The Effect of Microstructure on Constitutive Equations for Metals.

Pithuk Keattipun
Louisiana State University and Agricultural & Mechanical College

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Keattipun, Pithuk, Ph.D.
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THE EFFECT OF MICROSTRUCTURE
ON CONSTITUTIVE EQUATIONS
FOR METALS

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Mechanical Engineering

by

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ABSTRACT

A closed-loop system for constant true strain rate test was modified using a Zenith Z-158 microcomputer connected to an optical sensor and MTS tensile testing machine. This new system has several desirable features: 1) the system is easy to operate; 2) the system works with any round shape of ASTM standard specimen; 3) the system works with a constant true strain rate or any form of strain rate; and 4) the system can be controlled to pause or stop at any pre-selected time or amount of true axial strain.

Three types of materials, electrical grade iron, austenitic stainless steel, and ferritic stainless steel, were selected for a constant true strain rate test at room temperature. The results from this study lead to the conclusions that: 1) the true stress-true plastic strain curves of all materials employed in this study obey two forms of the generalized power law; 2) the true plastic strains at maximum load appears to depend on strain rates; 3) the true stresses at maximum load of electrical grade iron and ferritic stainless steel appear to depend on the initial grain size; and 4) the true plastic strain at maximum load of austenitic stainless steel appears to depend on initial grain size.

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Grain strain studies conducted after constant true strain rate tests show that the distribution of grain strain is not uniform over the entire necking region and is independent of the strain rate and grain size. The results of including the grain strain effect into the constitutive equations show that the true stress at maximum load of electrical grade iron and ferritic stainless steel can be expressed in terms of the linear intercept in the axial direction of the corresponding strain.
CHAPTER 1
INTRODUCTION AND THEORETICAL BACKGROUND

1.1 INTRODUCTION

Calculations of deformation behavior in metal forming operations require mathematical formulas relating true stress to true plastic strain. Among those equations proposed by previous investigators [1-15], two types of constitutive equations based on incremental theory, an exponential form and a saturation-type relation, are considered to be valid at large plastic strain. These two types of equations contain phenomenological material parameters connecting true stress, \( \sigma \), true plastic strain, \( \epsilon \), true plastic strain rate, \( \dot{\epsilon} \), and temperature, \( T \). Of the parameters proposed by previous investigators, none have included microstructural parameters in the constitutive equations.

The development of microstructural anisotropy under plastic deformation, based on the definition of grain strain proposed by Hartley and Unal [16], is due to the change in the shape of grain boundary network. The measurement of grain strain in a particular direction can be defined by the natural logarithm of the ratio of the mean linear intercept of the deformed structure to the original structure measured
in the same direction. The grain strain, defined in terms of stereological parameters characterizing the grain boundary network, is related to the bulk strain, defined in terms of original and final dimensions of a specimen.

A closed-loop system for the uniaxial tensile testing at constant true plastic strain rate described by Hartley and Jenkins [1] consists of a servohydraulic testing machine and an optical sensor unit. Using the optical sensor and a feedback control loop, the actuator velocity is controlled by the instantaneous minimum cross-sectional dimension of the specimen.

In this work uniaxial tensile testing at constant true strain rate was performed with a modification of the closed-loop system described by Hartley and Jenkins [1] using a new optical sensor unit introduced by Hartley [17], and changing from analog control to digital control. Two types of equations, an exponential form and a saturation type relation, were examined using nonlinear least-square fit curve described by Hartley [18]. Grain strain measurement, described by Hartley and Ünal [16], was used to determine the relationship between bulk axial strain and grain strain.

1.2 REVIEW OF PLASTICITY

Theories of plasticity are more complicated than the theory of elasticity. Complications are due to the behavior
of plastic deformation which depend not only on the initial and final states of stress or strain as for elastic deformation, but also on the loading path. Determinations of the plastic deformation of metals subjected to stress between yield and fracture require mathematical formulas relating the mechanical responses of material to its history. The mathematical formulas can be generally divided into two types:

1) total deformation theories,

and 2) incremental theories.

The general assumptions for these theories are

1. material is considered to be continuous,

2. principal axes of plastic stress and strain coincide, and

3. volume is constant.

An outline of principal features of these theories follows.

1.2.1 Total Deformation Theories

Total deformation theories, relating the current stress to the current plastic strain, do not depend on the loading path, but depend on the average of the entire deformation history. This type of theory is very simple and offers mathematical convenience.

Nádai [19] proposed a method to describe a relationship between true stress, \( \sigma \), and true plastic strain, \( \varepsilon \), based on three assumptions [19]:
1. the principal direction of extension always coincide with the principal stress,
2. volume is constant, and
3. the figure composed of the Mohr's three principal strain circles remains geometrically similar to three principal stresses of the Mohr's circles.

The third assumption requires that the Lode's stress parameter, $\mu$, is equal to the Lode's strain parameter, $\nu$,

$$\mu = \nu,$$  \hspace{1cm} (1.2.1)

where

$$\mu = (2\sigma_2 - \sigma_1 - \sigma_3)/\sigma_3,$$  \hspace{1cm} (1.2.2)

and

$$\nu = (2\varepsilon_2 - \varepsilon_1 - \varepsilon_3)/\varepsilon_3.$$  \hspace{1cm} (1.2.3)

In addition, the principal shearing stresses,

$$\tau_1 = (\sigma_2 - \sigma_3)/2,$$  \hspace{1cm} (1.2.4a)

$$\tau_2 = (\sigma_3 - \sigma_1)/2,$$  \hspace{1cm} (1.2.4b)

$$\tau_3 = (\sigma_1 - \sigma_2)/2,$$  \hspace{1cm} (1.2.4c)

and the principal shearing strains,

$$\gamma_1 = \varepsilon_2 - \varepsilon_3,$$  \hspace{1cm} (1.2.5a)

$$\gamma_2 = \varepsilon_3 - \varepsilon_1,$$  \hspace{1cm} (1.2.5b)

$$\gamma_3 = \varepsilon_1 - \varepsilon_2.$$  \hspace{1cm} (1.2.5c)
are obtained as the following:

\[ \tau_1 + \tau_2 + \tau_3 = 0, \quad (1.2.6) \]

\[ \gamma_1 + \gamma_2 + \gamma_3 = 0. \quad (1.2.7) \]

By the assumption of constant volume the principal strains are obtained as

\[ \varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0. \quad (1.2.8) \]

Therefore, the equations proposed by Nádai describing the relationship between stresses and plastic strains are

\[ \varepsilon_1 = c[\sigma_1 - (1/2)(\sigma_2 + \sigma_3)], \quad (1.2.9a) \]

\[ \varepsilon_2 = c[\sigma_2 - (1/2)(\sigma_3 + \sigma_1)], \quad (1.2.9b) \]

\[ \varepsilon_3 = c[\sigma_3 - (1/2)(\sigma_1 + \sigma_2)], \quad (1.2.9c) \]

where \( c \) is an arbitrary constant.

Hencky [20] proposed equation similar to Nádai's based on the assumption that the stress deviator is proportional to the strain deviator,

\[ \sigma' = 2G_p \varepsilon', \quad (1.2.10) \]

where

\[ \sigma'_1 = (2\sigma_1 - \sigma_2 - \sigma_3)/3, \quad (1.2.11a) \]

\[ \sigma'_2 = (2\sigma_2 - \sigma_1 - \sigma_3)/3, \quad (1.2.11b) \]
\[ \sigma'_3 = \frac{(2\sigma_3 - \sigma_1 - \sigma_2)}{3}, \quad (1.2.11c) \]

and
\[ \epsilon'' = \frac{(\epsilon_1 + \epsilon_2 + \epsilon_3)}{3}, \quad (1.2.12a) \]
\[ \epsilon'_1 = \epsilon_1 - \epsilon'', \quad (1.2.12b) \]
\[ \epsilon'_2 = \epsilon_2 - \epsilon'', \quad (1.2.12c) \]
\[ \epsilon'_3 = \epsilon_3 - \epsilon'', \quad (1.2.12d) \]

and \( G_p \) is a plastic shear modulus. From equation (1.2.10) and the assumption of constancy of volume, \( \epsilon'' = 0 \) and \( \epsilon' = \epsilon \), Hencky's equation are written as

\[ \epsilon_1 = \frac{1}{E_p}[(\sigma_1 - (1/2)(\sigma_2 + \sigma_3))], \quad (1.2.13a) \]
\[ \epsilon_2 = \frac{1}{E_p}[(\sigma_2 - (1/2)(\sigma_3 + \sigma_1))], \quad (1.2.13b) \]
\[ \epsilon_3 = \frac{1}{E_p}[(\sigma_3 - (1/2)(\sigma_1 + \sigma_2))], \quad (1.2.13c) \]

where \( E_p \) is defined as a plastic modulus equal to the ratio of significant stress, \( \bar{\sigma} \), to significant strain, \( \bar{\epsilon} \). Therefore,

\[ E_p = \frac{\bar{\sigma}}{\bar{\epsilon}}. \quad (1.2.14) \]

In total deformation theories, the stress deviator is proportional to the total plastic strain, such as in the Nádai and Hencky equations. This type of theory is valid for a small plastic strain and when the material is subjected to a proportional loading, but it is not
satisfactory for large deformation. Budiansky [21] showed that when the direction of loading was changed during the test, this type of theory is not considered to be reliable. Therefore, the total deformation theories, which are very simple for small plastic deformation, cannot be used for large plastic strain or to predict the stress-strain behavior under arbitrary loading histories.

1.2.2 Incremental Theories

Incremental theories relating the stress to the incremental plastic strain are more complicated than total deformation theories. Incremental theories, dependent upon loading path, are valid at large plastic strain and can be used to predict the stress-strain behavior under arbitrary loading histories.

It is generally accepted that the true stress in a flow curve is a function of true plastic strain, true plastic strain rate, and temperature,

\[ \sigma = f(\varepsilon, \dot{\varepsilon}, T). \]  \hspace{1cm} (1.2.15)

By taking a partial derivative with respect to time, the incremental constitutive equation

\[ \dot{\sigma} = \dot{\varepsilon}_\sigma \varepsilon + \dot{\sigma}_\sigma + \dot{T} \sigma_T, \]  \hspace{1cm} (1.2.16)
connects the rates of changes of the true stress, \( \sigma \), true plastic strain, \( \varepsilon \), true plastic strain rate \( \dot{\varepsilon} \), and temperature, \( T \). The partial derivatives of the current states considered to be material parameters are the functions of deformation history of the material through its influence on the current structure.

Let \( \gamma = \sigma_\varepsilon / \sigma \), \( m = (\dot{\varepsilon} / \sigma) \sigma_\varepsilon^* \),

then equation (1.2.16) becomes,

\[
\frac{\dot{\sigma}}{\sigma} = \dot{\varepsilon} \gamma + (\ddot{\varepsilon} / \dot{\varepsilon})m + \dot{T}(\sigma_T / \sigma)
\] (1.2.19)

In a particular test condition, uniaxial, isothermal stress-strain behavior at large plastic strain, and constant true strain rate,

\[
\ddot{\varepsilon} = \dot{T} = 0.
\] (1.2.20)

Equation (1.2.19) reduces to

\[
\frac{\dot{\sigma}}{\sigma} = \gamma \dot{\varepsilon}.
\] (1.2.21)

This equation is path dependent, so that it is not possible to write an analytic expression relating stress to
the plastic strain which is valid through the arbitrary loading histories. However, it is possible to measure the relationship between stress and plastic strain through experiment.

As proposed by Hartley and Srinivasan [23], if the coefficients of $\dot{\varepsilon}$, and $\gamma$, in equation (1.2.21) obey one of the two forms:

\[ \gamma \propto (\varepsilon + \varepsilon_0)^{n} \]  

or \[ \gamma \propto \left[ (\sigma_s - \sigma) / \sigma \right] (\varepsilon + \varepsilon_i)^{r} \]

where $\varepsilon_0$, $\varepsilon_i$, $n$, $r$, and $\sigma_s$ are phenomenological parameters from experimental data, then the generalized power law or saturation type equation follow.

Integration of equation (1.2.21), based on the two forms of $\gamma$ in equations (1.2.22) and (1.2.23), yields two general equations:

1. generalized power law

\[ \sigma = \sigma_0 \exp\left\{\left[ (\varepsilon + \varepsilon_0) / \varepsilon^* \right]^{n}\right\} \]  

and

2. saturation type equation

\[ \sigma = \sigma_s - (\sigma_s - \sigma_i) \exp\{ - [ (\varepsilon + \varepsilon_i) / \varepsilon ]^r \} \]
where $\sigma_1$, $\varepsilon^*$ and $\bar{\varepsilon}$ are phenomenological material parameters which depend on initial structure and loading histories. With the same testing process on the same material, the same set of these parameters may characterize the behaviors of material [2].

Application of Considere criterion [22], at the true stress and true plastic strain at maximum load (ultimate tensile strength), $\sigma_m$ and $\varepsilon_m$, gives

$$\gamma = 1, \quad \text{(1.2.26)}$$
or $$\frac{d\sigma}{d\varepsilon} = \sigma, \quad \text{(1.2.27)}$$

permitting the phenomenological parameters of equations (1.2.24) and (1.2.25), $\sigma_0$, $\sigma_1$, $\varepsilon^*$ and $\bar{\varepsilon}$ to be expressed in terms of $\varepsilon_m$ and $\sigma_m$, which are the true plastic strain and true stress at zero loading rate (true ultimate tensile strength). Differentiating equations (1.2.24) and (1.2.25) with respect to $\varepsilon$ and evaluating the derivative at $\sigma_m$ and $\varepsilon_m$ and using the fact that $d\sigma/d\varepsilon=\sigma$ at zero loading rate permits equations (1.2.24) and (1.2.25) to be written [2];

$$\sigma = \sigma_m \exp\left\{\frac{(\varepsilon_m+\varepsilon_0)}{n}\left[\left(\frac{\varepsilon+\varepsilon_0}{\varepsilon_m+\varepsilon_1}\right)^n-1\right]\right\}, \quad \text{(1.2.28)}$$

and

$$\sigma = \sigma_s - (\sigma_s-\sigma_m)\exp\left\{\sigma_m \frac{(\varepsilon+\varepsilon_1)}{(\varepsilon_m+\varepsilon_1)}\right\} \left[1-\left(\frac{\varepsilon+\varepsilon_1}{(\varepsilon_m+\varepsilon_1)^T}\right)\right]. \quad \text{(1.2.29)}$$
The phenomenological material parameters in equations (1.2.24) and (1.2.25) relate to those in equations (1.2.28) and (1.2.29) by

\[ \sigma_0 = \sigma_m \exp\left[\frac{-\left(\varepsilon_m + \varepsilon_0\right)}{n}\right], \quad (1.2.30) \]
\[ (\varepsilon *)^{-n} = \left(\frac{\varepsilon_m + \varepsilon_0}{\sigma_m} \right)^{1-n}/n, \quad (1.2.31) \]
\[ \sigma_i = \sigma_s - (\sigma_s - \sigma_m)\exp\left\{\frac{\sigma_m (\varepsilon_m + \varepsilon_i)}{r(\sigma_s - \sigma_m)}\right\}, \quad (1.2.32) \]
and \[ (\varepsilon ^{-r}) = \frac{[\sigma_m (\varepsilon_m + \varepsilon_i)^{1-r}]}{[r(\sigma_s - \sigma_m)]}. \quad (1.2.33) \]

For metals and alloys, the rate of work-hardening after initial yielding, \(d\sigma/d\varepsilon\), decreases with increasing strain. This condition can be obtained only if \(n\) and \(r\) have values between 0 and 1 (see equation (1.2.22) and (1.2.23)). In the saturation type relation, equation (1.2.29), saturation stress, \(\sigma_s\), must be greater than \(\sigma_m\). This permits the stress-strain curve to approach steady-state as \(\varepsilon\) approaches \(\infty\). In the generalized power law, as \(\varepsilon\) approaches \(\infty\), both \(\sigma\) and \(d\sigma/d\varepsilon\) in equation (1.2.28) approach \(\infty\) (see equations (1.2.22) and (1.2.24)). The minimum in the slope of the stress-strain curve occurs at some particular point, \(\varepsilon_c\),

\[ \varepsilon_c = \left[\frac{(1-n)}{\left(\varepsilon_m + \varepsilon_0\right)^{1-n}}\right]^{1/n} - \varepsilon_0, \quad (1.2.34) \]

where \(d^2\sigma/d\varepsilon^2 = 0\) at \(\varepsilon = \varepsilon_c\). At \(\varepsilon > \varepsilon_c\), \(\sigma_\varepsilon\) increases while
\( \gamma \) continues to decrease. Parameters, \( \epsilon_O \) and \( \epsilon_I \), in equations (1.2.28) and (1.2.29) represent the initial structure of material prior to the tests [3]. Then, \( \epsilon_O \) and \( \epsilon_I \) may vanish for annealed materials.

Several investigators attempted to describe uniaxial stress-strain behavior using several forms of mathematical relationship which are similar to equations (1.2.28) and (1.2.29) [2].

Hartley et al. [4] proposed

\[
\sigma = \sigma_O + K(\epsilon + \epsilon_O)^n, \quad (1.2.35)
\]

where \( \sigma_O \), \( K \), \( \epsilon_O \) and \( n \) are phenomenological material parameters.

By expanding the exponential term of equation (1.2.28) and equating the expansion to equation (1.2.35), neglecting terms of third order and higher in the argument leads to

\[
\exp\left\{\left[\frac{\epsilon + \epsilon_O}{\epsilon_m + \epsilon_O}\right]\frac{\epsilon + \epsilon_O}{\epsilon_m + \epsilon_O}\right\} = 1 + \left[\frac{\epsilon + \epsilon_O}{\epsilon_m + \epsilon_O}\right]^n. \quad (1.2.36)
\]

Then equation (1.2.28) becomes similar to equation (1.2.35)

where \( \sigma_O = \gamma \exp\left[-\frac{\epsilon + \epsilon_O}{\epsilon_m + \epsilon_O}\right], \quad (1.2.37) \)

and \( K = \frac{\sigma_O}{(\epsilon_m + \epsilon_O)^n} \). \quad (1.2.38)
When setting $\varepsilon_o = 0$, equation (1.2.35) reduces to an equation similar to the Ludwik equation [5],

$$\sigma = \sigma_o + Ke^n,$$  \hspace{1cm} (1.2.39)

where $\sigma_o$ in Ludwik equation is the yield stress. Morrison [6] defined $\sigma_o$ in terms of elastic modulus, $E$,

$$\sigma_o = (K/E^n)^{1/(1-n)}.$$  \hspace{1cm} (1.2.40)

The logarithm of equation (1.2.28) is

$$\ln(\sigma/\sigma_m) = (\varepsilon_m + \varepsilon_o) \left[ (\varepsilon_m + \varepsilon_o)^n - 1 \right]/n$$  \hspace{1cm} (1.2.41)

Equation (1.2.30) causes $\sigma_o \to 0$ as $n \to 0$. Applying L'Hospital's rule to the right hand side of equation (1.2.41) when $n \to 0$, in which

$$\lim_{n \to 0} (\varepsilon_m + \varepsilon_o) \left[ (\varepsilon_m + \varepsilon_o)^n - 1 \right]/n$$

$$= \lim_{n \to 0} (\varepsilon_m + \varepsilon_o) \left[ (\varepsilon_m + \varepsilon_o)^n \ln(\varepsilon_m + \varepsilon_o)/(\varepsilon_m + \varepsilon_o) \right]$$

$$= (\varepsilon_m + \varepsilon_o) \ln((\varepsilon_m + \varepsilon_o)/(\varepsilon_m + \varepsilon_o)).$$

Then equation (1.2.41) becomes

$$\ln(\sigma/\sigma_m) = (\varepsilon_m + \varepsilon_o) \ln((\varepsilon_m + \varepsilon_o)/(\varepsilon_m + \varepsilon_o)),$$

or

$$\sigma = \sigma_m \left[ (\varepsilon_m + \varepsilon_o)/(\varepsilon_m + \varepsilon_o) \right]^{(\varepsilon_m + \varepsilon_o)}.$$  \hspace{1cm} (1.2.42)
Equation (1.2.42) is similar to the equation developed by Swift [7],

\[ \varepsilon = \varepsilon_1 + C s^2, \quad (1.2.43) \]

where \[ s = (\varepsilon_m + \varepsilon_o)^{-1}, \quad (1.2.44) \]
\[ \varepsilon_1 = -\varepsilon_o, \quad (1.2.45) \]
and \[ C = s^{-1} \sigma_m - s, \quad (1.2.46) \]

in a previous study to describe the stress-strain relationship.

