 DIM Stressi(500),Strain(500)
220 DIM Lstress(500),Lstrain(500),Cstress(500)
230 PRINT "ENSURE THE PROPER FILE NUMBERS"
240 PRINT "ARE LISTED IN THE @PATH STATEMENTS"
250 PRINT "PRIOR TO RUNNING THIS PROGRAM"
260 PRINT "INITIAL CORRECTION CORRI=.9723"
270 PRINT "FINAL CORRECTION CORRF=1/(A-LOG(B))"
280 PRINT "THIS FACTOR IS APPLICABLE UP TO NECKING"
290 Corri=.9723
300 B=1+(2.R/R)
310 A=1+(2/R/R)
320 "INPUT "ENTER VALUE FOR YOUNG'S MODULUS",Ym"
330 INPUT "ENTER MAX LOAD",Mlod
340 IF Count_out=1 THEN COUNTING VARIABLE
350 IF Creater=1 THEN GOTO 680
360 IF Creater=0 THEN
370 PRINT "CREATING STRESS FILE"
380 CREATE BDAT "Stress",501.8
390 PRINT "CREATING STRAIN FILE"
400 CREATE BDAT "Strain",501.8
410 PRINT "CREATING LSTRESS FILE"
420 CREATE BDAT "Lstress",501.8
430 PRINT "CREATING LSTRAIN FILE"
440 CREATE BDAT "Lstrain",501.8
450 PRINT "CREATING CSTRESS FILE"
460 CREATE BDAT "Cstress",501.8
610 PRINT "CREATING CLSTRESS FILE"
620 CREATE BDAT "Clstress",501.8
630 PRINT "CREATING STRAINP FILE"
640 CREATE BDAT "Strainp",501.8
650 PRINT "CREATING LSTRAINP FILE"
660 CREATE BDAT "Lstrainp",501.8
670 END IF
680 ! INPUT THE PROPER Lod AND Dia FILE NUMBER
690 ! THE FILES NUMBERS MATCH THE SPECIMEN NO.
700 ! i.e. ASSIGN @Path1 TO "Lod"
710 BEEP 300..5
720 PRINT "ENSURE PROPER lod/Dia FILE DISC IN"
730 PRINT "PRESS CONTINUE TO PROCEED"
740 PAUSE
750 ASSIGN @Path1 TO "Lod"
760 ASSIGN @Path2 TO "Dia"
770 ! PATHS 3 AND 4 ARE FOR ACTUATOR STROKE AND
780 ! TEST RUN TIME AND ARE NOT USED IN PROGRAM
790 ! ENTER INTO LOd/Dia ARRAYS THE VALUES OF THE
800 ! APPROPRIATE DATA FILE FOR CALCULATION OF
810 ! STRESS, STRAIN,....
820 INPUT "Specify number of data points 500 max",Rdg
830 FOR I=1 TO Rdg
840 ENTER @Path1:Lod(I)
850 ENTER @Path2:Dia(I)
860 IF Count_out=1 THEN
870 IF Lod(I)>-Miod THEN
880 Mlod=Lod(I) ! MAX-LOAD
890 Juts=I ! DATA POINT AT MAX-LOAD
900 ! THIS IS POINT WHERE THE LINEAR CORRECTION
910 ! BEGINS TO BE APPLIED, SEC ARRAY_ASSIGN
920 PRINT "READING",Juts
930 PRINT "MLOD=".Mlod
940 Mdia=Dia(I) ! DISP. AT MAX-LOAD
950 PRINT "MDIA=".Mdia
960 GOTO Correct_b
970 ELSE
980 Juts=Rdg
990 END IF
1000 END IF
1010 NEXT I
1020 GOTO 1230
1030 !
1040 Correct_b: ! DETERMINE SLOPE AND INTERCEPT
1050 ! VALUES TO APPLY LINEAR BRIDGEMAN
1060 ! CORRECTION TO POINTS AFTER NECKING
1070 Auts=(PI/4)*(10.0-Mdia)^2 AREA AT MAX-LOAD
1080 Stressuts=Mlod/Auts ! STRESS AT MAX-LOAD
1090 INPUT "LOAD AT FRACTURE",".Fno
1100 INPUT "FINAL DIA","D_f
1110 A_f=(PI/4)*(D_f)^2
1120 Fatress=Fload/A_f ! STRESS AT FRACTURE
1130 Mb=Corr_f-Corr_l)(Fatress-Stressuts)
1140 PRINT "MB ".Mb !SLOPE FOR LINEAR BRIDGEMAN
1150 !CORRECTION
1160 Intercep-Corr_l(Mb-Fatress) ! INTERCEPT
1170 ! VALUE FOR LINEAR BRIDGEMAN CORRECTION
1180 PRINT "INTERCEPT ",Intercep
1190 Count_out=Count_out+1
1200 ASSIGN @Path1 TO @Path2
1210  ASSIGN @Path2 TO  
1220  GOTO 680  
1230  PRINTER IS 1  
1240  BEEP 200,-.5  
1250  PRINT "INSTALL DISC TO SAVE DATA ON"  
1260  PRINT "PRESS CONTINUE TO RESUME"  
1270  PAUSE  
1280  ASSIGN @Path5 TO "Stress"  
1290  ASSIGN @Path6 TO "Strain"  
1300  ASSIGN @Path7 TO "Lstress"  
1310  ASSIGN @Path8 TO "Lstrain"  
1320  ASSIGN @Path9 TO "Cstress"  
1330  ASSIGN @Path10 TO "Clstress"  
1340  ASSIGN @Path11 TO "Strainp"  
1350  ASSIGN @Path12 TO "Lstrainp"  
1360  PRINT "ASSIGNING VALUES TO ARRAYS"  
1370  PRINTER IS 706  
1380  "COMPUTE AND ASSIGN VALUES TO ARRAYS"  
1390  Array.assign  
1400  FOR J=1 TO Rdg  
1410  Ai=(PI/4)-((D,0-Dia(J))^2)  
1420  Stress(J)=Log(Ai)/Ai  
1430  OUTPUT @Path5;Stress(J)  
1440  Strain(J)=Log(A0/A0)  
1450  OUTPUT @Path6;Strain(J)  
1460  IF Stress(J)<0 THEN  
1470  Lstress(J)=0  
1480  ELSE  
1490  Lstress(J)=LGT(Stress(J))  
1500  END IF  
1510  OUTPUT @Path7;Lstress(J)  
1520  IF Strain(J)<0 THEN  
1530  Lstrain(J)=0  
1540  ELSE  
1550  Lstrain(J)=LGT(Strain(J))  
1560  END IF  
1570  OUTPUT @Path8;Lstrain(J)  
1580  IF J(=max) THEN  
1590  Cstress(J)=Corrb-Stress(J)  
1600  ELSE  
1610  Corrb=(Mb-Stress(J))+Intercept  
1620  Cstress(J)=Corrb-Stress(J)  
1630  "PRINT "RDG",Rdg  
1640  "PRINT "Dia ",Dia(J)  
1650  "PRINT "Corrb",Corrb  
1660  END IF  
1670  OUTPUT @Path9;Cstress(J)  
1680  IF Cstress(J)<0 THEN  
1690  Cstress(J)=0  
1700  ELSE  
1710  Cstress(J)=LGT(Cstress(J))  
1720  END IF  
1730  OUTPUT @Path10;Cstress(J)  
1740  Strainp(J)=Strain(J)-(Cstress(J)/Ym)  
1750  OUTPUT @Path11;Strainp(J)  
1760  IF Strainp(J)<0 THEN  
1770  Lstrainp(J)=0  
1780  ELSE  
1790  Lstrainp(J)=LGT(Strainp(J))  
1800  END IF
1310 OUTPUT @Path12: Lstraijo(j)
1320 PRINT "req's complete", j
1330 NEXT j
1340 PRINTER IS 1
1350 BEEP 500, 1
1360 PRINT "INSTALL DISC WITH LOAD/DIA DATA"
1370 PRINT "PRESS CONTINUE TO CLOSE PATHS"
1380 PRINTER IS 1
1390 ASSIGN @Path1 TO -
1400 ASSIGN @Path2 TO -
1410 BEEP 250, 5
1420 PRINT "INSTALL STRESS/STRAIN...DATA DISC"
1430 PRINT "PRESS CONTINUE"
1440 PAUSE
1450 ASSIGN @Path5 TO -
1460 ASSIGN @Path6 TO -
1470 ASSIGN @Path7 TO -
1480 ASSIGN @Path8 TO -
1490 ASSIGN @Path9 TO -
1500 ASSIGN @Path10 TO -
1510 ASSIGN @Path11 TO -
1520 ASSIGN @Path12 TO -
1530 INPUT "RENAME FILES? 1-YES 0-NO", Cont
1540 PRINT "FILE SHOULD BE RENAMED USING"
1550 PRINT "THE APPROPRIATE SCIMEN NO."
1560 IF Cont<1 THEN
1570 GOTO 2510
1580 END IF
1590 Rnam: ROUTINE TO RENAME FILES
2100 BEEP 500, 2
2110 BEEP 1000, 2
2120 PRINT "Put in data disc!"....""
2130 PRINT "Hit continue key when ready"
2140 PAUSE
2150 OFF KEY
2160 PRINT "Select old file name using soft keys"
2170 ON KEY 0 LABEL "Stress" GOTO R nam_1
2180 ON KEY 1 LABEL "Strain" GOTO R nam_2
2190 ON KEY 2 LABEL "Lstress" GOTO R nam_3
2200 ON KEY 3 LABEL "Lstraijo" GOTO R nam_4
2210 ON KEY 4 LABEL "Cstress" GOTO R nam_5
2220 ON KEY 5 LABEL "Clstrainp" GOTO R nam_6
2230 ON KEY 6 LABEL "Cstress" GOTO R nam_7
2240 ON KEY 7 LABEL "Lstraijo" GOTO R nam_8
2250 R nam_0: GOTO R nam_0
2260 R nam_1: "Old Files= " Stress"
2270 GOTO R nam_3
2280 R nam_2: "Old Files= " Strain"
2290 GOTO R nam_3
2300 R nam_3: "Old Files= " Lstress"
2310 GOTO R nam_4
2320 R nam_4: "Old Files= " Lstraijo"
2330 GOTO R nam_9
2340 R nam_5: "Old Files= " Cstress"
2350 GOTO R nam_9
2360 R nam_6: "Old Files= " Cstress"
2370 GOTO R nam_9
2380 R nam_7: "Old Files= " Strainp"
2390 GOTO R nam_9
2400 R nam_8: "Old Files= " Lstraijo"
2410 R_nam: R
2420 OFF KEY
2430 INPUT "What is new file name?", New_file$ 
2440 RENAME Old_file$ TO New_file$ 
2450 PRINT USING "9.9;-" 
2460 PRINT "Any more files to rename?" 
2470 ON KEY 0 LABEL "MORE FILES" GOTO R_nam 
2480 ON KEY 4 LABEL "quit" GOTO 2510 
2490 R_nam_idle: GOTO R_nam_idle 
2500 BEEP 200.5 
2510 PRINT "PROGRAM COMPLETED " 
2520 END
APPENDIX E