Hollomon [8] proposed a simple power law relation,

\[ \sigma = K_0 \varepsilon^P, \quad (1.2.47) \]

where \( P \) is a slope from log-log plot of true stress-true plastic strain curve with an intercept of \( K_0 \) at \( \varepsilon = 1 \). Equation (1.2.47) also follows from equation (1.2.42) when setting \( \varepsilon_o = 0 \). The parameters in equation (1.2.47) relate to equation (1.2.42) by

\[ K_o = \sigma_m p^{-p}, \quad (1.2.48) \]
and \[ P = \varepsilon_m. \quad (1.2.49) \]

Deviations from equation (1.2.47) are often observed in a log-log plot at low and high strains giving two straight lines with different slopes.
Voce [9] suggested an equation that led to an asymptotic limit for the flow stress at large plastic strains,

\[
\frac{(\sigma_s - \sigma_o)}{(\sigma_s - \sigma_m)} = \exp\left[-\frac{(\varepsilon - \varepsilon_o)}{\varepsilon_c}\right], \tag{1.2.50}
\]

where \(\sigma_o\) is the measured yield stress, \(\varepsilon_o\) is an arbitrary strain, \(\varepsilon_c\) is a characteristic strain for material and \(\sigma_s\) is a saturation stress. Equation (1.2.50) can be rearranged into

\[
\sigma = \sigma_s - (\sigma_s - \sigma_o)\exp\left[-\frac{(\varepsilon - \varepsilon_o)}{\varepsilon_c}\right]. \tag{1.2.51}
\]

Applying Considéré criterion [8], of \(\gamma=1\) at \(\sigma=\sigma_m\) and \(\varepsilon=\varepsilon_m\) causes equation (1.2.51) to become similar to equation (1.2.29) in which \(\varepsilon_i=0\) and \(r=1\),

\[
\sigma = \sigma_s - (\sigma_s - \sigma_m)\exp\left[-\frac{\sigma_m \varepsilon_m}{(\sigma_s - \sigma_m)}\right]\frac{(\varepsilon/\varepsilon_m - 1)}{\varepsilon_m}. \tag{1.2.52}
\]

Equation (1.2.52) is related to equation (1.2.51) by

\[
\varepsilon_c = (\sigma_s - \sigma_m)/\sigma_m', \tag{1.2.53}
\]

and

\[
\sigma_o = \sigma_s - (\sigma_s - \sigma_m)\exp\left[\sigma_m (\varepsilon_0 + \varepsilon_o)/(\sigma_s - \sigma_m)\right] \tag{1.2.54}
\]

which satisfies Considéré criterion [8].
Kocks [10] expressed equation (1.2.52) in terms of work hardening rate \( \Theta \) at a stress \( \sigma \) as

\[
\Theta = \Theta_0 (1 - \sigma / \sigma_s),
\]

(1.2.55)

where \( \Theta_0 \) is the work hardening rate in the absence of dynamic recovery. The application of equation (1.2.55) to metals, particularly Al, led to saturation of the flow stress.

Hockett and Sherby [11] proposed

\[
\sigma = \sigma_s - (\sigma_s - \sigma_o) \exp(- (N \varepsilon)_P),
\]

(1.2.56)

where \( \sigma_o \) is yield stress, and \( P \) and \( N \) are phenomenological material parameters, to analyze the deformation behavior of \( \alpha \)U and \( \alpha \)Fe at room temperature, explaining a steady-state flow stress \( \sigma_s \) which was approached after extensive strain-hardening. Setting \( \varepsilon_1 = 0 \), equation (1.2.29) is related to equation (1.2.56) by

\[
P = r,
\]

(1.2.57)

\[
N \varepsilon_m = (\sigma_m (1 - r)) / [(\sigma_s - \sigma_m) r],
\]

(1.2.58)

and

\[
\sigma_o = \sigma_s - (\sigma_s - \sigma_m) \exp[\sigma_m \varepsilon_m / r(\sigma_s - \sigma_m)].
\]

(1.2.59)

Additional studies by Miller and Sherby [12], Ghosh [13], Lloyd and Kenny [14, 15] confirmed the validity of
the saturation equation for describing metal deforming at large plastic strain. Hartley and Srinivasan [2] showed that two types of equations, the generalized power law and the saturation type relation, fitted very well to data produced by isothermal, uniaxial testing of Zircaloy-4(R) at a constant total true strain rate at various temperatures. All material from previous studies exhibited $0 < r < 1$ and $0 < n < 1$. The parameters $\varepsilon_0$ and $\varepsilon_1$ depend on the state of internal strain prior to test and vanish for annealed material. Hartley and Srinivasan's experiment concluded that a Voce equation, $r = 1$ and $\varepsilon_1 = 0$, fitted their data better than the exponential form with $\varepsilon_0 = 0$ and $0 < n < 1$. Hartley and Keattipun [unpublished paper], used a nonlinear least-square procedure to fit the data of Hartley et al [23] to the relation described by Hartley [18]. Better fits were obtained. Hartley and Keattipun results showed that the material parameter $r$ has a value varied from 0 to 1 rather than $r$ equal to 1. This work also showed that parameter $n$ of 304-stainless steel has a value between 0 to 1 rather than approaching zero. This work considered $\varepsilon_0 = \varepsilon_1 = 0$ for annealed material. Results from some of the non-linear least-square fitted curve using Hartley method [18] are shown in table 1.2.1-1.2.4 and Fig. 1.2.1-1.2.4. The non-linear least-square fitted curve on saturation type equation has the lowest residual.
Table 1.2.1
Parameters in Generalized Power Law for Annealed 304-Stainless Steel (Data from Hartley et al. [23])

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Strain Rate (/sec)</th>
<th>Power Law $\sigma_m$ (MPa)</th>
<th>$\varepsilon_m$ (MPa)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.01</td>
<td>1181.9</td>
<td>0.571</td>
<td>0.056</td>
</tr>
<tr>
<td>300</td>
<td>0.01</td>
<td>1146.2</td>
<td>0.480</td>
<td>0.169</td>
</tr>
<tr>
<td>300</td>
<td>0.01</td>
<td>1070.7</td>
<td>0.422</td>
<td>0.230</td>
</tr>
<tr>
<td>300</td>
<td>0.05</td>
<td>979.7</td>
<td>0.457</td>
<td>0.064</td>
</tr>
<tr>
<td>485</td>
<td>0.05</td>
<td>632.5</td>
<td>0.319</td>
<td>0.025</td>
</tr>
<tr>
<td>575</td>
<td>0.05</td>
<td>601.0</td>
<td>0.334</td>
<td>0.000</td>
</tr>
<tr>
<td>675</td>
<td>0.05</td>
<td>593.0</td>
<td>0.350</td>
<td>0.000</td>
</tr>
<tr>
<td>775</td>
<td>0.05</td>
<td>509.1</td>
<td>0.327</td>
<td>0.044</td>
</tr>
</tbody>
</table>

Table 1.2.2
Parameters in Saturation Type Equation for Annealed 304-Stainless Steel (Data from Hartley et al. [23])

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Strain Rate (/sec)</th>
<th>Saturation Type Equation $\sigma_s$ (MPa)</th>
<th>$\sigma_m$ (MPa)</th>
<th>$\varepsilon_m$ (MPa)</th>
<th>$x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.01</td>
<td>3996.1</td>
<td>1210.5</td>
<td>0.595</td>
<td>0.858</td>
</tr>
<tr>
<td>300</td>
<td>0.01</td>
<td>2703.2</td>
<td>1219.9</td>
<td>0.545</td>
<td>1.000</td>
</tr>
<tr>
<td>300</td>
<td>0.01</td>
<td>3064.2</td>
<td>1120.5</td>
<td>0.471</td>
<td>0.900</td>
</tr>
<tr>
<td>300</td>
<td>0.05</td>
<td>2173.9</td>
<td>1017.5</td>
<td>0.503</td>
<td>0.995</td>
</tr>
<tr>
<td>485</td>
<td>0.05</td>
<td>1681.8</td>
<td>639.8</td>
<td>0.329</td>
<td>0.510</td>
</tr>
<tr>
<td>575</td>
<td>0.05</td>
<td>1030.8</td>
<td>613.2</td>
<td>0.330</td>
<td>0.596</td>
</tr>
<tr>
<td>675</td>
<td>0.05</td>
<td>1011.6</td>
<td>604.1</td>
<td>0.350</td>
<td>0.733</td>
</tr>
<tr>
<td>775</td>
<td>0.05</td>
<td>975.3</td>
<td>518.9</td>
<td>0.341</td>
<td>0.648</td>
</tr>
</tbody>
</table>
Table 1.2.3
Parameters in Generalized Power Law for Annealed Zircaloy-4 Tested in Tension Parallel to the Rolling Direction (Data from Hartley et al [23])

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Strain Rate (/sec)</th>
<th>Generalized Power Law</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\sigma_m$ (MPa)</td>
</tr>
<tr>
<td>300</td>
<td>0.034</td>
<td>572.7</td>
</tr>
<tr>
<td>485</td>
<td>0.034</td>
<td>368.7</td>
</tr>
<tr>
<td>575</td>
<td>0.034</td>
<td>271.6</td>
</tr>
<tr>
<td>675</td>
<td>0.034</td>
<td>226.6</td>
</tr>
<tr>
<td>775</td>
<td>0.034</td>
<td>191.0</td>
</tr>
<tr>
<td>875</td>
<td>0.034</td>
<td>127.4</td>
</tr>
<tr>
<td>975</td>
<td>0.034</td>
<td>69.3</td>
</tr>
</tbody>
</table>

Table 1.2.4
Parameters in Saturation Type Equation for Annealed Zircaloy-4 Tested in Tension Parallel to the Rolling Direction (Data from Hartley et al [23])

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Strain Rate (/sec)</th>
<th>Saturation Type Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\sigma_s$ (MPa)</td>
</tr>
<tr>
<td>300</td>
<td>0.034</td>
<td>723.7</td>
</tr>
<tr>
<td>485</td>
<td>0.034</td>
<td>526.9</td>
</tr>
<tr>
<td>575</td>
<td>0.034</td>
<td>499.6</td>
</tr>
<tr>
<td>675</td>
<td>0.034</td>
<td>393.5</td>
</tr>
<tr>
<td>775</td>
<td>0.034</td>
<td>278.4</td>
</tr>
<tr>
<td>875</td>
<td>0.034</td>
<td>291.1</td>
</tr>
<tr>
<td>975</td>
<td>0.034</td>
<td>91.6</td>
</tr>
</tbody>
</table>
Fig. 1.2.1 Generalized power law fit to 304 stainless steel tested at room temperature and strain rate 0.01 /sec. (Data from Hartley et al [23])

Fig. 1.2.2 Saturation type equation fit to 304 stainless steel tested at room temperature and strain rate 0.01 /sec. (Data from Hartley et al [23])
Fig. 1.2.3 Generalized power law fit to Zircaloy-4 tested at temperature 575 K and strain rate 0.034 /sec. (Data from Hartley et al [23])

Fig. 1.2.4 Saturation type equation fit to Zircaloy-4 tested at temperature 575 K and strain rate 0.034 /sec. (Data from Hartley et al [23])
1.2.3 Necking and Bridgman Correction

Necking occurs in ductile material by a localized reduction in diameter at maximum load. This is the beginning of plastic instability where the increase in strength due to strain hardening fails to compensate for the decrease in cross-sectional area. The formation of a neck in the tensile specimen introduces a triaxial state of stress in the region. The axis of the specimen at the center of the necked region is subjected to a hydrostatic tension producing radial and transverse stresses along with the axial stress. The value of the axial stress required to cause plastic flow is increased in this situation. The actual stress required to continue plastic flow after necking is smaller than the nominal true stress, i.e., the axial load divided by the instantaneous area at the minimum cross-section.

Bridgman [24] proposed a mathematical method which corrects the measured nominal true stress at necking region to the uniaxial flow stress that would exist without necking effect. This equation is based on the assumptions:

1. the specimen is symmetric on both sides of neck,
2. the outside radius of cross section of neck is circular with radius a,
3. the contour of the neck is approximated by its osculating circle of radius R
4. von Mises plasticity function for yield is applied, and
5. the strains over the cross section are uniform.

Bridgman's equation is,

\[
\text{correction factor} = \frac{1}{1+2R/a}\left[\ln\left(\frac{1+a}{2R}\right)\right]
\]  (1.2.60)

Then the actual uniaxial flow stress is obtained by multiplying two nominal stress by the correction factor.

Siebel [25], in an earlier investigation, presented a method to correct the stress at necking based on different assumption as

\[
\text{correction factor} = \frac{1}{1+a/4R}.
\]  (1.2.61)

The results from Siebel are very close to those given by the Bridgman equation. Table 1.2.5 compares Bridgman correction factor with Siebel's results.

Bridgman also presented an approximate correction factor in term of true plastic strain which is very close for steel. Marshall and Shaw [26] proposed the results from tensile tests on specimens machined to arbitrary values of longitudinal curvature at different stages supported Bridgman approximate correction factor in term of true plastic strain for steel. Fig. 1.2.5 [26] compares Bridgman correction factor and Marshall and Shaw data.
Table 1.2.5 [24,25]
The Correction Factor Results from Bridgman's and Siebel's Equations.

<table>
<thead>
<tr>
<th>a/R</th>
<th>Bridgman's correction factor</th>
<th>Siebel's correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>0.2</td>
<td>0.954</td>
<td>0.952</td>
</tr>
<tr>
<td>0.4</td>
<td>0.914</td>
<td>0.909</td>
</tr>
<tr>
<td>0.6</td>
<td>0.880</td>
<td>0.870</td>
</tr>
<tr>
<td>0.8</td>
<td>0.849</td>
<td>0.833</td>
</tr>
<tr>
<td>1.0</td>
<td>0.822</td>
<td>0.800</td>
</tr>
<tr>
<td>1.4</td>
<td>0.776</td>
<td>0.741</td>
</tr>
<tr>
<td>1.8</td>
<td>0.738</td>
<td>0.690</td>
</tr>
<tr>
<td>2.2</td>
<td>0.706</td>
<td>0.645</td>
</tr>
<tr>
<td>3.0</td>
<td>0.655</td>
<td>0.571</td>
</tr>
<tr>
<td>4.0</td>
<td>0.607</td>
<td>0.500</td>
</tr>
</tbody>
</table>

Fig. 1.2.5 The relationship between Bridgman correction factor and Marshall and Shaw results [26].
Eisenberg and Yen [27] using physical approximations proposed a mathematical method to correct the stress at necking in anisotropic bars based on the assumption:

1. the specimen is initially axial symmetric,
2. the loading path in deviatoric stress space is radial,
3. elastic strains are negligible,
4. anisotropy ratio is independent of time and position,
5. $\sigma_1 \approx \sigma_x$, $\sigma_2 \approx \sigma_y$, and $\sigma_3 \approx \sigma_z$ where $\sigma_1$, $\sigma_2$, and $\sigma_3$ are principal stresses, $\sigma_x$, $\sigma_y$, and $\sigma_z$ are stresses in x, y, and z (tensile direction) axes,
6. the direction of principal stress $\sigma_3$ is orthogonal to the ellipsoidal shape of the anisotropic neck.

The anisotropic solution is not entirely satisfactory but the isotropic solution is rigorously satisfied and be written in the general form

$$\tilde{\sigma}_z/Y = (1-K/2) + (K/2)[1+K(R/a)]ln[1+a/KR] \quad (1.2.62)$$

where $\tilde{\sigma}_z/Y$ is the inverse of Bridgman correction factor, constraint factor, K is a function of the assumed geometry of the principal stress surfaces which is equal to 1 in results presented by Eisenberg and Yen [27] results, a and R are the current cross-sectional radius of neck and the
specimen profile radius of curvature respectively. Bridgman's [24] results correspond to K=2 and Davidenkov and Spiridonova [28] results correspond to K -> ∞ in equation (1.2.62). Fig. 1.2.6 compares Eisenberg and Yen [27] results to Bridgman [24] results and Davidenkov and Spiridonova [28] results.

1.3 QUANTITATIVE METALLOGRAPHY

1.3.1 Grain Morphology

Grain shape can be described as a geometrical description such as sphere or ellipsoid or in terms of the property changed index. Desch [29] described grain shape as pentagonal dodecahedrons with curved faces and edges. Thompson [30] proposed that grain shape should be tetrakaidecahedron shape, 14 faces, 8 hexagonal, and 6 quadrilateral. William [31] suggested the shape of grain as β-tetrakaidecahedron which is a modification of Thompson. Patterson [32] reported that the numbers of edges and faces of grain are proportional to its volume which is similar to previous work shown by William and Smith [33]. Underwood [34] indicated the shape of grain lay between pentagonal dodecahedrons and β-tetrakaidecahedron. In the quantitative
Fig. 1.2.6 Corrections for triaxiality of stresses due to necking [27]
microscopy grains are considered to have one size and shape. This shape can be spherical, equiaxed, or cubic for an isotropic structure [35,36], and ellipsoid, nonequiaxed, or rectangular parallelepiped [37,38] for an anisotropic structure, or as recently developed by Patterson and DeHoff [39], a tetrakaidecahedron, for an anisotropic structure. For any shape as described above, with the assumption that the relative change in length is the same as change in the bulk piece [40], so it is possible for mathematical calculation to describe the behavior of deformation.

1.3.2 Measurement Techniques

Quantitative stereology deals with the quantitative relations between measurements made on two-dimensional sections through a three-dimensional structures, or micrographs, and the three-dimensional microstructural features. There are several techniques for measuring micrographs, but any technique can be possibly used to accomplish the desired accuracy [41].

Point-count method [34] is a method that refers to the numbers of test points that fall in the selected area of microstructure. For example, Fig. 1.3.1 [42], a test grid which consists of a uniform array of points is placed in a random position on a micrograph containing some α-phase. The numbers of points, $P_a$, that fall in the α-phase, divided
by the number of points used, $P_T$, gives the average fraction of points falling on the $\alpha$-phase, $P_P$. 

Lineal analysis [34] is an alternative method to point counting. A series of test lines are placed over the structures as shown in Fig.1.3.2 [43], and the fractional length of line within the $\alpha$-phase, $L_L$, is recorded.

The other method [44] refers to the points per unit area. By placing testing area randomly over the microstructures, the grain junctions, triple points, within the area are counted. The number of points divided by total area gives points per unit area, $P_A$. Fig.1.3.3 [45] illustrates this technique.

Chalkley [46] proposed a method to determine the surface-to-volume ratio of discrete particles. Short test lines of length $L$ are placed randomly on microstructures as shown in Fig.1.3.4 [47]. Two types of points are counted, the intersection of boundaries with test lines, $P$, and the free ends of lines in the $\alpha$-phase, $h$. The ratio of the mean particle surface area to the mean particle volume, $S_{\alpha}/V_{\alpha}$, is $4P/hL$.

Saltykov [48] obtained the $S_{\alpha}/V_{\alpha}$ ratio for discrete particles, such as $\alpha$-phase, in a two phase structure by placing a square grid on a micrograph as shown in Fig.1.3.5 [34]. The $S_{\alpha}/V_{\alpha}$ ratio is $2P_L/P_h$.

Another method [49] determines the number of spatial objects per unit area, $N_A$. A test area is placed on the
microstructure as shown in Fig. 1.3.6 [45]. The total numbers of grains, \( N_T \), are equal to the number of grains, \( N_W \), completely within the test area plus one-half of the number intercepted by the border, \( N_i \).

\[
N_T = N_W + (1/2)N_i \tag{1.3.1}
\]

Therefore the number of grains per unit area, \( N_A \),

\[
N_A = \frac{N_T}{A}, \tag{1.3.2}
\]

where \( A \) is the test area.

Two other important quantities are the mean grain intercept length or the mean linear intercept, \( \lambda \), and the number of intersections of grain boundaries per unit length of test line, \( N_L \), [34, 41]. The mean grain intercept length is obtained by placing a series of test lines on microstructure. The average distance between the intercepts at grain boundaries is \( \lambda \). To determine the number of intersections of grain boundaries per unit length of test line, a test line of length, \( L \), is applied randomly to a microstructure. The points of intersection made by the test lines and grain boundaries, \( N \), are counted. The total numbers of intersections divided by total length of test lines give the numbers of intersections of grain boundaries per unit length of test line, \( N_L \), in terms of number of
intersections per unit length as shown in Fig. 1.3.7 [34,44]. For isotropic or equiaxed structure, the test line can also be circle as shown in Fig. 1.3.8 [34,44]. This technique can be applied to objects, such as particles, instead of grain boundaries. When this technique is applied to particles, \( N_L \) is only one-half of total numbers of intersections divided by total length. These last two methods are frequently employed in quantitative stereology.

1.3.3 Basic Equation

In numerous publications [34,42,48], basic equations are concerned with points, lines, surfaces, and volumes in microstructure

\[
V_V = A_A = L_L = P_P \quad (1.3.3)
\]

\[
S_V = \left(\frac{4}{\pi}\right)L_A = 2P_L \quad (1.3.4)
\]

\[
L_V = 2P_A \quad (1.3.5)
\]

\[
P_V = \left(\frac{1}{2}\right)L_V S_V = 2P_A P_L \quad (1.3.6)
\]

\( P_P \) and \( L_L \) are defined by using point-count and lineal analysis techniques as described above. \( A_A \) is defined by using areal analysis [34]. \( L_A \) is determined by counting the numbers of intersections of a test line with the lineal element in a given area [34] and multiplied with \( \pi/2 \). \( P_L \) is equal to \( N_L \) as described by the last method. \( P_A \) is defined
as described previously. Table 1.3.1 and 1.3.2 [34] show a list of basic symbols and their relationship.

Equation (1.3.3) states the equality of volume fraction to the areal ratio, linear ratio, and point ratio of the selected feature, such as α-phase, in the microstructures. Equation (1.3.4) gives the surface area of some feature per unit volume in terms of the number of intersections of grain boundaries per unit length of test line or from the length of lineal features per unit area. This equation can be used to calculate the length of lineal features per unit area from the numbers of intersections of grain boundaries per unit length of test line or in the other way when one is not available. Equation (1.3.5) calculates the length of lineal features per unit volume from number of points per unit area, while equation (1.3.6) relates numbers of points per unit volume to the multiple product of equations (1.3.4) and (1.3.5).