BASIC COMPUTER PROGRAM FOR DATA DISPLAY

```
10 DIMENSION THE ARRAYS
20 DIM Lod(500), Dia(500), Stk(500), Stime(500), Lstress(500), Lstrain(500)
30 DIM Lststrain(500), Lstrainp(500), Cstress(500), Strainp(500)
40 DIM Lod(),Dia(),Stk(),Stime(),Lstress(),Lstrain(),Lststrain(),Lstrainp(),Cstress(),Strainp()
50 DIM Str(),St(),Strain(),strain()
60 DIM LogStr(),LogSt(),LogStrain(),LogStrainp(),LogCstress(),LogStrainp()
70 DIM Strainp(),Strainp()
80 DIM Lod(500), Dia(500), Stk(500), Stime(500), Lstress(500), Lstrain(500)
90 DIM Lststrain(500), Lstrainp(500), Cstress(500), Strainp(500)
100 DIM Lod(),Dia(),Stk(),Stime(),Lstress(),Lstrain(),Lststrain(),Lstrainp(),Cstress(),Strainp()
110 DIM Str(),St(),Strain(),strain()
120 DIM LogStr(),LogSt(),LogStrain(),LogStrainp(),LogCstress(),LogStrainp()
130 DIM Strainp(),Strainp()
140 DIM Count_out=0 !COUNTER
150 INPUT "Specify number of data points 500 max",Rdg
160 INPUT "INITIAL DIAMETER",D
170 INPUT "FINAL DIAMETER",F
180 INPUT "LOAD AT FRACTURE",Fload
190 INPUT "FINAL SPECIMEN RADIUS",Rn
200 INPUT "FINAAL NECK RADIUS OF CURVATURE",R
210 INPUT "ENTER YOUNG'S MODULUS",Y
220 INPUT "LOAD AT FRACTURE",Fload
230 INPUT "FINAL DIAMETER",D
240 INPUT "LOAD AT FRACTURE",Fload
250 INPUT "FINAL SPECIMEN RADIUS",Rn
260 INPUT "FINAAL NECK RADIUS OF CURVATURE",R
270 INPUT "ENTER YOUNG'S MODULUS",Y
280 INPUT "LOAD AT FRACTURE",Fload
290 INPUT "FINAL SPECIMEN RADIUS",Rn
300 INPUT "FINAAL NECK RADIUS OF CURVATURE",R
310 INPUT "ENTER YOUNG'S MODULUS",Y
320 INPUT "LOAD AT FRACTURE",Fload
330 INPUT "FINAL SPECIMEN RADIUS",Rn
340 INPUT "FINAAL NECK RADIUS OF CURVATURE",R
350 INPUT "ENTER YOUNG'S MODULUS",Y
360 PRINT "ENSURE THE PROPER FILES TO BE PLOTTED ARE LISTED IN THE ASSIGNMENT""PLOT STATEMENTS PRIOR TO RUNNING THIS PROGRAM"
370 PRINT
380 Count_out=0 !COUNTER
390 INPUT "Specify number of data points 500 max",Rdg
400 INPUT "INITIAL DIAMETER",D
410 INPUT "FINAL DIAMETER",F
420 INPUT "LOAD AT FRACTURE",Fload
430 INPUT "FINAL SPECIMEN RADIUS",Rn
440 INPUT "FINAAL NECK RADIUS OF CURVATURE",R
450 INPUT "ENTER YOUNG'S MODULUS",Y
460 A=(PI/4)-(D_0)^2
470 Lod=Log(A_0/F)
480 Fstrain=Log(A_0/F)
490 Lstrain=Log(A_0/F)
500 Cstress=Cstress(Fstrain)
510 Cstress=Cstress(Fstrain)
520 Fstrainp=Fstrainp(Fstrain)
530 Fstrainp=Fstrainp(Fstrain)
540 STOPPER: IF Rdg>500 THEN GOTO 340
550 PRINT
560 PRINT
570 Count_out+Count_out+1
580 PRINT "ASSIGNING PATHS"
590 IF Count_out=1 THEN
600 BEEP 100, 5
```
610 PRINT "INSTALL APPROPRIATE DATA DISC"
620 PRINT "PRESS CONTINUE TO RESUME"
630 PAUSE
640 IF Count_out=1 THEN
650 ASSIGN @Path1 TO "Lod"
660 ASSIGN @Path2 TO "Dia"
670 ASSIGN @Path3 TO "Stk"
680 ASSIGN @Path4 TO "Item"
690 END IF
700 IF Count_out=2 THEN
710 ASSIGN @Path5 TO "Stress"
720 END IF
730 IF Count_out=2 OR 4 THEN
740 ASSIGN @Path6 TO "Strain"
750 END IF
760 IF Count_out=3 THEN
770 ASSIGN @Path7 TO "Lstress"
780 END IF
790 IF Count_out=3 OR 5 THEN
800 ASSIGN @Path8 TO "Lstrain"
810 END IF
820 IF Count_out=4 THEN
830 ASSIGN @Path9 TO "Cstress"
840 END IF
850 IF Count_out=5 THEN
860 ASSIGN @Path10 TO "Cstress"
870 ASSIGN @Path11 TO "Strainp"
880 END IF
890 IF Count_out=6 THEN
900 ASSIGN @Path12 TO "Lstrainp"
910 END IF
920 OFF KEY
930 PRINT "ENTERING ASSIGNED PATHS"
940 FOR I=1 TO Rdg
950 IF Count_out=1 THEN
960 ENTER @Path1 : Lod(I)
970 ENTER @Path2 : Dia(I)
980 ENTER @Path3 : Stk(I)
990 ENTER @Path4 : Item(I)
1000 END IF
1010 IF Count_out=2 THEN
1020 ENTER @Path5 : Stress(I)
1030 ENTER @Path6 : Strain(I)
1040 END IF
1050 IF Count_out=3 THEN
1060 ENTER @Path7 : Lstress(I)
1070 ENTER @Path8 : Lstrain(I)
1080 END IF
1090 IF Count_out=4 THEN
1100 ENTER @Path9 : Cstress(I)
1110 END IF
1120 IF Count_out=5 THEN
1130 ENTER @Path10 : Cstress(I)
1140 END IF
1150 IF Count_out=5 THEN
1160 ENTER @Path11 : Strainp(I)
1170 ENTER @Path12 : Lstrainp(I)
1180 END IF
1190 IF Count_out=6 THEN
1200 ENTER @Path12 : Lstrainp(I)
1210 END IF
1220 NEXT I
1230 !OUTPUT THE DATA
1240 Dat_out:
1250 PRINT "SELECT HARD OR SOFT COPY"
1260 BEEP 900..5
1270 IF Count_out=1 THEN PRINT "LOAD/DISP"
1280 IF Count_out=2 THEN PRINT "STRESS/STRAIN"
1290 IF Count_out=3 THEN PRINT "CSTRESS/STRAIN"
1300 IF Count_out=4 THEN PRINT "CLSTRESS/LSTRAIN"
1310 IF Count_out=5 THEN PRINT "CLSTRESS/LSTRAINP"
1320 IF Count_out=6 THEN PRINT "CLSTRESS/LSTRAINP"
1330 PRINT
1340 Plotz:
1350 DEG OFF KEY
1360 PRINT "Choose whether or not to plot"
1370 ON KEY 4 LABEL "NO PLOT" GOTO N_p
1380 ON KEY 0 LABEL "YES PLOT" GOTO Y_p
1390 GOTO 1400
1400 Y_p: ! PLOT ROUTINE
1410 OFF KEY
1420 GCLEAR
1430 INIT
1440 GRAPHICS ON
1450 PLOTTER IS 705,"HPGL"
1460 VIEWPORT 13.5,133.0,10.5,95.0
1470 PEN 1
1490 VIEWPORT 25.110.30,85
1500 IF Count_out=1 THEN !MAX COORDINATES FOR LOD VS. DIA DISPLACEMENT
1510 Max_x=.10
1520 Max_y=10
1530 Y_step=10
1540 WINDOW 0,Max_x,0,Max_y
1550 AXES Max_x/10,Max_y/Y_step,0.0
1560 END IF
1570 IF Count_out=2 THEN !MAX COORDINATES FOR STRESS/STRAIN
1580 Max_x=1.0
1590 Max_y=200
1600 Y_step=10
1610 WINDOW 0,Max_x,0,Max_y
1620 AXES Max_x/10,Max_y/Y_step,0.0
1630 END IF
1640 IF Count_out=3 THEN !MAX COORDINATES FOR LOG STRESS/STRAIN
1650 Max_x=3.0
1660 Max_y=2.5
1670 Y_step=10
1680 WINDOW Max_x,0,Max_y
1690 AXES Max_x/6,Max_y/Y_step,Max_x,0
1700 END IF
1710 IF Count_out=4 THEN !MAX COORDINATES FOR C STRESS/STRAIN
1720 Max_x=0
1730 Max_y=250
1740 Y_step=10
1750 WINDOW 0,Max_x,0,Max_y
1760 AXES Max_x/10,Max_y/Y_step,0.0
1770 END IF
1780 IF Count_out=5 THEN !MAX COORDINATES FOR CLSTRESS/LSTRAIN
1790 Max_x=3.0
1800 Max_y=2.5
Yetft,-5
1810 WINDOW Max_x/0,..01,Max_y/0.995
1820 AXES Max_x/6,Max_y/Y_step,Max_z/0.01
1840 END IF
1850 IF Count_out=6 THEN !MAX COORDINATES FOR CLSTRAIN/CLSTRESS
1860 Max_x:/4,0
1870 Max_y=2.5
1880 Y_step=5
1890 WINDOW Max_x/0,..01,Max_y/0.995
1900 AXES Max_x/8,Max_y/Y_step,Max_z/0.01
1910 END IF
1920 CSIZE 2.0
1930 VIEWPORT 13.5,133,10.5,95
1940 LORG 4
1950 IF Count_out=1 THEN
1960 FOR I=0 TO Max_x STEP Max_x/10
1970 MOVE I,-Max_y/20
1980 LABEL USING "K";I
1990 NEXT I
2000 MOVE Max_x/2,-Max_y/8
2010 END IF