1.3.4 Oriented Structures

Oriented (anisotropic) structures often occur in the nature. In these structures, large differences in the values of certain stereological parameters can be obtained from measurements made in different directions. Techniques similar to those described previously in section 1.3.2 can be applied to oriented structures. For example, \( N_L \) or \( P_A \) can be measured by keeping the test line or the test plane
Table 1.3.1 [34]
List of Symbols Used in Basic Equation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_P$</td>
<td>$m^0$</td>
<td>Number of points in areal features per test point</td>
</tr>
<tr>
<td>$P_L$</td>
<td>$m^{-1}$</td>
<td>Number of points intersecting unit length of test line</td>
</tr>
<tr>
<td>$P_A$</td>
<td>$m^{-2}$</td>
<td>Number of points per unit test area</td>
</tr>
<tr>
<td>$P_V$</td>
<td>$m^{-3}$</td>
<td>Number of points per unit test volume</td>
</tr>
<tr>
<td>$L_L$</td>
<td>$m/m$</td>
<td>Length of lineal intercepts per unit length of test line</td>
</tr>
<tr>
<td>$L_A$</td>
<td>$m/m^2$</td>
<td>Length of lineal elements per unit test area</td>
</tr>
<tr>
<td>$L_V$</td>
<td>$m/m^3$</td>
<td>Length of lineal elements per unit test volume</td>
</tr>
<tr>
<td>$A_A$</td>
<td>$m^2/m^2$</td>
<td>Area of intercepted features per unit test area</td>
</tr>
<tr>
<td>$S_V$</td>
<td>$m^2/m^3$</td>
<td>Surface area per unit test volume</td>
</tr>
<tr>
<td>$V_V$</td>
<td>$m^3/m^3$</td>
<td>Volume of features per unit test volume</td>
</tr>
<tr>
<td>$N_L$</td>
<td>$m^{-1}$</td>
<td>This is equivalent to $P_L$, number of segments of test line that lie in the features per unit length of test line.</td>
</tr>
</tbody>
</table>

Table 1.3.2 [34]
Relationship of Measured (〇) to Calculated (□) Quantities

<table>
<thead>
<tr>
<th>Microstructural Feature</th>
<th>$m^0$</th>
<th>$m^{-1}$</th>
<th>$m^{-2}$</th>
<th>$m^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points</td>
<td>$P_P$</td>
<td>$P_L$</td>
<td>$P_A$</td>
<td>$P_V$</td>
</tr>
<tr>
<td>Lines</td>
<td>$L_L$</td>
<td>$L_A$</td>
<td>$L_V$</td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>$A_A$</td>
<td>$S_V$</td>
<td>$V_V$</td>
<td></td>
</tr>
<tr>
<td>Volumes</td>
<td>$V_V$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1.3.1 Typical point-count grid with the intersections referred to the test points for determining area fraction of $\alpha$-phase [42]

Fig. 1.3.2 Typical test line placed on the microstructure intersecting $\alpha$-phase boundaries [43]
Fig. 1.3.3 Typical circular test line placed on single-phase for determining the number of triple points per unit area [45]

Fig. 1.3.4 Chalkley method for determining the surface-to-volume ratio of α-particle [47]
Fig. 1.3.5 Saltykov method for determining the surface-to-volume ratio of α-particle [34]

Fig. 1.3.6 The method for determining the number of grains per unit area [34]
Fig. 1.3.7 Random test line of length $L$ for determining the numbers of intersections of grain boundaries per unit length of test line $N_L$ for an isotropic structure [34, 41]

Fig. 1.3.8 Circular test grid for determining $N_L$ for an isotropic structure [34, 44]
in one particular direction such as transverse or longitudinal.

The relations between $\tilde{N}_L$ and $S_V$ and between $\tilde{P}_A$ and $L_V$ can be written as [44]

$$\tilde{N}_L(\theta, \phi) = S_V(\theta, \phi)_{\text{proj}}, \quad (1.3.7)$$
$$\tilde{P}_A(\theta, \phi) = L_V(\theta, \phi)_{\text{proj}}, \quad (1.3.8)$$

where $\theta$ and $\phi$ are the two angles of spherical coordinates defined relative to some system of axes; $\tilde{N}_L(\theta, \phi)$ and $\tilde{P}_A(\theta, \phi)$ are the average values of $N_L$ and $P_A$ measured in particular orientation; and $S_V(\theta, \phi)_{\text{proj}}$ and $L_V(\theta, \phi)_{\text{proj}}$ are the grain boundaries area per unit volume projected on a plane normal to the test line and the total length of edges in the structure projected onto a line normal to the test planes.

Oriented systems can be divided into two types: partially oriented and completely oriented. There are three types of partially oriented system: line in a plane, line in space, and surface in space [34].

Saltykov [34, 44, 50] developed a simple technique called "the rose of the number of the intersections" to describe the anisotropy of the structure. Test lines are placed on the structure making known angles with a particular orientation axis. The number of intersections of the oriented feature with the test line, $\tilde{N}_L$ is determined for each angle $\theta$, and the plot of $\tilde{N}_L$ versus $\theta$ is defined as
the rose of the number of intersections. Fig. 1.3.9 [34,44] illustrates the rose for some typical oriented structures.

DeHoff and Rhines [34,44] present equations which define the degrees of orientation,

\[ W = \frac{(L_A)_{or}}{(L_A)_{tot}}, \]  
\[ (L_A)_{ran} = 1.571 \frac{N_L^\perp}{N_L}, \]  
\[ (L_A)_{or} = \frac{N_L^\perp - N_L^\parallel}{N_L}, \]  
\[ (L_A)_{tot} = N_L^\perp + 0.571(N_L^\parallel), \]  

where the equations refer to the random (ran) and oriented (or) portions of the test lines, and to the total (tot) length per unit area. \((N_L^\perp)\) and \((N_L^\parallel)\) are measured with test lines perpendicular and parallel to the orientation direction, respectively. If it is completely oriented, \((N_L^\parallel)\) will be zero and \((L_A)_{tot} = (N_L^\perp) = (L_A)_{or}\). Therefore \(W = 1\).

For line in a space, the equations are [34,44]:

\[ (L_v)_{ran} = 2(P_A^\parallel), \]  
\[ (L_v)_{or} = (P_A^\perp) - (P_A^\parallel), \]  
\[ (L_v)_{tot} = (P_A^\perp) + (P_A^\parallel), \]  

where \((P_A^\perp)\) and \((P_A^\parallel)\) refer to the measurements of point density, as described previously, on planes perpendicular and parallel to the orientation, respectively.
For surface in a space, the equations are [34]:

\[
\begin{align*}
(S_V)_{\text{ran}} &= 2(\bar{P}_L) ||, \quad (1.3.16) \\
(S_V)_{\text{or}} &= (\bar{P}_L) \perp - (\bar{P}_L) ||, \quad (1.3.17) \\
(S_V)_{\text{tot}} &= (\bar{P}_L) \perp + (\bar{P}_L) ||, \quad (1.3.18)
\end{align*}
\]

where \((\bar{P}_L)\perp\) and \((\bar{P}_L)\parallel\) refer to \((\bar{N}_L)\perp\) and \((\bar{N}_L)\parallel\) which are measured, as described previously, with test lines perpendicular and parallel to the orientation direction, respectively.

Saltykov [34,44,50] classified the microstructures into four idealized types, isotropic, linear, planar, and planar-linear structures as shown in Fig.1.3.10 [44]. The planar-linear structure is composed of three types of surface elements [50], isometric, linear, and planar elements. Therefore, the equations defining the amount of surface area for each type are:

\[
\begin{align*}
(S_V)_{\text{ran}} &= 2(\bar{N}_L) ||, \quad (1.3.19) \\
(S_V)_{\text{lin}} &= 1.571[(\bar{N}_L) \perp - (\bar{N}_L) ||], \quad (1.3.20) \\
(S_V)_{\text{pl}} &= (\bar{N}_L) \perp - (\bar{N}_L) ||, \quad (1.3.21) \\
(S_V)_{\text{tot}} &= (S_V)_{\text{ran}} + (S_V)_{\text{lin}} + (S_V)_{\text{pl}}, \quad (1.3.22) \\
(S_V)_{\text{pl-lin}} &= (S_V)_{\text{lin}} + (S_V)_{\text{pl}}, \quad (1.3.23)
\end{align*}
\]

where \((\bar{N}_L)\perp\) is a measurement on transverse analysis plane with test lines perpendicular to orientation axis and
Fig. 1.3.9 Illustrated the rose of the number of intersections for each particular orientation [34, 44].
Fig. 1.3.10 Saltykov classification of the microstructure [44].
parallel to orientation plane, \( (\bar{N}_L)_{||} \) is measured on longitudinal analysis plane with test lines parallel to orientation plane, and \( (\bar{N}_L)_{\perp} \) is a measurement on longitudinal or transverse plane with test line perpendicular to orientation plane. The equations refer to linear (lin), planar (pl), and planar-linear (pl-lin). The degree of orientation of surfaces, \( W^S \), can be expressed as a fraction,

\[
\begin{align*}
W^S_{pl} &= \frac{(S_V)_{pl}}{(S_V)_{tot}} \quad (1.3.24) \\
W^S_{lin} &= \frac{(S_V)_{lin}}{(S_V)_{tot}} \quad (1.3.25) \\
W^S_{pl-lin} &= \frac{(S_V)_{pl-lin}}{(S_V)_{tot}} \quad (1.3.26)
\end{align*}
\]

Instead of using degree of orientation, \( W \), the elongation ratio, \( Q \), can be defined as

\[
Q = \frac{(\bar{N}_L)_{\perp}}{(\bar{N}_L)_{||}} \quad (1.3.27)
\]

where \( Q \) is related to \( W \)

\[
Q = \frac{(1+0.571W)}{(1-W)} \quad (1.3.28)
\]

1.3.5 Previous Studies in Grain Strain

Rachinger [51] studied aluminum grains deformed in tension to determine relationship between bulk strain and
average grain strain. The average length of the grains, L, and the average width of the grains, B, referred to tensile-stress direction, is measured with linear-traverse method, by taking longitudinal and transverse counts on samples sectioned to half thickness. Assuming an initial value of unity for L/B (equiaxed grains), homogeneous deformation and ellipsoidal deformed grain shape, and accounting for the difference between average grain strain and bulk strain by grain boundary sliding, the slip strain, $\varepsilon_{s}$, is equal to $(L/B)^{2/3} - 1$. The experimental results showed that there is no grain boundary sliding at room temperature or at high strain rate with increased temperature. However, the deformation at low strain rate at temperatures over 200°C was due to two factors, a change in shape of each individual grain and a relative movement of a grain as a whole past its neighbors (i.e. grain boundary sliding). In a recent experiment, however, Ellis [52] had found no evidence of grain boundary sliding on the deformation of single phase fcc, bcc, and hcp metals at temperature below recrystallization temperatures.

Hensler and Gifkins [53] used a method that was similar to Rachinger's method to find the amount of interior strain due to intragranular slip during creep experiment. Instead of using linear-traverse method, the maximum length and width of each individual grain were measured from the micrograph of sample areas in the sectioned specimens. The
average length, $L$, average width, $B$, and the average $L/B$ from individual measure were used to calculate the slip strain, $E_s$. This technique was claimed to be more accurate than Rachinger's original work.

Flinn and Philofsky [54] proposed a new method for measuring the strain distribution across the interior of a specimen based on an analysis described by Philofsky and Hilliard [55]. This measurement involved the evaluation of the change in grain boundary shape as seen on a plane of polish before and after deformation. With an assumption that the grains were approximately elliptical in shape, the change in the ratio of minor axis to major axis ($b/a$) was sufficient to characterize the strain. $(\bar{P}_L ||)$ and $(\bar{P}_L \perp)$ were determined from measurements of the number of intersections per unit length that grain boundaries made with straight lines placed parallel to the major and minor axes, respectively. The $a_0$ and $a_2$ coefficients of the orientation distribution [54] were determined from equations:

$$a_0 = (1/2)[(\bar{P}_L \perp) + (\bar{P}_L ||)]$$  \hspace{1cm} (1.3.29)
$$a_2 = (3/4)[(\bar{P}_L \perp) - (\bar{P}_L ||)]$$  \hspace{1cm} (1.3.30)

The $(b/a)$ ratios on the transverse planes or the $(a/c)$ ratios on the longitudinal planes were related to $(a_2/a_0)$ by
the following equation, i.e. the relationship of \( \frac{a_2}{a_0} \) and \( \frac{b}{a} \),

\[
\frac{a_2}{a_0} = \frac{\int_0^\pi \cos(2\phi)(1-[1-(b/a)^2]\sin^2\phi)^{-3/2} \, d\phi}{\int_0^\pi \{1-[1-(b/a)^2]\sin^2\phi\}^{-3/2} \, d\phi}
\]

(1.3.32)

The actual lengths of the axes \( a, b, \) and \( c \) were evaluated by ratio to \( b \) and the following equation,

\[
b = \frac{16a^2a_0}{\int_0^{\pi/2} \{1-[1-(b/a)^2]\}\{1-[1-(b/a)^2]\sin^2\phi\}^{-3/2} \, d\phi}.
\]

(1.3.33)

This procedure was used to measure the strain across the walls of hollow drawn Monel tubes. The grain shapes were determined along radial \(|a|\), hoop \(|b|\), and longitudinal \(|c|\) directions. The following relations were used for the grain strains,

\[
\begin{align*}
\varepsilon_r &= \frac{a}{a_0} \quad \text{(radial),} \quad \text{(1.3.33)} \\
\varepsilon_\theta &= \frac{b}{b_0} \quad \text{(hoop),} \quad \text{(1.3.34)} \\
\varepsilon_z &= \frac{c}{c_0} \quad \text{(elongation),} \quad \text{(1.3.35)}
\end{align*}
\]

where \( a_0, b_0, \) and \( c_0 \) were the grain dimensions from undeformed specimens. The results showed that the anisotropy increased with reduction of the tube wall. The
strain varied across the tube wall in all three principal directions. Grain strains were usually larger when compared to the bulk strain.

Hartley and Unal [16,56] suggested that the grain strain could be described by the logarithm of the average number of intercepts per unit length on test lines before and after deformation, measured along principal directions. In the recent work, Hartley and Unal [16,56] indicated that the above definition of grain strain correlated well with bulk strain for the necked region of a round bar subjected to uniaxial tensile deformation. This correlation is based on the following assumptions:

1. deformation occurs at constant volume,
2. the number of grains per unit volume or the generic shape of grains does not change,
3. the principal axes of symmetry for the deformed network develop parallel to the principal directions characterizing bulk deformation.

In general, the principal bulk total true strain can be defined as

$$\varepsilon_i = \ln\left(\frac{d_i^f}{d_i^o}\right) \quad i = 1, 2, 3 \quad (1.3.36)$$

where $d_i^f$ is the dimension after deformation, and $d_i^o$ is the dimension before deformation.

From the assumption of constant volume, therefore
\[ \epsilon_1 + \epsilon_2 + \epsilon_3 = 0. \]  

(1.3.37)

Since, the numbers of intersections of grain boundaries per unit length of test line are equal to the grain boundary area per unit volume projected on a plane normal to the test line on the oriented structure,

\[ \tilde{N}_L = S_v, \]  

(1.3.38)

and \[ S_v = S/V, \]  

(1.3.39)

where \( S \) is the total grain boundary area projected on a plane normal to the test line. Also

\[ V = AL, \]  

(1.3.40)

where \( A \) is the cross-sectional area normal to the axis of symmetry, and \( L \) is the length of the specimen measured along the axis of symmetry.

Therefore,

\[
\frac{\text{d}s}{\text{d}L} = \frac{\text{d}(S_vV)}{\text{d}L} = A S_v = A \tilde{N}_L
\]

(1.3.41)

At two states, initial \( o \) and final \( f \),
\[ A_0 \tilde{N}_L^O = A_f \tilde{N}_L^f, \quad (1.3.42) \]

then

\[
\ln(\tilde{N}_L^O/\tilde{N}_L^f) = \ln(A_f/A_0) = -\ln(L_f/L_0) = -\varepsilon_a. \quad (1.3.43)
\]

Since, in a radial direction, \( r \) \([44], \)

\[ \tilde{N}_L = \lambda_r^{-1}, \quad (1.3.44) \]

where \( \lambda_r \) is the mean linear intercept in the radial direction.

Then

\[
\varepsilon_r = \ln(\tilde{N}_L^O/\tilde{N}_L^f) = \ln(\lambda_r^{-f}/\lambda_r^{-o}) \quad (1.3.45)
\]

In an axial direction, \( \varepsilon_a \) can be solved the same as in equation (1.3.45),

\[
\varepsilon_a = \ln(\tilde{N}_a^f/\tilde{N}_a^o). \quad (1.3.46)
\]

For axial symmetry \([41,52], \)

\[
\tilde{N}_L^O (\tilde{N}_L^O)^2 = \tilde{N}_L^f (\tilde{N}_L^f)^2, \quad (1.3.47)
\]
and \( \tilde{N}_{La}^0 = \tilde{N}_{Lr}^0 = \tilde{N}_L^0 \) \( (1.3.48) \)

then

\[ 3 \ln(\tilde{N}_L^0) = \ln(\tilde{N}_{La}^f) + 2 \ln(\tilde{N}_{Lr}^f), \]

or

\[ \ln(\tilde{N}_{La}^f / \tilde{N}_L^0) + 2 \ln(\tilde{N}_{Lr}^f / \tilde{N}_L^0) = 0. \] \( (1.3.50) \)

Therefore,

\[ \varepsilon_a^g + 2 \varepsilon_r^g = 0 \] \( (1.3.51) \)

which corresponds to the vanishing of the sum of principal bulk strains due to conservation of volume.

The relationship between bulk strain and grain strain were found to be

\[ \varepsilon_r^g = \ln(\tilde{N}_L^0 / \tilde{N}_{Lr}^0) = -\varepsilon_a, \]

\[ \varepsilon_a^g = \ln(\tilde{N}_{La}^f / \tilde{N}_{Lr}^f) = 2\varepsilon_a. \] \( (1.3.52, 1.3.53) \)

Hartley and Unal's experimental results \( [16] \) had included the bulk strain at which deformation became relatively uniform throughout the effective gauge section, \( \varepsilon_a^u \). Therefore, in this case, the equations \( (1.3.52 \) and \( 1.3.53) \) become;

\[ \ln(\tilde{N}_{Lr}^f / \tilde{N}_L^0) = \varepsilon_a - \varepsilon_a^u, \] \( (1.3.52) \)

\[ \ln(\tilde{N}_{La}^f / \tilde{N}_L^0) = -2(\varepsilon_a - \varepsilon_a^u). \] \( (1.3.53) \)
So, the results from Hartley and Unal's experiment [16] showed that the definition of grain strain, defined by the stereometric measurements on the grain boundary network, is related to the bulk strain.

1.4 STATEMENT OF THE PROBLEM

It is generally known that the flow curve for a given material is affected by temperature, strain rate, and grain-size [1,2,57-63]. But none of the previous attempts [1-15,57-63] had included the effects of strain rate and grain size in the constitutive equation. This experiment will explore the relationship between the material parameters of the flow curve at large plastic strain and the strain rate, and also the relationship between the material parameters of the flow curve at large plastic strain and grain-size. The relationship between bulk strain and grain boundaries network also be considered and included into the studied of material parameters as described above. In this experiment, three types of materials were selected; electrical grade iron, ferritic stainless steel, and austenitic stainless steel. Each type of materials were cold-worked and followed with annealing at appropriated temperature to receive different grain sizes. The optical closed loop testing system was modified to permit a constant true strain rate test. Isothermal uniaxial tensile tests were conducted at different constant true strain rate on
each set of materials of the same type and the same grain size. With the limit of new optical closed loop testing system and the available of cold-worked machine, only three grain sizes and three constant true strain rate (0.05, 0.08, and 0.12 /sec) were used in this study. Each set of data from the same material, grain size, and strain rate were fitted by using nonlinear least-square analysis to receive the material parameters for the constitutive equation. The relationship between microstructure in deformed region and bulk strain were studied. The variation of material parameters with grain size and strain rate will be determined. This study included the effects of microstructure in deformed region with the constitutive equation.
2.1 INTRODUCTION

In order to reduce the complexity of the general form of an incremental constitutive equation as described in the previous chapter, testing at constant temperature and true strain rate is required. Two testing methods, open-loop and closed-loop, are generally employed to conduct constant true strain rate testing.

2.1.1 Open-loop Testing Systems

Open-loop testing systems [64-66] require that the entire gauge section is the deforming volume through the entire test. Therefore, neglecting elastic effects,

\[ A_0 L_0 = A_1 L_1, \]  

(2.1.1)

where \( A_0 \) and \( L_0 \) are the original cross-sectional area and length, \( A_1 \) and \( L_1 \) are the instantaneous cross-sectional area and length. At any instant, the true plastic strain in the axial direction, \( \varepsilon_1 \), is defined as

\[ \varepsilon_1 = \ln \left( \frac{L_1}{L_0} \right). \]  

(2.1.2)
Differentiation of equation (2.1.2) with respect to time gives the true axial strain rate, $\dot{\varepsilon}$, proportional to the deformation velocity, $\dot{L}_i$.

$$\dot{\varepsilon} = \frac{\dot{L}_i}{L_i}. \quad (2.1.3)$$

The true strain rate will be constant if the deformation velocity is given by

$$\dot{L}_i = \dot{\varepsilon} L_i$$
$$= \dot{\varepsilon} L_o \exp(\varepsilon)$$
$$= V_o \exp(\dot{\varepsilon} t) \quad (2.1.4)$$

Where $V_o = \dot{\varepsilon} L_o$ is the initial deformation velocity. This method is possible for uniform deformation before necking occurs. After necking occurs, the deforming volume is no longer the entire gauge section and equation 2.1.4 fails to produce a constant true strain rate. Therefore, in the testing involving large plastic deformation, this method is never satisfactory.

2.1.2 Closed-loop Testing Systems

Closed-loop testing systems can provide constant true strain rate throughout the entire test [1,17,67-69]. The deformation velocity is controlled by the instantaneous cross-sectional area of the deforming region. These systems
are not dependent on the length of the deforming region. From the definition of true strain,

\[ \varepsilon = \ln \left( \frac{L_i}{L_0} \right) = \ln \left( \frac{A_o}{A_i} \right) \]  \hspace{1cm} (2.1.5)

or \[ \dot{\varepsilon} = -\frac{\dot{A}_i}{A_i}. \] \hspace{1cm} (2.1.6)

When \( \dot{\varepsilon} \) is constant, then the integration of equation (2.1.6) becomes

\[ -\dot{\varepsilon} t = \ln \left( \frac{A_i}{A_o} \right) \]

or for a circular cross-section,

\[ D_i = D_o \exp \left( -\frac{\dot{\varepsilon} t}{2} \right), \] \hspace{1cm} (2.1.7)

where \( D_i \) and \( D_o \) are the instantaneous and the initial diameters, respectively. Systems which control the deformation velocity in order to maintain equation (2.1.7) have been described by several previous investigators [1,17,67-69]. MacGregor and Fisher [67] manually controlled the hydraulic testing machine to maintain constant true strain rate by using a dial gauge and a special clamp. Bartholomew et al [68], used a feedback signal from an optical sensing element controlled the strain rate. G'Sell and Jonas [69] used a feedback signal provided by the change
in length of a wire looped around the minimum section to control the strain rate.

Hartley and Jenkins [1] maintained the center of the specimen at a fixed location during a uniaxial tensile test with a special centering device and used an optical scanning device to read the instantaneous minimum cross-sectional diameter of the specimen. A desired diameter, as described by equation (2.1.7), was generated by a special analog device, diameter function generator. This system was controlled by a feedback signal generated by comparing the actual diameter with the desired diameter.

In a recent work, Hartley [17] improved the optical scanning device to eliminate the necessity for using a special centering device [1] and the requirement of a silhouetted specimen. The new improvements were:

1. increase in scanned length due to a larger aperture,
2. replacing Schottky barrier photodiode covered by a slit with a linear array of CCD diode (2048).

In this study, a similar system to Hartley and Jenkins [1] was modified by replacing the diameter function generator with computer controlling program and introducing a new optical scanning device described by Hartley [17] into the system.
2.2 EQUIPMENT

2.2.1 General System

A schematic diagram of the closed-loop testing system at constant true strain rate is shown in Fig. 2.2.1. The uniaxial tensile testing machine used in this study was the MTS Model 312.31 of 50,000 lbs maximum capacity, equipped with 304 stainless steel grips as shown in Fig. 2.2.2. Specimens were prepared according to ASTM A370 as shown in Fig. 2.2.3. The image of the gauge section was scanned past a fixed, 2048 element array of diodes, producing a series digital signals proportional to the diameter of sections normal to the tensile axis. The instantaneous minimum diameter of the cross sectional area selected from the diameters scanned and compared to the desired specimen diameter calculated from equation (2.1.7). A computer program calculated the desired displacement for the next step and sent the command signal through a 12 bit digital-to-analog converter board (D/A) ICS Model AI016 to the actuator ram. A Linear Variable Differential Transformer (LVDT) measured the instantaneous ram position, and the servo control adjusted the ram position to conform to the command signal. Diagrams of special circuits constructed for this system are given in Appendix A.
Fig. 2.2.1 Schematic diagram of closed loop tensile testing system.
Fig. 2.2.2 Grips used in tensile testing system.
Fig. 2.2.3 Specimen geometry used in tensile testing at constant true strain rate.
2.2.2 Optical Scanning Device

The optical scanning device described by Hartley [17] is shown in Fig. 2.2.4. A stepwise scan mirror scanned up and down through the 1/2 length gauge section of the specimen. For each scan, the stepwise scan mirror was stopped for a number of times, 30 times in this typical test, to permit 2048 element linear image sensor Fairchild charge coupled device Model CCD 142 to scan through the diameter. The charge coupled device (CCD) in this present system provided a scanning frequency of 0.5-2 MHz (1 MHz for this typical set up) with 2048 pixels resolution. One complete diameter scan took 2 msec which resulted of 60 msec for 30 times scanning. The amount of light reaching CCD was proportional to the amount of light not blocked by the specimen, which varied as the slit scanned the specimen profile. The electrical output of the CCD through the electric circuit was the video output related to the shape of the specimen, whose major peak was represented the diameter of the specimen and minor peak was represented the data ready flag set at each scanning as shown in Fig. 2.2.5. This major peak corresponds to a dark area on the CCD which the light could not reach. The video signal was converted to a digital signal by a special electronic circuit and then sent to Zenith Z-158 personal computer passing through 12 bits digital I/O port. The computer was programmed to control the stepwise scan mirror and to determine the
Fig. 2.2.4 Schematic of optical scanning device [17].
Fig. 2.2.5 Trace of the CCD waveform using oscilloscope type RM 503.
minimum diameter of the gauge section. This system does not include a calculation of the radius of curvature of the specimen profile. The diameter signal had been calibrated and obtained accuracies of less than 0.2% which resulted from the limiting of the CCD scanning rate.

2.2.3 Temperature Control System

Helium gas at room temperature was conducted past the specimen during closed-loop testing to minimize self-heating. A Chromel-Alumel thermocouple was attached to the specimen to measure the temperature of specimen at large plastic deformation. Cooling with helium gas resulted in no evidence of temperature increase during the test.

2.2.4 Data Processing System

The analog signal reading from load cell MTS Model 661.23A-01 and from the displacement of actuator were sent to the analog XY-recorder Watanabe Model WX 4302, and converted to a digital signal by the 12 bit analog-to-digital converter board (A/D) ICS Model AI016. The instantaneous minimum diameters, the corresponding loads, and the corresponding actuator displacement were stored in the Zenith Z-158 personal computer. Depending on the scanning speed of the CCD and the resolution of D/A board, there were 40-160 data received and recorded in the computer for each test. All data and material descriptions
were stored on 5-1/4 in. floppy disks for later analysis. A
program [Appendix B] was provided to calculate true
stress-true plastic strain, true plastic strain rate-time,
and the relationship between diameter and elongation. True
stress-true strain data were fitted by nonlinear curve fit
program.

2.3 COMPUTER PROGRAM

Three programs were included in this study:

(1) control program,
(2) data processing program,
and (3) nonlinear curve fit program.

All programs were written in Microsoft Basic and
compiled to reduce the execution time.

2.3.1 Controlling Program

This program was divided into three major parts:

1) initial information,
2) calibration and system test,
and 3) closed-loop testing control and data recording.

First and second parts of this program were not
discussed in this section but these two parts were included
in the complete program listed in Appendix B.

In the control part, first, computer calculated the
required deformation along the axial direction (elongation)
and generated the command signal. This command signal was
in a decimal number where 0-4095 bits was equal to 0-10 volts or 0-0.6 inch when the span-set setting was 275. Channel 0 of the multi-function I/O interface ICS Model AIO 16 converted this decimal number into voltage and sent to actuator ram. This part of program is illustrated by:

XX10  DHD%(J) = INT(SUM%/16)
XX20  DLD%(J) = (SUM%-16*DHD%(J))*16
XX30  OUT &H304,DLD%(J)
XX40  OUT &H305,DHD%(J)

where SUM% was the calculated decimal number required for the actuator ram, DHD%(J) and DLD%(J) were outputs to high byte (MSB), &H304, and to low byte (LSB), &H305, respectively.

An LVDT measured the instantaneous ram position, and the servo control adjusted the ram position to conform to the command signal. At the same time, the computer generated a step command signal to the stepwise scan mirror. This command signal was also a decimal number where 0-480 bits were equal to 0-1.172 volts or 0-0.5 inch scanning length. Channel 1 of AIO16 converted this decimal number into voltage before sending to the stepwise scan mirror. The mirror scanned up and down over the entire desired length of gauge section, 0.5 inch, with n-stops in either direction (up or down) to permit CCD scanned from left to
right measuring the instantaneous diameter of the specimen, for this typical test, n=30. This part of the program was described by the following:

```
XX10 FOR I=NMR TO XMR STEP SMR
XX20 OUT &H306,0 : OUT &H307,I
XX30 IF INP(&H341) < 128 THEN XX30
XX40 RD% = INP(&H340) + (INP(&H341) AND 127) * 256
XX50 NEXT I
```

The mirror scanned from I=NMR to I=XMR and stopped every step of SMR to permit CCD to scan through the instantaneous diameter; &H306 and &H307 are the output addresses of LSB and MSB to the stepwise scan mirror. The CCD scanned from left to right with 2048 pixels of maximum resolution. This decimal number, 1-2048, was delivered to the computer by passing through the 12 bit parallel digital I/O interface MetraByte Model PI012. The first 11 bits were data and bit 12 was used to check whether the flag was on or off. When the CCD finished scanning and was ready to deliver data, the flag was set to on position and still was on for 16 μsec. Line XX30 provided to check flag passed the highest bit to address &H341; &H340 and &H341 were the addresses of LSB and MSB. Since &H341 was shared between data and flag, "AND 127" must be included in this line to ensure that the flag was taken out of the data. After the mirror finished
scanning up and down, computer selected the minimum diameter and recorded the corresponding load from the load cell. Load from load cell was in voltage where 0-10 volts were equal to 2048-4095 or 0-5,000 lbs (or 0-50,000 lbs as desired). This voltage was transferred to computer through A/D channel 0 of AI016 interface as the following program:

```
XX10  OUT &H302,0
XX20  OUT &H300,0
XX30  IF INP(&H308) >= 128 THEN XX30
XX40  P% = INP(&H300)/16 + INP(&H301) *16
```

The first and second lines start conversion at the load from voltage to a decimal number on channel 0. Line XX30 checks the conversion status. If bit 7 of &H308 is equal to zero, it implies that the conversion is finished and the A/D is ready to send data. Line XX40 records data into the buffer memory as a decimal number, 2048-4095. After minimum diameter, corresponding load, and corresponding elongation were stored in the buffer memory, the computer calculates the next desired elongation and generates the command signal, then the process was repeated again until the test ended at selected amount of deformation or sample fracture.

A set of specimens from each material was subjected to tensile tests to produce the elongation and the reduction of diameter data. The relationship between reduction of
diameter and the deformation along axial direction of a ductile material was estimated by two equations, quadratic equation before necking occurred and linear equation after necking occurred. Parameters relating the reduction of diameter and the actuator displacement along the axial direction were calculated by linear fit of the elongation vs. reduction of diameter curves obtained from one or two dummy tensile tests on the material for each specimen. The calculated command signal for the desired actuator displacement along the axial direction of the specimen was determined by the following equations:

\[
\begin{align*}
F% & = OD - Z%(k+1) \\
H% & = OD - X%(k) \\
R% & = F% \times (A2 + F% \times A3) - H% \times (A2 + H% \times A3) \\
R% & = (F% - H%) \times A5
\end{align*}
\]

where OD is the initial diameter before test, Z%(k+1) is the desired diameter as described by equation (2.1.7), X%(k) is the instantaneous actual diameter, A2 and A3 are the parameters of the quadratic equation relating the reduction of diameter to the axial displacement before necking occurred, A5 is the slope of the linear equation relating the reduction of diameter to the axial displacement after necking occurs, and R% is the desired deformation along the axial direction or the increment of elongation for the next
step. This program also includes both upper and lower limits of the calculation of command signal. These limits were used to prevent the command signal from being too high or too low which might happen if the rate of reduction of the diameter was too fast or too slow. Both limits were calculated from the desired diameter at that step and the next step using the following equations:

\[
\begin{align*}
F\% &= OD - Z\%(k+1) \quad (2.3.5) \\
H\% &= OD - Z\%(k) \quad (2.3.6) \\
R\% &= F\% * (A2+F\%*A3) - H\% * (A2+H\%*A3) \quad (2.3.7) \\
R\% &= (F\%-H\%) * A5 \quad (2.3.8)
\end{align*}
\]

where \(Z\%(k)\) is the diameter that should be at the present time after last deformation occurred as described by equation (2.1.7). The upper limit is 1.5 times the calculated result and the lower limit is 0.5 of the calculated result. If the calculated command signal in a decimal number was equal to zero, the number one was substituted to prevent the system from stopping.

After the test was finished, load, diameter, and elongation in decimal numbers and all information on materials were stored on a floppy disk for later processing.
2.3.2 Data Processing Program

Since all data from the test were stored onto the floppy disk as decimal numbers received directly from the optical scanning device, load cell, and displacement command, it was necessary to transform these data into appropriate units. The diameter was calculated from the data by the following equation,

\[ D = X(I) \times ID/OD \]  \hspace{1cm} (2.3.9)

where \( D \) is the diameter in inches, \( X(I) \) is the measured diameter in decimal number, \( OD \) is the initial diameter before the test measured by the optical scanning device and expressed as a decimal number, and \( ID \) is the initial diameter in inches measured by a caliper before the test. The load corresponding to the diameter, \( D \), was calculated as

\[ P = -(Y(I)-OP) \times 0.6975 \times PS/(FP-OP) \]  \hspace{1cm} (2.3.10)

where \( P \) is the load in lbs, \( Y(I) \) is the load expressed as a decimal number obtained from the load cell, \( PS \) is the maximum limit of load cell in lbs (5,000 lbs or 50,000 lbs), \( FP \) is the load simulated by a shunt resistance across the bridge expressed as a decimal number, and \( OP \) is the load cell reading before the test (corresponding to zero load) expressed as a decimal number. The shunt resistance used in
this study was only 69.75 % of maximum load, therefore, the
factor 0.6975 appears in equation (2.3.10). The elongation
or the deformation of the material along the axial direction
was calculated by the following equation:

\[ LVII = \frac{LML \times LV(I)}{4095} \]  

(2.3.11)

where LVII was the elongation in inch, LML was the maximum
displacement when 10 volts (decimal 4095) was applied, and
LV(I) was the elongation expressed as a decimal number.

The true stress and true plastic strain can be
calculated using the above data and the following equations:

\[ S = \frac{P}{A} \]  

(2.3.12)

\[ E = 2\log\left(\frac{OD}{X(I)}\right) \]  

(2.3.13)

where \( S \) is the true stress in psi, \( A \) is equal to \( \pi D^2/4 \), and
\( E \) is the true plastic strain.

These data were stored in four files:

1) stress-strain file,
2) strain-time file,
3) elongation-diameter file,
4) elongation-load file.

These data were used to determine the parameters relating
true stress to true plastic strain in the constitutive
equation. The maximum load can be determined from the load
vs elongation data. Strain vs time was plotted to determine the accuracy of the constant strain rate. The parameters relating the elongation to the reduction of the diameter were determined by a linear least squares fit to the elongation vs diameter data.

The linear least square fit included in this program uses the method described by Draper and Smith [70]:

\[ \mathbf{b} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{Y} \]  \hspace{1cm} (2.3.14)

where \( \mathbf{b} \) was a \( p \times 1 \) vector of parameters to be estimated, \( \mathbf{X} \) was \( n \times p \) matrix of independent variables, \( \mathbf{Y} \) was \( n \times 1 \) vector of observation, \( \mathbf{X}' \) was a transpose of a matrix \( \mathbf{X} \), and \( (\mathbf{X}'\mathbf{X})^{-1} \) is the inverse of matrix \( \mathbf{X}'\mathbf{X} \). The complete program is included in Appendix B.

2.3.3 NonLinear Fit Curve Program

This program was used to load and to merge true stress and true plastic strain from selected files containing data on material having the same metallurgical condition and tested at the same strain rate. These data were fitted by using nonlinear regression described by Hartley (Modified Gauss-Newton) [18].

The general form of the non-linear model is

\[ Y = f(X_1, X_2, \ldots, X_n; b_1, b_2, \ldots, b_p) + \varepsilon \]  \hspace{1cm} (2.3.15)
or \[ Y = f(X,B) + \varepsilon. \] (2.3.16)

This method uses the Taylor series

\[ f(X,B) = f(X,B_o) + Z_o(B-B_o) \] (2.3.17)

where \( Z_o = f(X,B)/B \) is evaluated at \( B=B_o \).

Equation (2.3.17) can be rearranged as

\[ f(X,B) - f(X,B_o) = Z_o(B-B_o). \] (2.3.18)

Therefore the normal equation of equation (2.3.18) becomes

\[ Z_o'Z_o(B-B_o) = Z_o'Y \] (2.3.19)

where \( Y = f(X,B) - f(X,B_o) \).

The estimate of \( (B-B_o) \) is given by

\[ (B-B_o) = (Z_o'Z_o)^{-1}Z_o'Y \] (2.3.20)

The initial values of the parameter \( B \), \( B_o \) were estimated based on the available information or guesses. \( SSE(B) \) is equal to \( \sum_{i=1}^{n}[y_i-f(x_i',b_i)]^2 \). If \( SSE(B) \) is less than \( SSE(B_o) \), this method continues by replacing \( B_o \) with \( B \) and repeats the first step until the solution converges. After
the solution converged which $\text{SSE}(B)$ is greater than $\text{SSE}(B_0)$, then $B$ is replaced with $B_0 + (B - B_0)/2$ and it start to compute again. The process repeats until a smallest $\text{SSE}(B)$ is found, then the iteration is completed. The complete program of this nonlinear regression was included in Appendix B.

2.4 MATERIAL SELECTION AND PREPARATION

2.4.1 Material Selection

The three types of materials used in this study, electrical grade iron, ferritic stainless steel type RA446, and austenitic stainless steel type RA310, were received as 0.5 inch diameter rods. Electrical grade iron was obtained from Carpenter Steel Co., ferritic and austenitic stainless steel rods were obtained from Rolled Alloys Inc. Nominal chemical analyses of these materials is shown in Table 2.4.1.

2.4.2 Cold-Work and Machining Processes

The ferritic stainless steel rods and electrical grade iron rods were cold-worked at the Department of Material Science and Engineering, University of Florida by swaging at room temperature from 0.5 inch to 0.375 inch in diameter. The austenitic stainless steel rods were swaged at room temperature from 0.5 inch to 0.405 inch diameter. Table 2.4.2 shown the amount of cold-work for each material.
Table 2.4.1
Vendors Typical Analysis of Received Materials.

<table>
<thead>
<tr>
<th>Element</th>
<th>Electrical grade iron</th>
<th>Austenitic stainless steel (RA 310)</th>
<th>Ferritic stainless steel (RA 446)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.020</td>
<td>0.076</td>
<td>0.070</td>
</tr>
<tr>
<td>Mn</td>
<td>0.120</td>
<td>1.480</td>
<td>0.460</td>
</tr>
<tr>
<td>P</td>
<td>0.010</td>
<td>0.019</td>
<td>0.032</td>
</tr>
<tr>
<td>S</td>
<td>0.010</td>
<td>0.015</td>
<td>0.008</td>
</tr>
<tr>
<td>Si</td>
<td>0.120</td>
<td>0.500</td>
<td>0.390</td>
</tr>
<tr>
<td>Cr</td>
<td>0.100</td>
<td>24.630</td>
<td>25.890</td>
</tr>
<tr>
<td>Ni</td>
<td>0.080</td>
<td>19.180</td>
<td>-</td>
</tr>
<tr>
<td>Al</td>
<td>0.030</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mo</td>
<td>-</td>
<td>0.110</td>
<td>-</td>
</tr>
<tr>
<td>Cu</td>
<td>-</td>
<td>0.100</td>
<td>-</td>
</tr>
<tr>
<td>N</td>
<td>-</td>
<td>0.043</td>
<td>0.070</td>
</tr>
<tr>
<td>Fe</td>
<td>balance</td>
<td>balance</td>
<td>balance</td>
</tr>
</tbody>
</table>

Table 2.4.2
The Amount of Cold-Work (CW) of Test Materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Initial Diameter (inch)</th>
<th>Final Diameter (inch)</th>
<th>CW (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>0.5</td>
<td>0.375</td>
<td>43.75</td>
</tr>
<tr>
<td>RA 310</td>
<td>0.5</td>
<td>0.405</td>
<td>34.39</td>
</tr>
<tr>
<td>RA 446</td>
<td>0.5</td>
<td>0.375</td>
<td>43.75</td>
</tr>
</tbody>
</table>
Specimens from each type of material were machined according to ASTM A370 as shown in Fig. 2.2.3 at the Engineering Shops, Division of Engineering Research, Louisiana State University.

2.4.3 Annealing Processes

A Lindberg Model 54253 tube furnace with Lindberg Model 59545 temperature controller having a maximum temperature of 1773 °K was used for annealing as shown in Fig. 2.4.1. Argon gas was passed through anhydrous CaSO₄, Drierite™, before entering the system. The gas outlet was immersed into a heavy oil to prevent outside air leaking back into the system. The variation of temperature inside the furnace was determined using a type K thermocouple, Chromel - Alumel, obtained from Omega Engineering Co. with results given in Table 2.4.3. At the beginning and the end of the annealing process the temperature of the furnace at the position of specimen was measured several times to ensure that the temperature was stable during annealing. The results showed that the maximum variation at all temperatures of this study did not exceed ± 4°K. Before the annealing process began, the specimen was placed in the furnace at the end of the tubing where the temperature was lower than 400 °K, then argon gas was passed through the system at least one hour before the specimen was moved to the annealing position. The annealing processes were done
Fig. 2.4.1 The schematic of annealing system.
### Table 2.4.3
Variation of Temperature in The Annealing Furnace.

<table>
<thead>
<tr>
<th>Distance from front end (inch)</th>
<th>Setting temperature (°K)</th>
<th>Reading temperature (°K)</th>
<th>Temperature fluctuation (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>1353</td>
<td>1311</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>1353</td>
<td>1327</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>1353</td>
<td>1341</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>1353</td>
<td>1351</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>1353</td>
<td>1357</td>
<td>1</td>
</tr>
<tr>
<td>22</td>
<td>1353</td>
<td>1351</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>1353</td>
<td>1341</td>
<td>1</td>
</tr>
<tr>
<td>26</td>
<td>1353</td>
<td>1327</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>1473</td>
<td>1426</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>1473</td>
<td>1440</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>1473</td>
<td>1458</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>1473</td>
<td>1464</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>1473</td>
<td>1469</td>
<td>1</td>
</tr>
<tr>
<td>22</td>
<td>1473</td>
<td>1463</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>1473</td>
<td>1457</td>
<td>1</td>
</tr>
<tr>
<td>26</td>
<td>1473</td>
<td>1439</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>1573</td>
<td>1522</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>1573</td>
<td>1534</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>1573</td>
<td>1553</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>1573</td>
<td>1560</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>1573</td>
<td>1565</td>
<td>1</td>
</tr>
<tr>
<td>22</td>
<td>1573</td>
<td>1560</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>1573</td>
<td>1552</td>
<td>1</td>
</tr>
<tr>
<td>26</td>
<td>1573</td>
<td>1534</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: The specimen was situated at the position of highest temperature.
at different temperatures to get three different grain sizes. All materials of the same type were annealed at the same temperature at the end of each process to ensure a common distribution of solute at internal boundaries and internal defects. Table 2.4.4 - 2.4.6 show the annealing processes of each material including cooling system. At the highest annealing temperature of austenitic stainless steel, the annealing process were different. As shown in Fig. 2.4.2. each specimen was placed in a quartz tube sealed at both ends after evacuating and back filling with a small amount of argon gas to prevent the quartz tubing from collapsing at high temperature.