2020 IF Count_out=2 THEN
2030 FOR I=0 TO Max_x STEP Max_x/10
2040 MOVE I,-Max_y/20
2050 LABEL USING "K";I
2060 NEXT I
2070 MOVE Max_x/2,-Max_y/8
2080 END IF
2090 IF Count_out=3 THEN
2100 FOR I=0 TO Max_x STEP Max_x/6
2110 MOVE I,-Max_y/20
2120 LABEL USING "K";I
2130 NEXT I
2140 MOVE Max_x/2,-Max_y/8
2150 END IF
2160 IF Count_out=4 THEN
2170 FOR I=0 TO Max_x STEP Max_x/10
2180 MOVE I,-Max_y/20
2190 LABEL USING "K";I
2200 NEXT I
2210 MOVE Max_x/2,-Max_y/8
2220 END IF
2230 IF Count_out=5 THEN
2240 FOR I=0 TO Max_x STEP Max_x/6
2250 MOVE I,-Max_y/20
2260 LABEL USING "K";I
2270 NEXT I
2280 MOVE Max_x/2,-Max_y/8
2290 END IF
2300 IF Count_out=6 THEN
2310 FOR I=0 TO Max_x STEP Max_x/8
2320 MOVE I,-Max_y/20
2330 LABEL USING "K";I
2340 NEXT I
2350 MOVE Max_x/2,-Max_y/8
2360 END IF
2370 CSIZE 3.0
2380 IF Count_out=1 THEN LABEL USING "K";"Diametral Displacement, in."
2390 IF Count_out=2 THEN LABEL USING "K";"True Strain, in/in"
2400 IF Count_out=3 THEN LABEL USING "K";"Log True Strain"
2410 IF Count_out=4 THEN LABEL USING "K":"True Strain"
2420 IF Count_out=5 THEN LABEL USING "K":"Log True Strain"
2430 IF Count_out=6 THEN LABEL USING "K":"Log Plastic"
2440 IF Count_out=6 THEN
2450 MOVE Max_x/2,-Max_y/5
2460 LABEL USING "K":"True Strain"
2470 END IF
2480 LORG 0
2490 CSIZE 2
2500 IF Count_out=1 THEN
2510 FOR I=0 TO Max_y STEP Max_y/Y_step
2520 MOVE Max_x/40,I
2530 LABEL USING "K":"I"
2540 NEXT I
2550 END IF
2560 IF Count_out=2 THEN
2570 FOR I=0 TO Max_y/Y_step
2580 MOVE Max_x/40,I
2590 LABEL USING "K":"I"
2600 NEXT I
2610 END IF
2620 IF Count_out=3 THEN
2630 FOR I=0 TO Max_y/Y_step
2640 MOVE Max_x/.99,I
2650 LABEL USING "K":"I"
2660 NEXT I
2670 END IF
2680 IF Count_out=4 THEN
2690 FOR I=0 TO Max_y/Y_step
2700 MOVE Max_x/25,I
2710 LABEL USING "K":"I"
2720 NEXT I
2730 END IF
2740 IF Count_out=5 THEN
2750 FOR I=0 TO Max_y/Y_step
2760 MOVE Max_x/99,I
2770 LABEL USING "K":"I"
2780 NEXT I
2790 END IF
2800 CSIZE 3.0
2810 LDIR 90
2820 LORG 6
2830 IF Count_out=1 THEN
2840 MOVE Max_x/10,Max_y/2
2850 END IF
2860 IF Count_out=2 THEN
2870 MOVE Max_x/8,Max_y/2
2880 END IF
2890 IF Count_out=3 THEN
2900 MOVE Max_x/9.5,Max_y/2
2910 END IF
2920 IF Count_out=4 THEN
2930 MOVE Max_x/9.5,Max_y/2
2940 END IF
2950 IF Count_out=1 THEN LABEL USING "K":"Load: Kip"
2960 IF Count_out=2 THEN LABEL USING "K":"True Stress: ksi"
2970 IF Count_out=3 THEN LABEL USING "K":"Log True Stress(Ksi)"
2980 IF Count_out<4 THEN LABEL USING "K"; "Corrected True Stress (ksi)"
2990 IF Count_out>=5 THEN LABEL USING "K"; "Log True Stress (ksi)"
3000 IF Count_out<5 THEN
3010 MOVE Max_x/.8,Max_y/2
3020 LABEL USING "K"; "Corrected"
3030 END IF
3040 LDOR 0
3050 LOG 5
3060 CSIZE 1.5
3070 PENUP
3080 IF Count_out<3 THEN
3090 MOVE 0.0
3100 END IF
3110 IF Count_out<3 THEN
3120 PENUP
3130 END IF
3140 IF Count_out<4 THEN
3150 MOVE 0.0
3160 END IF
3170 IF Count_out<5 THEN
3180 PENUP
3190 END IF
3200 IF Count_out<6 THEN
3210 PENUP
3220 END IF
3230 ! PLOT THE VARIOUS CURVES
3240 FOR J=1 TO Rdq
3250 IF Count_out<1 THEN
3260 DRAW Dia(J),Lod(J)
3270 END IF
3280 IF Count_out<2 THEN
3290 DRAW Strain(J),Stress(J)
3300 END IF
3310 NEXT J
3320 IF Count_out<3 THEN
3330 FOR J=1 TO Rdq
3340 MOVE Lstrain(J),Lstress(J)
3350 END IF
3360 NEXT J
3370 ! PLOT FRACTURE POINT
3380 MOVE Lstrain(Lstress)
3390 LABEL USING "K"; ""
3400 END IF
3410 IF Count_out<5 THEN
3420 FOR J=1 TO Rdq
3430 DRAW Strain(J),Cstress(J)
3440 NEXT J
3450 ! PLOT FRACTURE POINT
3460 MOVE Fstrain,Cstress
3470 LABEL USING "K"; ""
3480 END IF
3490 IF Count_out<5 THEN
3500 FOR J=5 TO Rdq
3510 MOVE Lstrain(J),Cstress(J)
3520 NEXT J
3530 ! PLOT FRACTURE POINT
3540 MOVE Lstrain,Cstress
3550 LABEL USING "K"; ""
IF Count_out=6 THEN
! THIS ROUTINE PLOTS LOG CORRECTED TRUE STRESS VS. LOG PLASTIC TRUE STRAIN
FOR J=27 TO Rog
! THE FIRST PLASTIC STRAIN >.001 LOG TRUE STRAIN
! THIS VALUE MUST BE ENTERED FOR EACH SPECIMEN
MOVE Lstrainp(J),Cistress(J)
DRAW Lstrainp(J),Cistress(J)
NEXT J
! PLOT FRACTURE POINT
MOVE Lfstrainp,Clfstress
LABEL USING "K";"*
END IF
PEN Up
! GRAPH TITLE
VIEWPORT 13.5,133.0,10.5,95.0
LDIR 0
CSIZE 4
MOVE Max_x/2,Max_y/.90
INPUT "ENTER SPECIMEN NO.",No
LABEL USING K";"SPECIMEN NO.",No
PENUp
IF Count_out=1 THEN PRINT "LOAD/DISP"
IF Count_out=2 THEN PRINT "STRESS/STRAIN"
IF Count_out=3 THEN PRINT "LSTRESS/LSTRAIN"
IF Count_out=4 THEN PRINT "CSTRESS/STRAIN"
IF Count_out=5 THEN PRINT "CLSTRESS/CLSTRAIN"
IF Count_out=6 THEN PRINT "CLSTRESS/LSTRAINP"
ON KEY 0 LABEL "HARD COPY" GOTO Har
ON KEY 4 LABEL "SOFT COPY" GOTO Sof
Stop_idle: GOTO Stop_idle
Har: PRINTER IS 706
Sof:1
OFF KEY
IF Count_out=1 THEN PRINT "I LOAD DISPL STROKE TIME"
PRINT ", (KIP) (IN) (IN) (SEC)
FOR I=1 TO Rog
PRINT USINGFmt1:1.Lod(I),Dia(I),Stk(I),Itime(I)
NEXT I
END IF
IF Count_out=2 THEN PRINT ", I STRESS STRAIN ",
PRINT ", (Ksi) (In/In)
FOR I=1 TO Rog
PRINT USINGFmt2:1.Stress(I),Strain(I)
NEXT I
END IF
IF Count_out=3 THEN PRINT " I LSTRESS LSTRAIN ",
FOR I=5 TO Rog
PRINT USINGFmt2:1,Lstress(I),Lstrain(I)
NEXT I
END IF
IF Count_out=4 THEN PRINT " I CSTRESS STRAIN ",
FOR I=1 TO Rog
PRINT USINGFmt2:1,Cstress(I),Strain(I)
NEXT I
END IF
4180 IF Count_out<5 THEN
4190 PRINT "1 I CLSTRESS LSTRAIN"
4200 FOR I=5 TO Rdq
4210 PRINT USING Fmt2:I.Clstress(I).Lstrain(I)
4220 NEXT I
4230 END IF
4240 IF Count_out=6 THEN
4250 PRINT "1 I CLSTRESS LSTRAINP"
4260 FOR I=23 TO Rdq
4270 PRINT USING Fmt2:I.Clstress(I).Lstrain(I)
4280 NEXT I
4290 END IF
4300 Fmt1: IMAGE DDD.SX.2(11X,SD.DDDE)
4310 Fmt2: IMAGE DDD.SX.2(11X,SD.DDDE)
4320 N_p: !
4330 OFF KEY
4340 IF Count_out<6 THEN GOTO Stopper
4350 ASSIGN @Path1 TO *
4360 ASSIGN @Path2 TO *
4370 ASSIGN @Path3 TO *
4380 ASSIGN @Path4 TO *
4390 ASSIGN @Path5 TO *
4400 ASSIGN @Path6 TO *
4410 ASSIGN @Path7 TO *
4420 ASSIGN @Path8 TO *
4430 ASSIGN @Path9 TO *
4440 ASSIGN @Path10 TO *
4450 ASSIGN @Path11 TO *
4460 ASSIGN @Path12 TO *
4470 OFF KEY
4480 ON KEY 4 LABEL "Stop" GOTO S_10
4490 ON KEY 0 LABEL "RERUN" GOTO 330
4500 Pause_idle: GOTO Pause_idle
4510 S_10:STOP
4520 PRINT "PROGRAM COMPLETED"
4530 END
APPENDIX F