2.4.4 Constant True Strain Rate Test

Uniaxial tensile tests were conducted at constant true strain rates of 0.05, 0.08, and 0.12 sec\(^{-1}\), on three types of material each having three grain sizes using the equipment described in section 2.2 and the control program in section 2.3. All specimens were tested at room temperature, 300°K, in air with a stream of helium gas directed at the deforming region. The helium gas was taken directly from the bottle and directed onto the specimen by a flexible tube. Using this procedure, there was no detectable change of temperature at the deforming region as measured by thermocouple type K. The deformation was continuous and monotonic from yielding to fracture at each
Table 2.4.4
Annealing Processes of Electrical Grade Iron.

<table>
<thead>
<tr>
<th>Mean linear intercept (μm)</th>
<th>ASTM grain size No.</th>
<th>Annealing processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.16</td>
<td>7</td>
<td>1073 °K in argon for 1 hr. followed by water quench.</td>
</tr>
<tr>
<td>50.92</td>
<td>5</td>
<td>1173 °K in argon for 10 hr. and 1073 °K for 1 hr. followed by water quench.</td>
</tr>
<tr>
<td>90.44</td>
<td>4</td>
<td>1353 °K in argon for 1 hr., 1223 °K for 15 hr., and 1073 °K for 1 hr. followed by water quench.</td>
</tr>
</tbody>
</table>

Table 2.4.5
Annealing Processes for Austenitic Stainless Steel.

<table>
<thead>
<tr>
<th>Mean linear intercept (μm)</th>
<th>ASTM grain size No.</th>
<th>Annealing processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.72</td>
<td>6</td>
<td>1353 °K in argon for 1 hr. followed by water quench.</td>
</tr>
<tr>
<td>77.70</td>
<td>4</td>
<td>1473 °K in argon for 1 hr., and 1353 °K for 1 hr. followed by water quench.</td>
</tr>
<tr>
<td>189.59</td>
<td>2</td>
<td>1573 °K in argon for 1 hr., 1473 °K for 1 hr., and 1353 °K for 1 hr. followed by water quench.</td>
</tr>
</tbody>
</table>
Table 2.4.6
Annealing Processes for Ferritic Stainless Steel.

<table>
<thead>
<tr>
<th>Mean linear intercept (µm)</th>
<th>ASTM grain size No.</th>
<th>Annealing processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.9</td>
<td>8</td>
<td>1073 °K in argon for 1 hr. followed by water quench.</td>
</tr>
<tr>
<td>59.62</td>
<td>5</td>
<td>1323 °K in argon for 1 hr., and 1073 °K for 1 hr. followed by water quenched</td>
</tr>
<tr>
<td>126.71</td>
<td>3</td>
<td>1373 °K in argon for 1 hr., 1323 °K for 1 hr., and 1073 °K for 1 hr. followed by water quench.</td>
</tr>
</tbody>
</table>

Fig. 2.4.2 The sealed quartz tubing for annealing austenitic stainless steel at high temperature.
strain rate. A tree diagram of materials tested and test conditions was shown in Fig. 2.4.3. Three specimens of the same grain size and same material were tested at the same constant strain rate to provide 40-160 data points of load, minimum diameter, and elongation per each specimen. The most two self-consistent sets of these three data sets were selected to produce the true stress-true plastic strain curves, then the nonlinear fit curve program described in section 2.3 was used to determine the parameters relating true stress to true plastic strain.

In a typical test, the scanning mirror, initial diameter, initial load, reference loads of 5,000 lbs or 50,000 lbs of shunt resistance, and the overall performance of the system were calibrated prior to each test to reduce errors of the process. At the end of each test, the constancy of the true strain rate was verified using the program in section 2.3. If the true strain rate was not constant, the parameters relating the axial displacement to the reduction of diameter were recalculated and a new test was conducted until a constant true strain rate was obtained. The continuity of elongation during the test was also verified by using a result from analog XY recorder of load versus time and elongation versus time. Fig 2.4.4 - 2.4.6 show plots of time-true plastic strain curve, the reduction of diameter-elongation curve, and analog XY-recorder results for typical tests.
Electrical Grade Iron

Strain Rate

0.05 /sec 0.08 /sec 0.12 /sec

GS=7 GS=5 GS=4 GS=7 GS=5 GS=4 GS=7 GS=5 GS=4

Austenitic Stainless Steel

Strain Rate

0.05 /sec 0.08 /sec 0.12 /sec

GS=6 GS=4 GS=2 GS=6 GS=4 GS=2 GS=6 GS=4 GS=2

Ferritic Stainless Steel

Strain Rate

0.05 /sec 0.08 /sec 0.12 /sec

GS=8 GS=5 GS=3 GS=8 GS=5 GS=3 GS=8 GS=5 GS=3

Fig. 2.4.3 Tree diagram of tested materials and conditions.
Fig. 2.4.4 True plastic strain versus time.

Fig. 2.4.5 Reduction of diameter versus elongation.
Fig. 2.4.6 Graph of load versus time and elongation versus time recorded by XY-recorder.
2.5 QUANTITATIVE METALLOGRAPHIC STUDY

2.5.1 Metallographic Preparation

Metallographic specimens tested at constant true strain rate as described in the previous section were prepared for quantitative microstructural analysis. Longitudinal and transverse sections of the undeformed material from each grain size of each type of material were cut with a diamond wheel using Isomet™ low speed saw and cutting oil to prevent introducing deformation into the structure during the cutting process. As described in the previous section, the specimens were divided into twenty-seven sets with three specimens per set. One specimen selected from each set, representing the structure of typical material, grain size, and deformation under typical strain rate, was cut along the longitudinal and transverse of deforming direction at three locations in the deforming region using the same cutting method as described above. Fig 2.5.1 and Table 2.5.1 - 2.5.3 show the locations selected for each specimen representing the structure of each set. All specimens were mounted in an epoxy resin, Koldmount™, as shown in Fig 2.5.2 and Fig. 2.5.3. Grinding was performed on using silicon carbide paper, 180, 240, 320, 400, and 600 grits, with water as lubricant. Then specimens were polished with 9 μm diamond paste on metcloth, 6 and 3 μm diamond paste on microcloth with Metadi™ fluid as
lubricant, and alumina 1 and 0.05 μm on microcloth with water as lubricant.

All polished specimens were etched to reveal the grain boundaries. Several chemical etchant solutions described in the Metals Handbook vol 8 were tried. The most satisfactory etchant solutions found for both deformed and undeformed materials are summarized in Table 2.5.4 - 2.5.5.

2.5.2 Quantitative Stereological Measurements

The micrographs of etched specimens of both deformed and undeformed specimens were taken on a 4" x 5" Polaroid(R) camera connected to the Versamet Unitron Model 5099 metallograph. Quantitative measurements were made on these micrographs using the line intercept method as described in section 1.3. On the undeformed specimens, a circular test line of 5 cm. in diameter was placed in several locations on the micrograph of transverse analysis plane of specimen to cover the entire micrograph, and the intersection of boundaries with the circular test line were counted. The number of grain boundary intersections per unit length of test line, \( N_L \), and mean linear intercept, \( \lambda \), were calculated from the following equations:

\[
\lambda = \frac{1}{N_L} \tag{2.5.1}
\]
**Table 2.5.1**
The True Axial Plastic Strain at Sectioning Location of Electrical Grade Iron

<table>
<thead>
<tr>
<th>ASTM Grain Size</th>
<th>Strain Rate</th>
<th>0.05/sec</th>
<th>0.08/sec</th>
<th>0.12/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E1</td>
<td>E2</td>
<td>E3</td>
<td>E1</td>
</tr>
<tr>
<td>7</td>
<td>0.38</td>
<td>0.49</td>
<td>0.79</td>
<td>0.31</td>
</tr>
<tr>
<td>5</td>
<td>0.24</td>
<td>0.40</td>
<td>0.86</td>
<td>0.22</td>
</tr>
<tr>
<td>4</td>
<td>0.26</td>
<td>0.44</td>
<td>0.82</td>
<td>0.22</td>
</tr>
</tbody>
</table>

**Table 2.5.2**
The True Axial Plastic Strain at Sectioning Location of Austenitic Stainless Steel

<table>
<thead>
<tr>
<th>ASTM Grain Size</th>
<th>Strain Rate</th>
<th>0.05/sec</th>
<th>0.08/sec</th>
<th>0.12/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E1</td>
<td>E2</td>
<td>E3</td>
<td>E1</td>
</tr>
<tr>
<td>6</td>
<td>0.36</td>
<td>0.49</td>
<td>0.60</td>
<td>0.34</td>
</tr>
<tr>
<td>4</td>
<td>0.42</td>
<td>0.71</td>
<td>0.90</td>
<td>0.35</td>
</tr>
<tr>
<td>2</td>
<td>0.43</td>
<td>0.66</td>
<td>1.19</td>
<td>0.38</td>
</tr>
</tbody>
</table>

**Table 2.5.3**
The True Axial Plastic Strain at Sectioning Location of Ferritic Stainless Steel

<table>
<thead>
<tr>
<th>ASTM Grain Size</th>
<th>Strain Rate Constant</th>
<th>0.05/sec</th>
<th>0.08/sec</th>
<th>0.12/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E1</td>
<td>E2</td>
<td>E3</td>
<td>E1</td>
</tr>
<tr>
<td>8</td>
<td>0.19</td>
<td>0.37</td>
<td>0.73</td>
<td>0.14</td>
</tr>
<tr>
<td>5</td>
<td>0.19</td>
<td>0.33</td>
<td>0.63</td>
<td>0.16</td>
</tr>
<tr>
<td>3</td>
<td>0.21</td>
<td>0.31</td>
<td>0.64</td>
<td>0.16</td>
</tr>
</tbody>
</table>
Table 2.5.4
The Etchant for Microscopic Examination.

<table>
<thead>
<tr>
<th>No.</th>
<th>Etchant Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5% Nital: 5 ml HNO₃ in 100 ml ethanol</td>
</tr>
<tr>
<td>2</td>
<td>Glyceregia: 10 ml HNO₃, 50 ml HCl, 30 ml glycerol</td>
</tr>
<tr>
<td>3</td>
<td>10 ml HNO₃, 10 ml acetic acid, 15 ml HCl, 2-5 drops glycerol</td>
</tr>
<tr>
<td>4</td>
<td>10 gm Oxalic acid and 100 ml water</td>
</tr>
</tbody>
</table>

Table 2.5.5
Etching Procedures for Microscopic Examination.

<table>
<thead>
<tr>
<th>Material</th>
<th>Etchant No.</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical grade iron</td>
<td>1</td>
<td>swab specimen for a few seconds</td>
</tr>
<tr>
<td>Austenitic stainless steel</td>
<td>4</td>
<td>Electrolytic at 6 volts for a few seconds</td>
</tr>
<tr>
<td>Ferritic stainless steel</td>
<td>2 and 3</td>
<td>Drop etchant no.2 on the polished surface and swab specimen with etchant no. 3 for a few seconds.</td>
</tr>
</tbody>
</table>
Fig. 2.5.1 The deforming regions selected for each specimen.

Fig. 2.5.2 The undeformed specimen mounted in an epoxy resin.

Fig. 2.5.3 The deformed specimen mounted in an epoxy resin.
\[ N_L = \frac{P \cdot M}{(L_T \cdot 10000)} \]  

(2.5.2)

where \( N_L \) was the number of grain boundary intersections per \( \mu m \), \( P \) was the number of grain boundary intersections, \( M \) was the magnification, \( L_T \) was the total length of test line, and \( \lambda \) was mean linear intercept in \( \mu m \). The ASTM grain size number, \( GS\# \), of undeformed specimens were calculated by using the calculation method described by Hilliard [71] as the following:

\[ GS\# = -10 - 6.64 \log(\lambda/10000). \]  

(2.5.3)

On deformed materials, the measurement method was different. On the transverse analysis plane a circular test line was used to measure the numbers of grain boundary intersections per unit length of test line and mean linear intercept as described above. For the longitudinal analysis plane, a straight test line 10 cm. long was placed parallel to the deforming direction at several locations to cover the entire micrograph to obtain the mean number of grain boundary intersections per unit length of test line, \( N_L \). The mean linear intercept was calculated as for undeformed material. Fig. 2.5.4 illustrates the quantitative measurement on the transverse and longitudinal analysis planes of deformed materials.
Fig. 2.5.4 Quantitative measurement on transverse and longitudinal analysis planes.
CHAPTER 3
EXPERIMENTAL RESULTS

This chapter is divided into three parts, the first part presents the true stress-true plastic strain curves and the results of fitted curves. The second part presents the results of quantitative stereological measurement. The last part of this chapter combines the results of quantitative stereological measurement and constant true strain rate tests. The stress-strain curves were computed without including a correction factor for necking.

3.1 TRUE STRESS-TRUE PLASTIC STRAIN CURVES

3.1.1 Electrical Grade Iron

Fig. 3.1.1 - Fig. 3.1.9 present true stress-true plastic strain curves for electrical grade iron in various grain sizes tested at room temperature and various constant true strain rates. Both the data (dotted line) and a curve fitted to the data by a non-linear least squares technique (solid line) are shown. Two equations based on the generalized power law show the best fit to all data.
Two forms of generalized power law are:

at $0 < \varepsilon < \varepsilon_m$,

$$\sigma = \sigma_m [(\varepsilon/\varepsilon_m)^{\varepsilon_m}]$$ \hspace{1cm} (3.1.1)

at $\varepsilon_m \leq \varepsilon < \text{fracture}$,

$$\sigma = \sigma_m \exp\{[\varepsilon_m/n][(\varepsilon/\varepsilon_m)^{n-1}]\}$$ \hspace{1cm} (3.1.2)

Fig. 3.1.10 - Fig. 3.1.15 compare true stress-true plastic strain curves with various grain sizes and various strain rates. Fig. 3.1.16 - Fig. 3.1.39 show the relationships among the parameters of the fitted curves, the initial grain size and strain rate. Table 3.1.1 summarizes the parameters of the fitted curves.

Fig. 3.1.1 True stress-true plastic strain curves of electrical grade iron of ASTM grain size #7 at true strain rate of 0.05/sec.
Fig. 3.1.2 True stress-true plastic strain curves of electrical grade iron of ASTM grain size #7 at true strain rate of 0.08/sec.

Fig. 3.1.3 True stress-true plastic strain curves of electrical grade iron of ASTM grain size #7 at true strain rate of 0.12/sec.
Fig. 3.1.4 True stress-true plastic strain curves of electrical grade iron of ASTM grain size #5 at true strain rate of 0.05/sec.

Fig. 3.1.5 True stress-true plastic strain curves of electrical grade iron of ASTM grain size #5 at true strain rate of 0.08/sec.
Fig. 3.1.6 True stress-true plastic strain curves of electrical grade iron of ASTM grain size #5 at true strain rate of 0.12/sec.

Fig. 3.1.7 True stress-true plastic strain curves of electrical grade iron of ASTM grain size #4 at true strain rate of 0.05/sec.
Fig. 3.1.8 True stress-true plastic strain curves of electrical grade iron of ASTM grain size #4 at true strain rate of 0.08/sec.

Fig. 3.1.9 True stress-true plastic strain curves of electrical grade iron of ASTM grain size #4 at true strain rate of 0.12/sec.
Fig. 3.1.10 True stress-true plastic strain curves of electrical grade iron of ASTM grain size #7 at true strain rate of 0.05, 0.08, and 0.12/sec.

Fig. 3.1.11 True stress-true plastic strain curves of electrical grade iron of ASTM grain size #5 at true strain rate of 0.05, 0.08, and 0.12/sec.
Fig. 3.1.12 True stress-true plastic strain curves of electrical grade iron of ASTM grain size #4 at true strain rate of 0.05, 0.08, and 0.12/sec.

Fig. 3.1.13 True stress-true plastic strain curves of electrical grade iron of ASTM grain sizes #7, #5, and #4 at true strain rate 0.05/sec.
Fig. 3.1.14 True stress-true plastic strain curves of electrical grade iron of ASTM grain sizes #7, #5, and #4 at true strain rate 0.08/sec.

Fig. 3.1.15 True stress-true plastic strain curves of electrical grade iron of ASTM grain sizes #7, #5, and #4 at true strain rate 0.12/sec.
Fig. 3.1.16 True stresses at maximum load of electrical grade iron of ASTM grain sizes #7 vs true strain rate.

Fig. 3.1.17 True strains at maximum load of electrical grade iron of ASTM grain sizes #7 vs true strain rate.
Fig. 3.1.18 Parameter N of electrical grade iron of ASTM grain sizes #7 vs true strain rate.

Fig. 3.1.19 True stresses at maximum load of electrical grade iron of ASTM grain sizes #5 vs true strain rate.
Fig. 3.1.20 True strains at maximum load of electrical grade iron of ASTM grain sizes #5 vs true strain rate.

Fig. 3.1.21 Parameter N of electrical grade iron of ASTM grain sizes #5 vs true strain rate.
Fig. 3.1.22  True stresses at maximum load of electrical grade iron of ASTM grain sizes #4 vs true strain rate.

Fig. 3.1.23  True strains at maximum load of electrical grade iron of ASTM grain sizes #4 vs true strain rate.
Fig. 3.1.24 Parameter N of electrical grade iron of ASTM grain sizes #4 vs true strain rate.

Fig. 3.1.25 True stresses at maximum load of electrical grade iron at strain rate 0.05/sec vs initial mean linear intercept.
Fig. 3.1.26  True strains at maximum load of electrical grade iron at strain rate 0.05/sec vs initial mean linear intercept.

Fig. 3.1.27  Parameter N of electrical grade iron at strain rate 0.05/sec vs initial mean linear intercept.
Fig. 3.1.28 True stresses at maximum load of electrical grade iron at strain rate 0.08/sec vs initial mean linear intercept.

Fig. 3.1.29 True strains at maximum load of electrical grade iron at strain rate 0.08/sec vs initial mean linear intercept.
Fig. 3.1.30 Parameter N of electrical grade iron at strain rate 0.08/sec vs initial mean linear intercept.

Fig. 3.1.31 True stresses at maximum load of electrical grade iron at strain rate 0.12/sec vs initial mean linear intercept.
Fig. 3.1.32  True strains at maximum load of electrical grade iron at strain rate 0.12/sec vs initial mean linear intercept.

Fig. 3.1.33  Parameter N of electrical grade iron at strain rate 0.12/sec vs initial mean linear intercept.
Fig. 3.1.34 True stresses at maximum load of electrical grade iron of various grain sizes vs true strain rate.

Fig. 3.1.35 True strains at maximum load of electrical grade iron of various grain sizes vs true strain rate.
Fig. 3.1.36 Parameter $N$ of electrical grade iron of various grain sizes vs true strain rate.

Fig. 3.1.37 True stresses at maximum load of electrical grade iron of various true strain rate vs initial mean linear intercept.
Fig. 3.1.38 True strains at maximum load of electrical grade iron of various true strain rate vs initial mean linear intercept.

Fig. 3.1.39 Parameter N of electrical grade iron of various true strain rate vs initial mean linear intercept.
Table 3.1.1
Parameters in generalized power law for annealed electrical grade iron tested in tension at constant true strain rate.

<table>
<thead>
<tr>
<th>Strain Rate (/sec)</th>
<th>Mean Linear Intercept (micro m)</th>
<th>Stress at Maximum Load (MPa)</th>
<th>Strain at Maximum Load</th>
<th>Parameter N</th>
<th>Stress at Maximum Load (MPa)</th>
<th>Strain at Maximum Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>26.302</td>
<td>385.74 ± 2.29</td>
<td>0.2430 ± 0.0086</td>
<td>0.4932 ± 0.0133</td>
<td>394.18</td>
<td>0.2374</td>
</tr>
<tr>
<td>0.05</td>
<td>50.924</td>
<td>363.56 ± 2.31</td>
<td>0.2402 ± 0.0097</td>
<td>0.4565 ± 0.0164</td>
<td>362.16</td>
<td>0.2135</td>
</tr>
<tr>
<td>0.05</td>
<td>90.440</td>
<td>348.86 ± 5.57</td>
<td>0.2000 ± 0.0252</td>
<td>0.5005 ± 0.0407</td>
<td>342.73</td>
<td>0.1815</td>
</tr>
<tr>
<td>0.08</td>
<td>26.302</td>
<td>394.42 ± 3.82</td>
<td>0.2276 ± 0.0159</td>
<td>0.4943 ± 0.0231</td>
<td>362.46</td>
<td>0.2001</td>
</tr>
<tr>
<td>0.08</td>
<td>50.924</td>
<td>352.56 ± 5.68</td>
<td>0.2042 ± 0.0257</td>
<td>0.4775 ± 0.0433</td>
<td>360.12</td>
<td>0.2008</td>
</tr>
<tr>
<td>0.08</td>
<td>90.440</td>
<td>351.37 ± 6.73</td>
<td>0.2083 ± 0.0388</td>
<td>0.3771 ± 0.0841</td>
<td>360.90</td>
<td>0.2181</td>
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<tr>
<td>0.12</td>
<td>26.302</td>
<td>387.47 ± 5.03</td>
<td>0.2318 ± 0.0213</td>
<td>0.4700 ± 0.0315</td>
<td>394.43</td>
<td>0.2358</td>
</tr>
<tr>
<td>0.12</td>
<td>50.924</td>
<td>355.36 ± 3.75</td>
<td>0.2025 ± 0.0172</td>
<td>0.4958 ± 0.0271</td>
<td>363.39</td>
<td>0.2133</td>
</tr>
<tr>
<td>0.12</td>
<td>90.440</td>
<td>342.61 ± 2.62</td>
<td>0.1544 ± 0.0137</td>
<td>0.5098 ± 0.0262</td>
<td>339.47</td>
<td>0.1347</td>
</tr>
</tbody>
</table>
3.1.2 Austenitic Stainless Steel

Fig. 3.1.40 - Fig. 3.1.48 present true stress-true plastic strain curves for type 310 austenitic stainless steel of various grain sizes tested at room temperature and various constant true strain rates. Both the data (dotted line) and curve fitted to the data by a non-linear least squares technique (solid line) on equation (3.1.1) and equation (3.1.2) are shown. Fig. 3.1.49 - Fig. 3.1.54 compare true stress-true plastic strain curves with various grain sizes and various strain rates. Fig. 3.1.55 - Fig. 3.1.78 show the relationships among the parameters of the fitted curves, the initial grain size and strain rate. Table 3.1.2 summarizes the parameters of the fitted curves.