BASIC COMPUTER PROGRAM FOR CONSTITUTIVE EQUATION TESTING

**PROGRAM STORED AS “POWERFIT”**

THE PURPOSE OF THIS PROGRAM IS TO PLOT LOG BRIDGEMAN CORRECTED TRUE STRESS VS LOG BRIDGEMAN CORRECTED TRUE STRAIN VALUES FOR EACH HSLA-100 STEEL SPECIMEN TESTED.

1. TO APPLY A POWER FUNCTION FIT BY THE METHOD OF LEAST SQUARES TO THE LOG BRIDGEMAN CORRECTED TRUE STRESS/LOG PLASTIC TRUE STRAIN VALUES FOR EACH HSLA-100 STEEL SPECIMEN TESTED.
2. COMPUTATION OF THE STRAIN HARDENING EXPONENT, M, AND THE STRENGTH COEFFICIENT, K1. PLOT A STRAIGHT LINE BETWEEN LOG PLASTIC STRAIN -.001 AND 1.0 USING SLOPE M, AND INTERCEPT LOG K1. THIS LINE OVERLAYS THE PLOT OF BRIDGEMAN CORRECTED TRUE STRESS VS LOG PLASTIC TRUE STRAIN.
3. COMPUTE THE CORRELATION COEFFICIENT, R AS A MEASURE OF THE FIT BETWEEN THE TWO CURVES.
4. ARRAY VALUES CAN BE PRINTED OUT

**POWER EQ. FORM LOG(STRESS)=LOG(K1) + MLOG(STRAIN)**

STRESS IS THE BRIDGEMAN CORRECTED TRUE STRESS
STRAIN IS THE TRUE PLASTIC STRAIN
THE EXPRESSION SHOULD YIELD A LINEAR RELATION M IS THE SLOPE OF THE LINE AND IS CALLED THE STRAIN HARDENING EXPONENT INTERCEPT CALCULATIONS YIELD THE VALUE FOR K1

**DIMENSION ARRAYS**

PRINT "ENSURE APPROPRIATE FILE NO. IS FOLLOWING THE Cstress/Lstrainp arrays";
PRINT "APPROPRIATE DATA DISC MUST BE INSTALLED TO RUN PROGRAM"

INPUT "FINAL SPECIMEN RADIUS,Rn",Rn
INPUT "FINAL NECKED RADIUS OF CURVATURE,R",R
Corrf=1/((1+2*R/Rn)+(LOG1+Rn/(12+R)))
PRINT "FINAL CORRECTION FACTOR -";Corrf
THE BRIDGEMAN CORRECTION TO POINTS 1-3DG HAVE BEEN DETERMINED AND APPLIED IN CSTRESS WHEN THE CSTRESS ARRAY WAS GENERATED THEN THE LGT OF THOSE ARRAY POINTS WAS TAKEN TO YIELD THE CSTRESS ARRAY.