![Graph](image-url)  
**Fig. 3.1.40** True stress-true plastic strain curves of austenitic stainless steel of ASTM grain size #6 at true strain rate of 0.05/sec.
Fig. 3.1.41 True stress-true plastic strain curves of austenitic stainless steel of ASTM grain size #6 at true strain rate of 0.08/sec.

Fig. 3.1.42 True stress-true plastic strain curves of austenitic stainless steel of ASTM grain size #6 at true strain rate of 0.12/sec.
Fig. 3.1.43 True stress-true plastic strain curves of austenitic stainless steel of ASTM grain size #4 at true strain rate of 0.05/sec.

Fig. 3.1.44 True stress-true plastic strain curves of austenitic stainless steel of ASTM grain size #4 at true strain rate of 0.08/sec.
Fig. 3.1.45 True stress-true plastic strain curves of austenitic stainless steel of ASTM grain size #4 at true strain rate of 0.12/sec.

Fig. 3.1.46 True stress-true plastic strain curves of austenitic stainless steel of ASTM grain size #2 at true strain rate of 0.05/sec.
Fig. 3.1.47 True stress-true plastic strain curves of austenitic stainless steel of ASTM grain size #2 at true strain rate of 0.08/sec.

Fig. 3.1.48 True stress-true plastic strain curves of austenitic stainless steel of ASTM grain size #2 at true strain rate of 0.12/sec.
Fig. 3.1.49  True stress-true plastic strain curves of austenitic stainless steel of ASTM grain size #6 at true strain rates of 0.05, 0.08, and 0.12/sec.

Fig. 3.1.50  True stress-true plastic strain curves of austenitic stainless steel of ASTM grain size #4 at true strain rates of 0.05, 0.08, and 0.12/sec.
Fig. 3.1.51 True stress-true plastic strain curves of austenitic stainless steel of ASTM grain size #2 at true strain rates of 0.05, 0.08, and 0.12/sec.

Fig. 3.1.52 True stress-true plastic strain curves of austenitic stainless steel of ASTM grain sizes #6, #4, and #2 at true strain rate 0.05/sec.
Fig. 3.1.53 True stress-true plastic strain curves of austenitic stainless steel of ASTM grain sizes #6, #4, and #2 at true strain rate 0.08/sec.

Fig. 3.1.54 True stress-true plastic strain curves of austenitic stainless steel of ASTM grain sizes #6, #4, and #2 at true strain rate 0.12/sec.
Fig. 3.1.55 True stresses at maximum load of austenitic stainless steel of ASTM grain sizes #6 vs true strain rate.

Fig. 3.1.56 True strains at maximum load of austenitic stainless steel of ASTM grain sizes #6 vs true strain rate.
Fig. 3.1.57 Parameter N of austenitic stainless steel of ASTM grain sizes #6 vs true strain rate.

Fig. 3.1.58 True stresses at maximum load of austenitic stainless steel of ASTM grain sizes #4 vs true strain rate.
Fig. 3.1.59 True strains at maximum load of austenitic stainless steel of ASTM grain sizes #4 vs true strain rate.

Fig. 3.1.60 Parameter N of austenitic stainless steel of ASTM grain sizes #4 vs true strain rate.
Fig. 3.1.61 True stresses at maximum load of austenitic stainless steel of ASTM grain sizes #2 vs true strain rate.

Fig. 3.1.62 True strains at maximum load of austenitic stainless steel of ASTM grain sizes #2 vs true strain rate.
Fig. 3.1.63 Parameter N of austenitic stainless steel of ASTM grain sizes #2 vs true strain rate.

Fig. 3.1.64 True stresses at maximum load of austenitic stainless steel at strain rate 0.05/sec vs initial mean linear intercept.
Fig. 3.1.65 True strains at maximum load of austenitic stainless steel at strain rate 0.05/sec vs initial mean linear intercept.

Fig. 3.1.66 Parameter N of austenitic stainless steel at strain rate 0.05/sec vs initial mean linear intercept.
Fig. 3.1.67 True stresses at maximum load of austenitic stainless steel at strain rate 0.08/sec vs initial mean linear intercept.

Fig. 3.1.68 True strains at maximum load of austenitic stainless steel at strain rate 0.08/sec vs initial mean linear intercept.
Fig. 3.1.69 Parameter N of austenitic stainless steel at strain rate 0.08/sec vs initial mean linear intercept.

Fig. 3.1.70 True stresses at maximum load of austenitic stainless steel at strain rate 0.12/sec vs initial mean linear intercept.
Fig. 3.1.71 True strains at maximum load of austenitic stainless steel at strain rate 0.12/sec vs initial mean linear intercept.

Fig. 3.1.72 Parameter N of austenitic stainless steel at strain rate 0.12/sec vs initial mean linear intercept.
Fig. 3.1.73 True stresses at maximum load of austenitic stainless steel of various grain sizes vs true strain rate.

Fig. 3.1.74 True strains at maximum load of austenitic stainless steel of various grain sizes vs true strain rate.
Fig. 3.1.75 Parameter N of austenitic stainless steel of various grain sizes vs true strain rate.

Fig. 3.1.76 True stresses at maximum load of austenitic stainless steel at various true strain rate vs initial mean linear intercept.
Fig. 3.1.77  True strains at maximum load of austenitic stainless steel of various true strain rate vs initial mean linear intercept.

Fig. 3.1.78  Parameter N of austenitic stainless steel of various true strain rate vs initial mean linear intercept.
Table 3.1.2
Parameters in generalized power law for annealed austenitic stainless steel tested in tension at constant true strain rate.

<table>
<thead>
<tr>
<th>Strain Rate (/sec)</th>
<th>Mean Linear Intercept (micro m)</th>
<th>Stress at Maximum Load (MPa)</th>
<th>Strain at Maximum Load</th>
<th>Parameter N</th>
<th>Stress at Maximum Load (MPa)</th>
<th>Strain at Maximum Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>40.72</td>
<td>811.18 ± 6.70</td>
<td>0.3465 ± .0098</td>
<td>0.2551 ± .0304</td>
<td>791.86</td>
<td>0.3104</td>
</tr>
<tr>
<td>0.05</td>
<td>77.70</td>
<td>799.64 ± 6.89</td>
<td>0.3773 ± .0102</td>
<td>0.2684 ± .0289</td>
<td>794.06</td>
<td>0.3427</td>
</tr>
<tr>
<td>0.05</td>
<td>189.59</td>
<td>800.59 ± 13.98</td>
<td>0.3687 ± .0204</td>
<td>0.1997 ± .0013</td>
<td>792.98</td>
<td>0.3547</td>
</tr>
<tr>
<td>0.08</td>
<td>40.72</td>
<td>810.34 ± 7.50</td>
<td>0.3384 ± .0110</td>
<td>0.3197 ± .0293</td>
<td>810.34</td>
<td>0.3201</td>
</tr>
<tr>
<td>0.08</td>
<td>77.70</td>
<td>806.66 ± 7.84</td>
<td>0.3579 ± .0112</td>
<td>0.2811 ± .0322</td>
<td>802.13</td>
<td>0.3385</td>
</tr>
<tr>
<td>0.08</td>
<td>189.59</td>
<td>799.00 ± 15.40</td>
<td>0.3833 ± .0220</td>
<td>0.2890 ± .0642</td>
<td>789.09</td>
<td>0.3682</td>
</tr>
<tr>
<td>0.12</td>
<td>40.72</td>
<td>798.98 ± 9.30</td>
<td>0.3197 ± .0142</td>
<td>0.2925 ± .0403</td>
<td>822.35</td>
<td>0.3326</td>
</tr>
<tr>
<td>0.12</td>
<td>77.70</td>
<td>805.38 ± 9.52</td>
<td>0.3384 ± .0141</td>
<td>0.1310 ± .0539</td>
<td>789.58</td>
<td>0.3020</td>
</tr>
<tr>
<td>0.12</td>
<td>189.59</td>
<td>781.94 ± 12.82</td>
<td>0.3528 ± .0165</td>
<td>0.2635 ± .0572</td>
<td>781.44</td>
<td>0.3402</td>
</tr>
</tbody>
</table>
3.1.3 Ferritic Stainless Steel

Fig. 3.1.79 - Fig. 3.1.87 present true stress-true plastic strain curves for type 446 ferritic stainless steel on various grain sizes tested at room temperature and various constant true strain rates. Both the data (dotted line) and a curve fitted to the data by a non-linear least squares technique (solid line) on equation (3.1.1) and equation (3.1.2) are shown. Fig. 3.1.88 - Fig. 3.1.93 compare true stress-true plastic strain curves with various grain sizes and various strain rates. Fig. 3.1.94 - Fig. 3.1.117 show the relationships among the parameters of the fitted curves, the initial grain size and strain rate. Table 3.1.3 summarizes parameters of the fitted curves.

**Fig. 3.1.79** True stress-true plastic strain curves of ferritic stainless steel of ASTM grain size #8 at true strain rate of 0.05/sec.
Fig. 3.1.80  True stress-true plastic strain curves of ferritic stainless steel of ASTM grain size #8 at true strain rate of 0.08/sec.

Fig. 3.1.81  True stress-true plastic strain curves of ferritic stainless steel of ASTM grain size #8 at true strain rate of 0.12/sec.
Fig. 3.1.82 True stress-true plastic strain curves of ferritic stainless steel of ASTM grain size #5 at true strain rate of 0.05/sec.

Fig. 3.1.83 True stress-true plastic strain curves of ferritic stainless steel of ASTM grain size #5 at true strain rate of 0.08/sec.
Fig. 3.1.84 True stress-true plastic strain curves of ferritic stainless steel of ASTM grain size #5 at true strain rate of 0.12/sec.

Fig. 3.1.85 True stress-true plastic strain curves of ferritic stainless steel of ASTM grain size #3 at true strain rate of 0.05/sec.
Fig. 3.1.86  True stress-true plastic strain curves of ferritic stainless steel of ASTM grain size #3 at true strain rate of 0.08/sec.

Fig. 3.1.87  True stress-true plastic strain curves of ferritic stainless steel of ASTM grain size #3 at true strain rate of 0.12/sec.
Fig. 3.1.88 True stress-true plastic strain curves of ferritic stainless steel of ASTM grain size #8 at true strain rates of 0.05, 0.08, and 0.12/sec.

Fig. 3.1.89 True stress-true plastic strain curves of ferritic stainless steel of ASTM grain size #5 at true strain rates of 0.05, 0.08, and 0.12/sec.
Fig. 3.1.90  True stress-true plastic strain curves of ferritic stainless steel of ASTM grain size #3 at true strain rates of 0.05, 0.08, and 0.12/sec.

Fig. 3.1.91  True stress-true plastic strain curves of ferritic stainless steel of ASTM grain sizes #8, #5, and #3 at true strain rate 0.05/sec.
Fig. 3.1.92 True stress-true plastic strain curves of ferritic stainless steel of ASTM grain sizes #8, #5, and #3 at true strain rate 0.08/sec.

Fig. 3.1.93 True stress-true plastic strain curves of ferritic stainless steel of ASTM grain sizes #8, #5, and #3 at true strain rate 0.12/sec.
Fig. 3.1.94 True stresses at maximum load of ferritic stainless steel of ASTM grain sizes #8 vs true strain rate.

Fig. 3.1.95 True strains at maximum load of ferritic stainless steel of ASTM grain sizes #8 vs true strain rate.
Fig. 3.1.96 Parameter $N$ of ferritic stainless steel of ASTM grain sizes #8 vs true strain rate.

Fig. 3.1.97 True stresses at maximum load of ferritic stainless steel of ASTM grain sizes #5 vs true strain rate.
Fig. 3.1.98 True strains at maximum load of ferritic stainless steel of ASTM grain sizes #5 vs true strain rate.

Fig. 3.1.99 Parameter N of ferritic stainless steel of ASTM grain sizes #5 vs true strain rate.
Fig. 3.1.100  True stresses at maximum load of ferritic stainless steel of ASTM grain sizes #3 vs true strain rate.

Fig. 3.1.101  True strains at maximum load of ferritic stainless steel of ASTM grain sizes #3 vs true strain rate.
Fig. 3.1.102 Parameter N of ferritic stainless steel of ASTM grain sizes #3 vs true strain rate.

Fig. 3.1.103 True stresses at maximum load of ferritic stainless steel at strain rate 0.05/sec vs initial mean linear intercept.
Fig. 3.1.104 True strains at maximum load of ferritic stainless steel at strain rate 0.05/sec vs initial mean linear intercept.

Fig. 3.1.105 Parameter N of ferritic stainless steel at strain rate 0.05/sec vs initial mean linear intercept.
Fig. 3.1.106 True stresses at maximum load of ferritic stainless steel at strain rate 0.08/sec vs initial mean linear intercept.

Fig. 3.1.107 True strains at maximum load of ferritic stainless steel at strain rate 0.08/sec vs initial mean linear intercept.
Fig. 3.1.108 Parameter N of ferritic stainless steel at strain rate 0.08/sec vs initial mean linear intercept.

Fig. 3.1.109 True stresses at maximum load of ferritic stainless steel at strain rate 0.12/sec vs initial mean linear intercept.
Fig. 3.1.110 True strains at maximum load of ferritic stainless steel at strain rate 0.12/sec vs initial mean linear intercept.

Fig. 3.1.111 Parameter N of ferritic stainless steel at strain rate 0.12/sec vs initial mean linear intercept.
Fig. 3.1.112 True stresses at maximum load of ferritic stainless steel of various grain sizes vs true strain rate.

Fig. 3.1.113 True strains at maximum load of ferritic stainless steel of various grain sizes vs true strain rate.
Fig. 3.1.114 Parameter N of ferritic stainless steel of various grain sizes vs true strain rate.

Fig. 3.1.115 True stresses at maximum load of ferritic stainless steel at various true strain rate vs initial mean linear intercept.
Fig. 3.1.116 True strains at maximum load of ferritic stainless steel of various true strain rate vs initial mean linear intercept.

Fig. 3.1.117 Parameter N of ferritic stainless steel of various true strain rate vs initial mean linear intercept.
Table 3.1.3
Parameters in generalized power law for annealed ferritic stainless steel tested in tension at constant true strain rate.

<table>
<thead>
<tr>
<th>Strain Rate (°/sec)</th>
<th>Mean Linear Interception (micro m)</th>
<th>Stress at Maximum Load (MPa)</th>
<th>Strain at Maximum Load</th>
<th>Parameter N</th>
<th>Stress at Maximum Load (MPa)</th>
<th>Strain at Maximum Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>22.90</td>
<td>610.85 ± 3.70</td>
<td>0.1558 ± 0.0084</td>
<td>0.4756 ± 0.0227</td>
<td>624.15</td>
<td>0.1626</td>
</tr>
<tr>
<td>0.05</td>
<td>59.62</td>
<td>565.66 ± 3.19</td>
<td>0.1532 ± 0.0074</td>
<td>0.3657 ± 0.0270</td>
<td>579.21</td>
<td>0.1632</td>
</tr>
<tr>
<td>0.05</td>
<td>126.71</td>
<td>556.39 ± 4.62</td>
<td>0.1656 ± 0.0101</td>
<td>0.3463 ± 0.0458</td>
<td>559.06</td>
<td>0.1603</td>
</tr>
<tr>
<td>0.08</td>
<td>22.90</td>
<td>609.75 ± 5.86</td>
<td>0.1483 ± 0.0132</td>
<td>0.4933 ± 0.0354</td>
<td>632.43</td>
<td>0.1754</td>
</tr>
<tr>
<td>0.08</td>
<td>59.62</td>
<td>558.93 ± 5.68</td>
<td>0.1407 ± 0.0139</td>
<td>0.4506 ± 0.0463</td>
<td>579.32</td>
<td>0.1729</td>
</tr>
<tr>
<td>0.08</td>
<td>126.71</td>
<td>545.65 ± 5.60</td>
<td>0.1373 ± 0.0137</td>
<td>0.4235 ± 0.0490</td>
<td>559.28</td>
<td>0.1526</td>
</tr>
<tr>
<td>0.12</td>
<td>22.90</td>
<td>604.60 ± 6.59</td>
<td>0.1447 ± 0.0150</td>
<td>0.4577 ± 0.0440</td>
<td>615.36</td>
<td>0.1589</td>
</tr>
<tr>
<td>0.12</td>
<td>59.62</td>
<td>569.76 ± 5.35</td>
<td>0.1441 ± 0.0130</td>
<td>0.3776 ± 0.0470</td>
<td>578.17</td>
<td>0.1526</td>
</tr>
<tr>
<td>0.12</td>
<td>126.71</td>
<td>557.23 ± 8.72</td>
<td>0.1399 ± 0.0161</td>
<td>0.5020 ± 0.0456</td>
<td>569.07</td>
<td>0.1498</td>
</tr>
</tbody>
</table>
3.2 STERELOGICAL MEASUREMENTS OF GRAIN BOUNDARY NETWORK

3.2.1 Electrical Grade Iron

Micrographs of both longitudinal and transverse sections of electrical grade iron ASTM grain size #5 tested at strain rate 0.12 are presented in Fig. 3.2.1 - 3.2.3. The results of measuring the linear intercepts as described in previous chapter and curves fitted by linear least squares analysis are illustrated in Fig. 3.2.4. Table 3.2.1 summarizes the slopes and intercepts of the least square fits illustrated in Fig. 3.2.4.
(a) Longitudinal section. Axial direction is vertical. 100X

(b) Transverse section. Radial direction is vertical. 100X

Fig. 3.2.1 Microstructure of electrical grade iron of grain size #5 tested at strain rate 0.12/sec sectioned at bulk strain equal to 0.2\%.
Fig. 3.2.2 Microstructure of electrical grade iron of grain size #5 tested at strain rate 0.12/sec sectioned at bulk strain equal to 0.45.
Fig. 3.2.3 Microstructure of electrical grade iron of grain size #5 tested at strain rate 0.12/sec sectioned at bulk strain equal to 0.79.
Fig. 3.2.4 Least square fit curves of the data of electrical grade iron GS#5 tested at tested strain rate 0.12/sec plotted as log of mean linear intercept of both axial and transverse directions versus axial bulk strain.
Table 3.2.1
Summary of parameters obtained from linear least squares fit curve of the electrical grade iron data plotted as log of mean linear intercept versus axial bulk strain.

<table>
<thead>
<tr>
<th>ASTM Grain Size#</th>
<th>Strain Rate</th>
<th>Measuring Direction</th>
<th>Intercept and 95% CI</th>
<th>Slope and 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.05</td>
<td>Transverse</td>
<td>3.247 ± .052</td>
<td>-0.524 ± .103</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>3.249 ± .092</td>
<td>1.568 ± .183</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>Transverse</td>
<td>3.247 ± .038</td>
<td>-0.523 ± .085</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>3.321 ± .098</td>
<td>1.385 ± .218</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>Transverse</td>
<td>3.273 ± .043</td>
<td>-0.517 ± .092</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>3.273 ± .088</td>
<td>1.640 ± .191</td>
</tr>
<tr>
<td>5</td>
<td>0.05</td>
<td>Transverse</td>
<td>3.881 ± .039</td>
<td>-0.665 ± .079</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>3.844 ± .086</td>
<td>0.960 ± .176</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>Transverse</td>
<td>3.874 ± .040</td>
<td>-0.660 ± .088</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>3.863 ± .069</td>
<td>0.967 ± .151</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>Transverse</td>
<td>3.902 ± .037</td>
<td>-0.647 ± .078</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>3.886 ± .088</td>
<td>1.020 ± .187</td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
<td>Transverse</td>
<td>4.461 ± .030</td>
<td>-0.613 ± .062</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>4.506 ± .077</td>
<td>1.046 ± .161</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>Transverse</td>
<td>4.476 ± .029</td>
<td>-0.559 ± .064</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>4.533 ± .065</td>
<td>0.985 ± .141</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>Transverse</td>
<td>4.500 ± .026</td>
<td>-0.593 ± .057</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>4.536 ± .090</td>
<td>1.037 ± .198</td>
</tr>
</tbody>
</table>
3.2.2 Austenitic Stainless Steel

Micrographs of both longitudinal and transverse sections of type 310 austenitic stainless steel grain size #6 tested at strain rate 0.08/sec are presented in Fig. 3.2.11 - 3.2.13. The results of measuring the linear intercepts as described in previous chapter and curves fitted by linear least squares analysis are illustrated in Fig. 3.2.14. Table 3.2.2 summarizes the slopes and intercepts of the least square fits illustrated in Fig. 3.2.14.
(a) Longitudinal section. Axial direction is vertical. 200X

(b) Transverse section. Radial direction is vertical. 200X

Fig. 3.2.5 Microstructure of austenitic stainless steel grain size #6 tested at strain rate 0.08/sec sectioned at bulk strain equal to 0.34.
Fig. 3.2.6 Microstructure of austenitic stainless steel of grain size #6 tested at strain rate 0.08/sec sectioned at bulk strain equal to 0.46.
Fig. 3.2.7 Microstructure of austenitic stainless steel of grain size #6 tested at strain rate 0.08/sec sectioned at bulk strain equal to 0.76.
Fig. 3.2.8 Least square fit curves of the data of type 310 austenitic stainless steel ASTM GS#6 tested at strain rate 0.08/sec plotted as ln of mean linear intercept of both axial and transverse directions versus axial bulk strain.
Table 3.2.2
Summary of parameters obtained from linear least squares fit curve of the type 310 austenitic stainless steel data plotted as log of mean linear intercept versus axial bulk strain.

<table>
<thead>
<tr>
<th>ASTM Grain Size</th>
<th>Strain Rate Const.</th>
<th>Measuring Direction</th>
<th>Intercept and 95% CI</th>
<th>Slope and 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.05</td>
<td>Transverse</td>
<td>3.709 ± .047</td>
<td>-0.651 ± .111</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>3.685 ± .112</td>
<td>1.436 ± .263</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>Transverse</td>
<td>3.688 ± .047</td>
<td>-0.601 ± .100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>3.764 ± .105</td>
<td>1.540 ± .223</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>Transverse</td>
<td>3.707 ± .028</td>
<td>-0.588 ± .052</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>3.703 ± .130</td>
<td>1.682 ± .237</td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
<td>Transverse</td>
<td>4.372 ± .037</td>
<td>-0.580 ± .061</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>4.380 ± .120</td>
<td>1.413 ± .196</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>Transverse</td>
<td>4.352 ± .033</td>
<td>-0.589 ± .066</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>4.415 ± .130</td>
<td>1.488 ± .256</td>
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<tr>
<td></td>
<td>0.12</td>
<td>Transverse</td>
<td>4.382 ± .040</td>
<td>-0.558 ± .074</td>
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<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>4.321 ± .120</td>
<td>1.573 ± .221</td>
</tr>
<tr>
<td>2</td>
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<td>Transverse</td>
<td>5.227 ± .031</td>
<td>-0.509 ± .043</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>5.294 ± .103</td>
<td>1.227 ± .145</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>Transverse</td>
<td>5.230 ± .029</td>
<td>-0.560 ± .059</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>5.262 ± .101</td>
<td>1.120 ± .206</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>Transverse</td>
<td>5.217 ± .026</td>
<td>-0.526 ± .046</td>
</tr>
<tr>
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<td></td>
<td>Axial</td>
<td>5.257 ± .109</td>
<td>1.252 ± .191</td>
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</table>
3.2.3 Ferritic Stainless Steel

Micrographs of both longitudinal and transverse sections of type 446 ferritic stainless steel grain size #8 tested at strain rate 0.12/sec are presented in Fig. 3.2.21 - 3.2.23. The results of measuring the linear intercepts as described in previous chapter and curves fitted by linear least squares analysis are illustrated in Fig. 3.2.24. Table 3.2.3 summarizes the slopes and intercepts of the least square fits illustrated in Fig. 3.2.24.
Fig. 3.2.9  Microstructure of ferritic stainless steel
grain size #8 tested at strain rate 0.12/sec
sectioned at bulk strain equal to 0.19.
Fig. 3.2.10 Microstructure of ferritic stainless steel of grain size #8 tested at strain rate 0.12/sec sectioned at bulk strain equal to 0.30.
Fig. 3.2.11 Microstructure of ferritic stainless steel of grain size #8 tested at strain rate 0.12/sec sectioned at bulk strain equal to 0.66.
Fig. 3.2.12 Least square fit curves of the data of type 446 ferritic stainless steel ASTM GS#8 tested at strain rate 0.12/sec plotted as ln of mean linear intercept of both axial and transverse directions versus axial bulk strain.
Table 3.2.3
Summary of parameters obtained from linear least squares fit of the type 446 ferritic stainless steel data plotted as log of mean linear intercept versus axial bulk strain.

<table>
<thead>
<tr>
<th>ASTM Grain Size#</th>
<th>Strain Rate Const.</th>
<th>Measuring Direction</th>
<th>Intercept and 95% CI</th>
<th>Slope and 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.05</td>
<td>Transverse</td>
<td>3.125 ± .023</td>
<td>-0.461 ± .055</td>
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<tr>
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<td>Axial</td>
<td>3.110 ± .079</td>
<td>1.772 ± .188</td>
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<tr>
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<td>0.08</td>
<td>Transverse</td>
<td>3.127 ± .025</td>
<td>-0.529 ± .092</td>
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<tr>
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<td>Axial</td>
<td>3.121 ± .060</td>
<td>1.778 ± .225</td>
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<tr>
<td></td>
<td>0.12</td>
<td>Transverse</td>
<td>3.112 ± .025</td>
<td>-0.464 ± .068</td>
</tr>
<tr>
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<td></td>
<td>Axial</td>
<td>3.166 ± .053</td>
<td>1.766 ± .140</td>
</tr>
<tr>
<td>5</td>
<td>0.05</td>
<td>Transverse</td>
<td>4.076 ± .031</td>
<td>-0.585 ± .083</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>4.166 ± .078</td>
<td>1.614 ± .211</td>
</tr>
<tr>
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<td>0.08</td>
<td>Transverse</td>
<td>4.068 ± .026</td>
<td>-0.566 ± .074</td>
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<tr>
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<td></td>
<td>Axial</td>
<td>4.111 ± .057</td>
<td>1.633 ± .160</td>
</tr>
<tr>
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<td>0.12</td>
<td>Transverse</td>
<td>4.062 ± .028</td>
<td>-0.526 ± .080</td>
</tr>
<tr>
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<td></td>
<td>Axial</td>
<td>4.177 ± .075</td>
<td>1.558 ± .210</td>
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<tr>
<td>3</td>
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<td>4.827 ± .032</td>
<td>-0.677 ± .087</td>
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<tr>
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<td>4.836 ± .083</td>
<td>1.318 ± .224</td>
</tr>
<tr>
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<td>0.08</td>
<td>Transverse</td>
<td>4.805 ± .031</td>
<td>-0.696 ± .092</td>
</tr>
<tr>
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<td>Axial</td>
<td>4.868 ± .092</td>
<td>1.391 ± .276</td>
</tr>
<tr>
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<td>0.12</td>
<td>Transverse</td>
<td>4.813 ± .031</td>
<td>-0.709 ± .085</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial</td>
<td>4.804 ± .087</td>
<td>1.328 ± .242</td>
</tr>
</tbody>
</table>
3.3 TRUE STRESS - GRAIN STRAIN RELATIONSHIP

The mean linear intercept of grain boundaries in the axial direction for each material corresponding to the axial bulk strain at maximum load was estimated by using the parameters obtained from the linear least square fit of axial bulk strain $\gamma_a$ mean linear intercept of axial direction data. These mean linear intercepts are plotted with the corresponding true stresses and shown in Fig. 3.3.1 - Fig. 3.3.3 for electrical grade iron. Fig. 3.3.4 - Fig. 3.3.6 present the results of austenitic stainless steel. The results of ferritic stainless steel are shown in Fig. 3.3.7 - Fig. 3.3.9.
Fig. 3.3.1 The relationship of natural log of true stress and natural log of mean linear intercept of axial direction at maximum load of electrical grade iron tested at strain rate 0.05/sec.

Fig. 3.3.2 The relationship of natural log of true stress and natural log of mean linear intercept of axial direction at maximum load of electrical grade iron tested at strain rate 0.08/sec.
Fig. 3.3.3 The relationship of natural log of true stress and natural log of mean linear intercept of axial direction at maximum load of electrical grade iron tested at strain rate 0.12/sec.

Fig. 3.3.4 The relationship of natural log of true stress and natural log of mean linear intercept of axial direction at maximum load of austenitic stainless steel tested at strain rate 0.05/sec.
Fig. 3.3.5 The relationship of natural log of true stress and natural log of mean linear intercept of axial direction at maximum load of austenitic stainless steel tested at strain rate 0.08/sec.

Fig. 3.3.6 The relationship of natural log of true stress and natural log of mean linear intercept of axial direction at maximum load of austenitic stainless steel tested at strain rate 0.12/sec.
Fig. 3.3.7 The relationship of natural log of true stress and natural log of mean linear intercept of axial direction at maximum load of ferritic stainless steel tested at strain rate 0.05/sec.

Fig. 3.3.8 The relationship of natural log of true stress and natural log of mean linear intercept of axial direction at maximum load of ferritic stainless steel tested at strain rate 0.08/sec.
Fig. 3.3.9 The relationship of natural log of true stress and natural log of mean linear intercept of axial direction at maximum load of ferritic stainless steel tested at strain rate 0.12/sec.
4.1 OPTICAL SENSOR AND CONTROL FOR TESTING SYSTEM

The optical sensor and control scheme used on the closed loop testing system employed in these experiments has more advantages than the system described previously by Hartley and Jenkins [1]. In the previous system [1], a centering device was required to keep the portion of the specimen containing the minimum diameter in the scanning field of the vibrating mirror. Also an identifiable minimum cross-section had to be present in the initial specimen configuration. In the present system the specimen silhouette is sampled by the CCD diode. This method eliminated the need for a centering device, and for specimen to have an initial minimum diameter. Standard tensile specimens described by ASTM A370 could then be used. The constant true strain rate in the previous system [1] was obtained by adjustment of hardware, but the present system requires only sending a decimal number into the computer. This new development provides ease of operation and accuracy in obtaining the strain rate. Not only constant true strain rate can be selected for the test, but also other types of
strain rates, such as step functions, and sine waves can be chosen without any change of the hardware. Other advantages are that the test can be required to stop or pause at any interval of axial true strain rate, and the output data are ready in the computer for calculation and analysis without any additional work.

Some difficulties were encountered at the beginning of this experiment. After being converted to analog signal the digital command signal from the computer provided a step function rather than a continuous wave signal as in the previous system. This result reduced the strain rate to almost zero during the time between two successive command signals. This problem was corrected by installing a voltage filter into the circuit between the computer output and the MTS, resulting in a continuous signal, shown in Fig. 2.4.6, being received by the testing machine.

Despite the several advantages mentioned above, this system still has some limitations which can be removed. The 12 bit D/A converter can not convert to voltage decimal numbers greater than 4095. This results in limiting the constant true strain rate to a minimum of 0.05/sec. With a 16 bit D/A converter, capable of 65536 counts, and frictionless O-rings installed to the MTS, this system will be able to perform at much lower strain rates. When the constant strain rate was higher than 0.12/sec, the numbers of load-times data points were not sufficient to provide
accurate curve fitting. This resulted from the low sampling speed of the CCD diode, which was only 2 MHz. A faster CCD diode is required for higher strain rates. If the linear CCD diode array is replaced with a two dimensional array of CCD diodes with high resolution (now only 512x512 pixels is available), the speed of scanning will be increased and the scanning mirror will be no longer required. Doubling the number of CCD diode by installing a second linear array above the existing array will increase the scanning rate and permit a longer gauge section to be scanned by the system.

4.2 TRUE STRESS-TRUE STRAIN CURVES

Under the conditions in this study, electrical grade iron, austenitic stainless steel type 310, and ferritic stainless steel type 446 exhibited true stress-true plastic strain behavior described by two different forms of the generalized power law discussed in section 1.2.

A nonlinear regression curve fitting procedure was applied to all test data using saturation type equation and generalized power law discussed in section 1.2. The results that showed the best fit to all materials under the conditions in this study at all strain rate or grain size are the following forms of generalized power law:

\[ 0 < \varepsilon < \varepsilon_m, \]
\[ \sigma = \sigma_m \left( \frac{(\varepsilon + \varepsilon_0)}{(\varepsilon_m + \varepsilon_0)} \right)^{\varepsilon_m + \varepsilon_0}, \]

(4.2.1)
\[ \varepsilon_m \leq \varepsilon < \text{fracture}, \]

\[ \sigma = \sigma_m \exp\left[\frac{(\varepsilon + \varepsilon_0)}{n}\right] \left[\frac{((\varepsilon + \varepsilon_0)/(\varepsilon_m + \varepsilon_0))^{n-1}}{n-1}\right], \quad (4.2.2) \]

where \( \sigma_m \) and \( \varepsilon_m \) are the true stress and true plastic strain at maximum load, \( \varepsilon_0 \) a strain determined by the initial cold-worked state of the material, which vanishes in annealed materials, and \( n \) is a phenomenological material parameter. Equations (4.2.1) and equation (4.2.2) are similar to equations developed by Swift [7] and Hartley and Srinivasan [2], respectively.

The true stress-true plastic strain behavior of all materials under the conditions in this study, from the beginning point of uniform plastic deformation to the maximum load (zero loading rate), obey the relationship given in equation (4.2.1). The true stress-true plastic strain behavior from the maximum load to fracture obey the relationship given by equation (4.2.2) Table 3.1.1-3.1.3 presents material parameters calculated from test data. The parameters, \( \sigma_m \) and \( \varepsilon_m \), have the same value in both equations (4.2.1) and (4.2.2) for the same materials. The parameter \( n \) approaches zero during uniform deformation as described by equation (4.2.1). After necking occurs, the true stress-true plastic strain behavior obeys the relationship that include the parameter \( n \) as described by equation (4.2.2). Equation (4.2.1) is similar to a simple power law relationship that is often used to describe the true
stress-true plastic strain curve during uniform plastic deformation, i.e. Hollomon equation [8],

\[ \sigma = K_0 \varepsilon^P, \quad (4.2.3) \]

where \( K_0 \), the strength coefficient, is equal to \( \sigma_m \varepsilon_m^{-\varepsilon_m} \), and \( P \), the strain-hardening exponent, is equal to \( \varepsilon_m \). Equation (4.2.2) is a general form of generalized power law discussed in section 1.2 for describing the true stress-true plastic strain behavior at large plastic strain.

Two separate procedures were used to determine the values of the parameters \( \sigma_m \) and \( \varepsilon_m \) presented in Table 3.1.1-3.1.3. The data of load versus time were examined to obtain the value of maximum load (zero loading rate). The corresponding \( \sigma_m \) and \( \varepsilon_m \) were recorded in Table 3.1.1-3.1.3 under the heading "From Data". In many cases, the curvature of the load-time data near the maximum load point was very small, leading to considerable uncertainty in the determination of the elongation corresponding to maximum load. This uncertainty appears in the experimental values for \( \sigma_m \) and \( \varepsilon_m \) from data. Calculations show that these errors are less than 2% for \( \sigma_m \) and 5% for \( \varepsilon_m \).

A two-step fit of true stress-true plastic strain data using the nonlinear regression method described in section 2 led to the values of \( \sigma_m \), \( \varepsilon_m \), and parameter \( n \) given in Table 3.1.1-3.3.3. First, \( \sigma_m \) and \( \varepsilon_m \) from the measurement
of maximum load were used to estimate the value of $n$. During this step, the nonlinear fit iterated only on the parameter $n$, considering $\sigma_m$ and $\varepsilon_m$ as constants. In the second step, all values $\sigma_m'$, $\varepsilon_m'$, and $n$ obtained from the previous process were used as initial parameters of the iteration process of nonlinear regression procedure. The final values of parameters, $\sigma_m'$, $\varepsilon_m'$, and $n$ obtained by the nonlinear regression method after the iteration was completed were recorded in Table 3.1.1-3.1.3 under heading "Non Linear Regression Fitted Curve".

Table 3.1.1-3.1.3 shows that the parameters, $\sigma_m$ and $\varepsilon_m$, measured at maximum load, are similar to the corresponding parameters obtained from the curve fitting procedure. Fig. 3.1.1-3.1.9, Fig. 3.1.40-3.1.48, and Fig. 3.1.79-3.1.87 illustrate the excellent fit of equation (4.2.1) to the uniform plastic deformation region, and equation (4.2.2) to the non-uniform region. The nonlinear regression analysis gave a high significance of fit according to the F-test (Prob $>>$ 0.0001). These results support the use of the equation (4.2.1) and (4.2.2) to describe the true stress-true plastic strain relationship of materials in this study.

Fig. 3.1.10-3.1.12, 3.1.49-3.1.51, and 3.1.88-3.1.90 compare true stress-true plastic strain curves of electrical grade iron, austenitic stainless steel, and ferritic stainless steel tested at different strain rates. The
results do not show a significant variation of the true stress-true plastic strain curves with the strain rate. Fig. 3.1.16-3.1.24, 3.1.55-3.1.63 and 3.1.94-3.1.102 compare each parameter of the same material and grain size tested at different strain rate. The error bars on both sides of parameters are 95% confidence interval of corresponding parameters. Fig 3.1.34-3.1.36, 3.1.73-3.1.75, and 3.1.112-3.1.114 compare each parameter of all grain sizes of the same material tested at different strain rate. These graphs do not include 95% confidence interval. All of these results show that \( \sigma_m \) and \( n \) do not vary significantly with strain rate within the 95% confidence interval; \( \varepsilon_m \) decreased slightly as the strain rate increased. These results are similar to Hartley and Srinivasan's results [2] on annealed zircaloy-4 tested at room temperature.

Fig 3.1.13-3.1.15, 3.1.52-3.1.54, and 3.1.91-3.1.93 present the variation of true stress-true plastic strain curves of the same materials having different initial grain sizes tested at the same strain rate. Fig. 3.1.25-3.1.33, 3.1.64-3.1.72, and 3.1.103-3.1.111 present the variation of each parameter with initial mean linear intercept of the same material and strain rate. The error bars on both sides of data are the 95% confidence interval for the corresponding parameters. Fig. 3.1.37-3.1.39, 3.1.76-3.1.78, and 3.1.115-3.1.117 present the variation of each parameter with initial mean linear intercept of the
same material for different strain rates. The $\sigma_m$ observed in electrical grade iron and ferritic stainless steel slightly decreased with increasing initial mean linear intercept, whereas $\sigma_m$ for austenitic stainless steel does not show a significant change with grain size. Values of $\varepsilon_m$ for electrical grade iron appear to decrease with increasing initial mean linear intercept. Value of $\varepsilon_m$ for austenitic stainless steel appear to increase with increasing initial mean linear intercept. Values of $\varepsilon_m$ for the ferritic stainless steel did not depend on the value of initial mean linear intercept. Because of the limitation of the machine, and the annealing procedures, data for only three initial grain sizes for each material tested at three constant true strain rates 0.05/sec, 0.08/sec, and 0.12/sec, were available for analysis. However, under the conditions of this study, the results indicate that the true stress at maximum load (zero loading rate) decreases with increasing initial mean linear intercept for both electrical grade iron and ferritic stainless steel, and the true plastic strain at maximum load for most of the materials in this study decreases with increasing strain rate. The behavior of true stress-true plastic strain relationship between yield and at zero loading rate, $0 < \varepsilon < \varepsilon_m$, is accurately described by the Holloman equation [8], equation (4.2.3), and the parameters, $K_0$ and $P$, in Table 4.2.1. These two parameters
are calculated from $\sigma_m$ and $\varepsilon_m$ in Table 3.1.1-3.1.3 using the following equations,

$$ K_o = \sigma_m \varepsilon_m^{-\varepsilon_m} \quad (4.2.4) $$

and

$$ P = \varepsilon_m \quad (4.2.5) $$

The behavior of the true stress-true plastic strain relationship at large plastic strain beyond zero loading rate, $\varepsilon_m \leq \varepsilon < \text{fracture}$, is described by the generalized power law [2],

$$ \sigma = \sigma_m \exp\left\{\left(\frac{\varepsilon_m}{n}\right)[(\varepsilon/\varepsilon_m)^n - 1]\right\} \quad (4.2.6) $$

and the parameters in Table 3.1.1-3.1.3

As discussed in section 1.2, the generalized power law, equation (4.2.6), predicts that the slope of the true stress-true plastic strain curve reaches a minimum at some value of strain, $\varepsilon_C$. For strains greater than $\varepsilon_C$ the slope increases to $\infty$ as $\sigma \to \infty$. The critical strain, $\varepsilon_C$, can be calculated from equation (1.2.34) with $\varepsilon_0 = 0$ for annealed material,

$$ \varepsilon_C = \left[(1-n)/\varepsilon_m^{1-n}\right]^{1/n}. \quad (4.2.7) $$
Table 4.2.1
Summary of Parameters Calculated from Data in Table 3.1.1 - 3.1.3 for Hollomon Equation Describing the True Stress-True Plastic Strain Behavior Prior to Maximum Load.

<table>
<thead>
<tr>
<th>Material</th>
<th>Strain Rate (/sec)</th>
<th>Mean Linear Intercept (µm)</th>
<th>( K_0 ) (MPa)</th>
<th>P</th>
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Table 4.2.2  
Summary of the Critical at the Point of Inflection Calculated from Table 3.1.1-3.1.3 and the Fracture Strain Measured Experimentally

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<th>ε_c</th>
<th>Fracture Strain</th>
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<td>126.71</td>
<td>1.75</td>
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Values of $\varepsilon_c$ in this study were calculated from the parameters in Table 3.1.1-3.1.3 and are shown in Table 4.2.2. The values obtained from both types of stainless steel data shown in Table 4.2.2 indicate that the data fit equation (4.2.6) prior to the point of inflection at $\varepsilon_c$ in all cases. However, the values obtained for electrical grade iron data shown in Table 4.2.2 indicate that the point of inflection occurs at some value of strain between maximum load and fracture. The rates of work-hardening, $\frac{d\sigma}{d\varepsilon}$, of both types of stainless steel under the conditions of this study decrease after yield point as most metals and alloys and fracture prior to the point of inflection, $\varepsilon_c$. But the rate of work-hardening of electrical grade iron under the conditions of this study decreases continuously between the yield point and $\varepsilon_c$ and increases again after the point of inflection, $\varepsilon_c$, which occurs prior to fracture. Analysis of the slope of the true stress-true plastic strain curves for electrical grade iron from maximum load to fracture did not show a significant change in slope in all cases. At large plastic deformation of electrical grade iron specimens, the diameter was reduced to a very small size, therefore, the appearance of point of inflection before fracture point was possibly due to error in the reading of the optical sensor at large plastic deformation. Results of this study did not include the correction factor for triaxiality introduced by flow localization at necking.
region. Triaxial stress may possibly cause the point of inflection to appear and the work-hardening rate to increase before fracture.