**Determine the fracture point, corrf, corrected stress/log strain**

INPUT "YOUNG'S MODULUS,YM IN KQ/L",Ym
INPUT "INITIAL SPECIMEN DIAMETER",D0
A0=(PI/4)*(D0^2)
Df=2*R
Af=(PI/4)*(Df^2)
INPUT "LOAD AT FRACTURE",Flod
Fstress=Flod/Af
Fstrain=LOG(A0/Af)
Cstress=Corrf*Fstress
Lcfstress=LGT(Cfstress)
Fstrainp=Fstrain-(Cfstress/Ym)
Lstrainp=LGT(Fstrainp)
PRINT "LCFSTRESS-.LcfstresS"
PRINT "LFSTRAINP -"Lstrainp
ASSIGN @Path1 TO "Clstress"
ASSIGN @Path2 TO "Lstrainp"
INPUT "SPECIFY NUMBER OF ARRAY POINTS 500 MAX",Rdg
FOR i=1 TO Rdg
ENTER @Path1;Clstress(i)
ENTER @Path2;Lstrainp(i)
NEXT i
PRINT DATA
PRINT "SELECT HARD COPY OR SCREEN OUTPUT OF"
PRINT "Lstrainp and Clstress arrays"
OFF KEY
ON KEY 0 LABEL "HARD COPY" GOTO Har1
ON KEY 4 LABEL "SOFT COPY" GOTO Sof1
Stop_idle: GOTO Stop_idle
Har1: PRINTER IS 706
Sof1: GOTO Sof1
OFF KEY
PRINT "CLSTRESS LSTRAINP"
FOR i=1 TO Rdg
PRINT USING Fmt1:i;Clstress(i),Lstrainp(i)
NEXT i
Fmt1: IMAGE DDD.5X.2(IX,SD,DDDE)
FIT A STRAIGHT LINE TO THE ORDERED PAIRS
Lstrainp(i),Clstress(i)
SOLVING THE SIMULTANEOUS EQUATIONS AS
LISTED IN THE CRC HANDBOOK
A AND B ARE THE FRACTURE POINT Lstrainp and Clstress
values respectively
A=Lstrainp ! FRACTURE POINT LSTRAINP
B=Clstress ! FRACTURE POINT LCFSTRESS
C=A-B
D=A+C
E=D-B
F=-(Clstress(i) 2)
G=0
N=1
DATA PAIR COUNTER INCLUDES FRACTURE POINT
THE INITIAL VALUE FOR I IS USER INPUTTED
INPUT "FIRST DATA POINT, Rdg =",First
IF I>First GOTO Sof1
FOR i=First TO Rdg
A0=A+Lstrainp(i)
A=A0 ! NOW A IS SUMMING VARIABLE
B0+B+Cstress(i)
B=B0 ! NOW B IS SUMMING VARIABLE
C0=C+(Cstress(i)-Lstrainp(i))
C=C0 ! NOW C IS SUMMING VARIABLE
D0=D+(Lstrainp(i) 2)
D=D0 ! NOW D IS SUMMING VARIABLE
F0=F+(Clstress(i) 2)
F=F0 ! NOW F IS SUMMING VARIABLE
N=N+1 ! COUNTER FOR DATA PAIRS
NEXT i
N=N0
C=A 2
D=B 2
700  OFF KEY
710  PRINT "SELECT HARD COPY OR SCREEN OUTPUT OF"
720  PRINT "THE DATA OUTPUT"
730  ON KEY 0 LABEL "HARD COPY" GOTO Har2
740  ON KEY 4 LABEL "SCREEN OUTPUT" GOTO Sof2
750  GOTO 750
760  Har2:PRINTER IS 706
770  Sof2:
780  INPUT "SPECIMEN NO.-".No
800  INPUT "TEST TEMPERATURE-".Tt
810  PRINT "NSLA-100 HOURGLASS"
820  PRINT "SPECIMEN NO.".No
830  PRINT "TEST TEMPERATURE -".Tt:"DEG. C"
840  PRINT "YOUNG'S MODULUS -":Ym:" Ksi"
850  PRINT "FIRST DATA POINT *
860  INPUT "NUMBER OF DATA PAIRS-".N
870  M-((N-C)-(A*B))/((N-D)-E)
880  Kl-(B/N)-(M*A/N)
890  PRINT "SLOPE -":M
900  PRINT "INTERCEPT -":Kl
910  PRINT "COMPUTE CORRELATION R"
920  Corcoef-((N.C)-(A-B))/SQR((N*F)-G)
930  PRINT "CORRELATION COEFFICIENT.R -":Corcoef
940  PRINT "YES PLOT" GOTO Y.P
950  GOTO 950
960  Tp:
970  PLOT ROUTINE
980  OFF KEY
990  GRAPHICS ON
1000 PLOTTER IS .HP .3." HP
1010 VIEWPORT 25.110.30.85
1020 PEN:
1030 VIEWPORT 25.110.30.85
1040 AXES Max_x-4.0
1050 Max_y-3.0
1060 Max_x=2.5
1070 Max_y=5
1080 X_step=0.01
1090 AXES Max_x/6.Max_y/Y_step.Max_x-0.01
1100 CSIZE 2.0
VIEWPORT 12.5,133.10.5.95
LORG 4
FOR I=0 TO Max_x STEP Max_x/6
   MOVE I-.Max_y/20
   LABEL USING "K":I
   NEXT I
   MOVE Max_x/2.-Max_y/8
   CSIZE 3.0
   LABEL USING "K":"Log Plastic"
   MOVE Max_x/2.-Max_y/5
   LABEL USING "K":"True Strain"
ENDR

CSIZE 2
FOR I=0 TO Max_y STEP Max_y/Ystep
   MOVE Max_x/.99,I
   LABEL USING "K":I
   NEXT I
   CSIZE 3.0
   LDIR 90
   LORG 9
   CSIZE 2
   FOR J=First TO Rdg
   MOVE Lstrain(J),Cstress(J)
   DRAW Lstrainp(J),Cstress(J)
   LABEL USING "K":"=
   NEXT J
   PENUP
   PLOT FRACTURE POINT
   CSIZE 5
   MOVE Lfatrain,.Cfstress
   LABEL USING "K":"-
   PENUP
   THIS SECTION PLOTS THE CURVE FIT LINE
   FIRST POINT CORRESPONDS TO A STRAIN OF 0.1
   THE SECOND POINT CORRESPONDS TO A STRAIN OF 1.0
   X1=-3.0
   Y1=(MaxX)+X1
   X2=0
   Y2=(MaxY)+X2
   BEEP 500,3
   PRINT "CHANGE COLOR OF PEN 7 30 SEC DELAY"
   PRINT "PRESS PEN DOWN"
   WAIT 30
   DRAW X1,Y1
   X2,Y2
   GRAPH TITLE
   VIEWPORT 3.5,133.0,10.5.95.0
   LDIR 0
   CSIZE 4
   MOVE Max_x/2,Max_y/80
   INPUT "ENTER SPECIMEN NO.":No
   LABEL USING "K":"HSLA-100 HOURGLASS"
1990  MOVE Max_x/2,Max_y/.95
2000  LABEL USING "K":"SPECIMEN NO.".,No
2010  PENUP
2020  N.D: !
2030  OFF KEY
2040  Count_out=Count_out+1
2050  IF Count_out>1 THEN
2060  ASSIGN @Path1 TO =
2070  ASSIGN @Path2 TO =
2080  ELSE
2090  GOTO Plots
2100  END IF
2110  OFF KEY
2120  PRINTER IS 1
2130  ON KEY 4 LABEL "Stop" GOTO S_10
2140  ON KEY 0 LABEL "RERUN" GOTO T92
2150  Pause_idle: GOTO Pause_idle
2160  S_10:STOP
2161  PRINT "PROGRAM COMPLETE"
2170  END
LIST OF REFERENCES


6. ARMCO NI-COP ALLOY STEEL, product bulletin LH-3479.


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