This experiment suggests that the optical closed loop testing system used in this study should be modified by using a higher resolution D/A converter and higher speed CCD diode, a pair of CCD diode, or two dimensional arrays of scanning CCD diodes. A more accurate description of the dependence of true stress-true plastic strain rate curves on $\dot{\varepsilon}$ would be obtained by experiments on a wider range of strain rates than was possible this study.

Because of the difficulty of cold working materials used in this study, only three grain sizes were obtained by annealing cold-worked samples. A greater variety of grain sizes in the study would give a more accurate description of the dependence of true stress-true plastic strain curve on grain size.

Samples of electrical grade iron 0.5 inch in diameter should be used to reduce errors of diameter reading that might occur near fracture.

4.3 STEREOLOGICAL MEASUREMENTS OF GRAIN BOUNDARY NETWORK

Linear regression fits of the mean linear intercept of each material for each test condition plotted as $\ln \bar{\lambda}_a$ and $\ln \bar{\lambda}_t$ versus true axial strain, $\varepsilon_a$, gave a highly significant
linear fits according to the F-test (Prob > 0.0001) with percentages of variation (regression coefficient) falling in the ranges 0.72-0.93. Table 3.2.1-3.2.3 presents all parameters obtained from linear regression analysis.

As discussed in section 1.3, the principal bulk total true strains can be defined as

\[ \varepsilon_i = \ln\left(\frac{d_i^f}{d_i^O}\right) \quad i=1,2,3 \quad (4.3.1) \]

where \(d_i^f\) is the dimension after deformation, and \(d_i^O\) is the dimension before deformation. Dimensions are measured parallel to principal direction of deformation. The principal grain strain as described by Hartley and Unal [16] can also be defined as

\[ \varepsilon_i^g = \ln\left(\frac{\tilde{\lambda}_i^f}{\tilde{\lambda}_i^O}\right) \quad i=1,2,3 \quad (4.3.2) \]

where \(\tilde{\lambda}_i^f\) is the mean linear intercept of deformed structure and \(\tilde{\lambda}_i^O\) is the mean linear intercept of undeformed material, both measured along principal directions of deformation.

Therefore, the bulk true strain along the transverse direction of round specimen under tensile test can be defined as

\[ \varepsilon_t = \ln\left(\frac{R_f}{R^O}\right) \quad (4.3.3) \]
where $R$ is the radius of transverse section at the deformed region, $f$, and undeformed region, $o$. Equation (4.3.3) can be changed to

$$
\varepsilon_t = \ln\left[\frac{\pi(R_f)^2}{\pi(R_o)^2}\right]^{1/2},
$$

$$
\varepsilon_t = \frac{1}{2} \ln\left(\frac{A_f}{A_o}\right) (4.3.4)
$$

By the condition of volume constancy, then

$$
\varepsilon_t = -\frac{1}{2} \ln\left(\frac{L_f}{L_o}\right),
$$

$$
\varepsilon_t = -\frac{1}{2} \varepsilon_a (4.3.5)
$$

where $\varepsilon_a$ is the bulk true axial strain.

The grain strains are

$$
\varepsilon_a^g = \ln\left(\frac{\bar{\lambda}_a^f}{\bar{\lambda}_a^o}\right) (4.3.6)
$$

$$
\varepsilon_t^g = \ln\left(\frac{\bar{\lambda}_t^f}{\bar{\lambda}_t^o}\right) (4.3.7)
$$

where $\varepsilon_a^g$ and $\varepsilon_t^g$ are the grain strains along the axial and transverse direction respectively. $\bar{\lambda}_a^f$ and $\bar{\lambda}_t^f$ are the mean linear intercepts of deformed regions along the axial and transverse directions, and $\bar{\lambda}_o$ is the mean linear intercept of the undeformed region.
If deformation is homogeneous and uniform throughout the deformed material, then $\varepsilon_t = e^g_t$ and $\varepsilon_a = e^g_a$ which lead to the relationship of a natural logarithm of mean linear intercept of deformed and undeformed regions as

$$\ln(\bar{A}_t^f/\bar{A}_t^o) = \varepsilon_t = -1/2\varepsilon_a \quad (4.3.8)$$

and

$$\ln(\bar{A}_a^f/\bar{A}_a^o) = \varepsilon_a \quad (4.3.9)$$

Equations (4.3.8) and (4.3.9) are rearranged into two linear equations describing the relationship of grain strain to the bulk axial strain under the ideal homogeneous deformation,

$$\ln(\bar{A}_t^f) = \ln(\bar{A}_t^o) - 1/2\varepsilon_a \quad (4.3.8)$$

and

$$\ln(\bar{A}_a^f) = \ln(\bar{A}_a^o) + \varepsilon_a \quad (4.3.9)$$

where $\ln(\bar{A}^o)$ is the intercept of linear equation with slope of -0.5 for transverse direction and slope of 1 for axial direction.

The results of linear regression analysis of the natural logarithm of axial and transverse mean linear intercepts vs the natural logarithm of bulk axial strain shown in Table 3.2.1-3.2.3 the values for intercepts which agree with the natural logarithm of mean linear intercepts for undeformed material. The slopes obtained from the
analysis fall into the range 0.960-1.77 for axial direction and -0.461 to -0.709 for transverse directions. Slopes shown in Table 3.2.1-3.2.3 which representing the dependence of grain strains on bulk axial strain did not appear significantly different between strain rates or initial grain sizes.

Of the results shown in Table 3.2.1, the relation between grain strain and bulk axial strain at the necked region of electrical grade iron of ASTM grain size #7 tested at constant true strain rate of 0.05/sec are:

\[
\ln(\lambda_f) = 3.247 - 0.524 \varepsilon_a \quad (4.3.12)
\]

and

\[
\ln(\lambda_f) = 3.249 + 1.568 \varepsilon_a. \quad (4.3.13)
\]

The variation with bulk axial strain of the ratio of the axial and transverse mean linear intercepts

\[
\ln(\lambda_a/\lambda_f) = 0.002 + 2.092 \varepsilon_a, \quad (4.3.14)
\]

which is different from equation (4.3.10) and (4.3.11). The variation obtained for homogeneous and uniform deformation should be,

\[
\ln(\lambda_a/\lambda_f) = 1.5 \varepsilon_a. \quad (4.3.15)
\]
While the small value of the intercept in equation 4.3.14 is probably insignificant, the difference of slopes in equation (4.3.12) - (4.3.14) from the values predicted in equation (4.3.10) - (4.3.11) and (4.3.15) can result from a non-uniform distribution of grain strain in the neck region. Hartley et al [23] explained the results obtained from constant true strain rate tests of annealed 304 stainless steel by hypothesizing that the strain in the necked region was larger and more uniformly distributed at the inner region than the outer region. Then, the following equation was derived to replace equation (4.3.15),

\[
\ln\left(\frac{\varepsilon_f}{\varepsilon_t}\right) = 1.5 \left((1-C)\varepsilon_u + C\varepsilon_a\right),
\]

where \(C\) is a phenomenological coefficient and \(\varepsilon_u\) is the uniform strain calculated from the radius of the smallest value of the minimum section for which the deformation is uniform across the section. Table 4.3.1 summarizes these parameters.

Similar results to equations (4.3.12) - (4.3.13) were obtained from specimens of electrical grade iron having the same grain size, GS #7, but tested at different strain rates, 0.08/sec and 0.12/sec (see Table 3.2.1). Slopes obtained from the other two grain sizes of electrical grade iron, ASTM GS #5 and #4, gave different values from equations (4.3.12) - (4.1.13). The same results of slopes
Table 4.3.1
Summary of Parameters C and $\varepsilon^u_a$ in Equation (4.3.16)

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<th>$\varepsilon^u_a$</th>
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<td>0.087</td>
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<td>90.44</td>
<td>-0.053</td>
<td>-0.713</td>
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<td>0.12</td>
<td>26.30</td>
<td>-0.438</td>
<td>0.000</td>
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<td></td>
<td></td>
<td>50.92</td>
<td>-0.111</td>
<td>0.096</td>
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<td>90.44</td>
<td>-0.087</td>
<td>-0.277</td>
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<tr>
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<td>40.72</td>
<td>-0.391</td>
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<td>77.70</td>
<td>-0.329</td>
<td>-0.016</td>
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<td>40.72</td>
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<td>77.70</td>
<td>-0.421</td>
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<td>189.59</td>
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<td>22.90</td>
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<td>59.62</td>
<td>-0.466</td>
<td>-0.062</td>
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<td>126.71</td>
<td>-0.391</td>
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<td>0.12</td>
<td>22.90</td>
<td>-0.487</td>
<td>-0.074</td>
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<td>59.62</td>
<td>-0.389</td>
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<td>126.71</td>
<td>-0.358</td>
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changed at larger grain occurred with the austenitic stainless steel and ferritic stainless steel. Results in Table 3.2.2 - 3.2.3 show that the slopes decrease in specimens having the larger grain size. The problem might occur because of the difficulty of sampling the large grain. As grain size increases, the tensile sample contains fewer grains, and the numbers of intercepts with grain boundaries per unit length of test line decreases. In order to increase the numbers of intersection with grain boundaries, more micrograph of the closed area must be measured or lower magnification employed. Decreasing the number of intersections decreases the level of significance. This result a suggests that larger samples must be examined, requiring a larger testing machine. However, the slopes shown in Table 3.2.1-3.2.3 are not significantly different within the same material. The parameters obtained from specimens having the smallest grains are highly significant and preferred.

4.4 TRUE STRESS-GRAIN STRAIN RELATIONSHIP

Using equations (4.3.10) - (4.3.11) and the parameters obtained from Table 3.2.1-3.2.3 corresponding to selected materials and strain rates, the natural logarithm of mean linear intercept in the axial direction at maximum load was calculated for each material and strain rate. Fig.
3.3.1-3.3.9 present the variation of natural logarithm of true stress with the natural logarithm of mean linear intercept at maximum load. Results showed that the natural logarithm of true stress decreases as the natural logarithm of mean linear intercept of axial direction at maximum load increases for both electrical grade iron and ferritic stainless steel. The results do not indicate that the natural logarithm of true stress of austenitic stainless steel depend on the natural logarithm of mean linear intercept at maximum load.

These results are similar to the plot of true stresses at maximum load versus initial mean linear intercept. Therefore the true stress can be related to the natural logarithm of mean linear intercept of the deformed structure at various stages of deformation.

Under the materials and conditions in this study, a non-uniform distribution of strain occurred throughout the necked region as illustrated by the parameters given in Table 3.2.1-3.2.3. The relation between grain strain and bulk axial true strain may be written

\[
\ln(\lambda_i^f) = A + B_i \varepsilon_a
\]  

(4.4.1)

where \(i\) is the direction of measurement, \(A\) is the natural logarithm of mean linear intercept of initial grain size, and \(B_i\) is the slope of direction \(i\) received from Table 3.2.1
3.2.3 which is not significantly different on the same material. Therefore, the natural logarithm of true stress at any particular point at large plastic strain may be determined from the natural logarithm of mean linear intercept of the corresponding position by using the equation modified from equation (4.2.6) and equation (4.4.1) as

$$\ln(\sigma) - \ln(\sigma_m) = \left(\frac{\epsilon_m}{n}\right)\left\{\left[\ln(\bar{\epsilon}_i^f) - A_i\right]/(B_i \cdot \epsilon_m)\right\}^{n-1}$$  (4.4.2)

where $\sigma_m$, $\epsilon_m$, and $n$ are the corresponding parameters in Table 3.1.1-3.1.3. The parameters presented in Table 3.2.1-3.2.3 were obtained from the distribution of strain at necked region, therefore, these parameters are valid for deformation occurring after necking.
The following conclusions have been drawn concerning the new closed loop testing system as modified in this study, the behavior of true stress-true plastic strain curves under different conditions, and the evolution of grain structure of constant true strain rate tensile testing.

1. The closed loop testing system used in this study has several advantages:
   1.1 the system is easy to operate;
   1.2 the system works with any standard round shape specimen;
   1.3 the system works with a constant true strain rate or any specified form of strain rate;
   1.4 the system can be controlled to pause or stop at any selected time or any amount of true strain.

2. Limitations of the system and suggested improvements.
   2.1 At slow ram speed, there is some friction which cause the system to pause. This problem can be corrected by installing frictionless O-ring on the actutor ram.
   2.2 The resolution of the D/A converter used with the
system limits the minimum constant true strain rate to 0.05/sec. A new 16 bit D/A converter is required to let the system operate at strain rates lower than 0.05/sec.

2.3 The maximum strain rate of this system is limited to 0.12/sec. A CCD diode with faster scanning rate is required to obtain faster strain rates. A second diode may be added to the top of the existing one to decrease the scanning time. A two-dimensional array of scanning CCD diodes can correct this problem.

3. The behavior of true stress-true plastic strain curves of all materials under the conditions in this study can be described by two equations:

3.1 at $0 < \varepsilon < \varepsilon_m$

$$\sigma = K_0\varepsilon^p$$

3.2 at $\varepsilon_m \leq \varepsilon < \text{fracture}$

$$\sigma = \sigma_m \exp\left\{\left(\frac{\varepsilon_m}{n}\right)\left(\frac{\varepsilon}{\varepsilon_m}\right)^n\right\}$$

4. With increasing strain rate, the true plastic strain at maximum load of materials in this study appear to be decreased. The true stress at maximum load of all materials does not depend significantly on strain rate.
5. As the initial grain size became larger, the true stress at maximum load of electrical grade iron and ferritic stainless steel appear to be decreased. The true stress at maximum load of austenitic stainless steel does not appear to depend on the grain size. But the true plastic strain at maximum load appears to increase as the grain size increases. This effect does not occur in the electrical grade iron and ferritic stainless steel.

6. A point of inflection in true stress-true plastic strain curves is not found in either type of stainless steel but it appears in true stress-true plastic curves of electrical grade iron. This is possibly due to the effect of triaxial stress at necking region. Also the effect may be due to inaccuracies in measuring diameter at large strain. This effect causes the rate of work hardening to increase between the inflection point and fracture point.

7. The distribution of grain strain for all materials under the conditions in this study is found to be non-uniform over the entire necking region.

8. The form of the relation between grain strain and bulk axial strain of the materials under the conditions in this study is found independence of the strain rates and grain sizes.
9. In conditions similar to those employed in this study, the relation of grain strain to bulk axial strain should have the form

\[ \ln(\dot{\varepsilon}_i^f) = A + B_i \varepsilon_a. \]

10. The results of including the grain strain effect into the constitutive equations show that the true stress at maximum load of electrical grade iron and ferritic stainless steel can be expressed in terms of the mean linear intercept in the axial direction of the corresponding strain.

11. The relation between true stress-grain strain may be described by the following equation,

\[ \ln(\sigma/\sigma_m) = (\varepsilon_m/n)[(\ln(\dot{\varepsilon}_i^f)-A)/(B_i \cdot \varepsilon_m)]^{n-1}. \]

where \( A \) and \( B_i \) are phenomenological coefficients relating \( \dot{\varepsilon}_i^f \) to \( \varepsilon_a \).
REFERENCES


APPENDIX A

CCD Interface (R Gostkowski 8/7/84)
Window Comparator (R Gostkowski 8/7/84)
APPENDIX B

I. MTS CONTROL PROGRAM

10 DIM X%(1500), Y%(1500), Z%(1500), LV%(1500),
   DHU%(10), DLU%(10), DHD%(10), DLD%(10), NT$(3)
20 GOSUB 540 'Load screen command
30 CLS
40 GOSUB 5210
50 'Main Menu
60 LOCATE 1,1:PRINT "Main Menu"
70 FOR I = 2 TO 21:LOCATE I,1:PRINT CHR$(179)
80 NEXT I
90 LOCATE 1,1:PRINT CHR$(196)
100 FOR I = 2 TO 29:LOCATE I,1:PRINT CHR$(196)
110 NEXT I
120 LOCATE 1,1:PRINT CHR$(218)
130 FOR I = 2 TO 21:LOCATE I,1:PRINT " "
140 NEXT I
150 LOCATE 3,5:PRINT " F1_Menu & Exit Graph "
160 LOCATE 5,5:PRINT " F2_Sample Information "
170 LOCATE 7,5:PRINT " F3_Initial Data Read "
180 LOCATE 9,5:PRINT " F4_Calibration "
190 LOCATE 11,5:PRINT " F5_Type of Test "
200 LOCATE 13,5:PRINT " F6_Closed Loop Test "
210 LOCATE 15,5:PRINT " F7_Output Data "
220 LOCATE 17,5:PRINT " F8_Directory "
230 LOCATE 19,5:PRINT " F9_Simulated Test "
240 LOCATE 21,4:PRINT " F10_Exit "
250 COLOR FGND1,BGND1
260 A$ = INKEY$:IF A$ = "" THEN 250
270 A$ = RIGHT$(A$,1):ACS = ASC(A$)
280 IF ACS = 68 THEN 310
290 IF ACS < 60 OR ACS > 67 THEN 250
300 ON ACS-59 GOSUB 1580,810,970,7460,3350,3700,690,6100
310 'End program
320 END
330 'Switching Display to Color
340 DEF SEG = 0
350 'POKE &H410, (PEEK(&H410) AND &HCF) OR &H10
360 SCREEN 1,0,0,0 :SCREEN 0 :WIDTH 40

215
WIDTH 80 : LOCATE ,,1,6,7
RETURN
'Switching Display to Monochrome
DEF SEG = 0
POKE &H410,(PEEK(&H410) OR &H30)
SCREEN 0 : WIDTH 40 : WIDTH 80 : LOCATE ,,1,12,13
RETURN
'Screen format
ON ERROR GOTO 670
OPEN "display" FOR INPUT AS #1
INPUT #1, A$
CLOSE #1
BGND2 = ASC(LEFT$(A$, 1))-1
FGND2 = ASC(MID$(A$, 2, 1))-1
TMON = ASC(MID$(A$, 3, 1))-1
BGND3 = BGND2 : FGND3 = FGND2
FGND1 = ASC(MID$(A$, 6, 1))-8
BGND1 = ASC(MID$(A$, 7, 1))-1
RETURN
COLOR FGND2, BGND2 : CLS : LOCATE 23, 1 : COLOR
FGND1, BGND1
PRINT " Files in Drive "; CHR$(26)
COLOR FGND2, BGND2 : LOCATE 23, 20 : PRINT CHR$(15)
LOCATE 23, 20 : INPUT ",", A$
COLOR FGND1, BGND1 : CLS
FILES A$ + "*. *
LOCATE 23, 68 : PRINT "Fl_Main Menu"
A$ = INKEY$ : IF A$ = "" THEN 760
IF RIGHTS(A$, 1) <> CHR$(59) THEN 760
COLOR FGND2, BGND2 : CLS
RETURN
'REad initial value
COLOR FGND2, BGND2 : CLS
LOCATE 6, 37: COLOR FGND1, BGND1: PRINT " MENU"
COLOR FGND2, BGND2 : LOCATE 10, 31 : PRINT "1. Read Diameter"
LOCATE 13, 31 : PRINT "2. Read Load"
LOCATE 16, 31 : PRINT "3. Take off point"
LOCATE 23, 68 : PRINT "Fl_Main Menu"
LOCATE 23, 1 : COLOR FGND1, BGND1: PRINT " SELECT ONE"
CHR$(26)
COLOR FGND2, BGND2 : LOCATE 23, 16: PRINT CHR$(15) : LOCATE
23, 16
A$ = INKEY$ : IF A$ = "" THEN 900
IF RIGHTS(A$, 1) = CHR$(59) THEN 960
IF ASC(A$) < 49 OR ASC(A$) > 51 THEN 900
PRINT A$
ON ASC(A$) - 48 GOSUB 2750, 2470, 2880
GOTO 820
RETURN 'Calibration
COLOR FGND2,BGND2:CLS
LOCATE 6,37:COLOR FGND1,BGND1:PRINT "  MENU  ";
COLOR FGND2,BGND2:LOCATE 10,31:PRINT "1. Calibrate Load"
LOCATE 12,31 :PRINT "2. Calibrate LVDT"
LOCATE 14,31 :PRINT "3. Calibrate Mirror"
LOCATE 16,31 :PRINT "4. Calibrate Optical Sensor"
LOCATE 23,68 :PRINT "Fl_Main Menu"
LOCATE 23,1:COLOR FGND1,BGND1:PRINT "SELECT ONE ";
CHR$(26)
COLOR FGND2,BGND2:LOCATE 23,16:PRINT CHR$(15)
LOCATE 23,16 :A$ = INKEY$ :IF A$ = "" THEN 1080
IF RIGHTS(AS,1) = CHR$(59) THEN 1140
IF ASC(AS) < 49 OR ASC(A$) > 52 THEN 1080
PRINT A$
ON ASC(A$)-48 GOSUB 2600,1150,1270,4790
GOTO 990
RETURN
CLS:LOCATE 23,28 :PRINT "Press any key to start."
A$ = INKEY$:IF A$ = "" THEN 1160
CLS:OUT &H304,0 :OUT &H305,0
LOCATE 13,28 :PRINT "Measure length of the LVDT."
LOCATE 23,28 :PRINT "Press any key to continue."
A$ = INKEY$:IF A$ = "" THEN 1200
CLS:FOR I = 0 TO 255:OUT &H304,255:OUT &H305,I:NEXT I
LOCATE 13,28 :PRINT "Measure length of the LVDT."
LOCATE 23,28 :PRINT "Press any key to continue."
A$ = INKEY$:IF A$ = "" THEN 1240
FOR I = 255 TO 0 STEP -1:OUT &H304,0 :OUT &H305,I :NEXT I
RETURN
CLS:LOCATE 10,28:PRINT "1. MINIMUM : " ;NMR
LOCATE 12,28:PRINT "2. MAXIMUM : " ;XMR
LOCATE 14,28:PRINT "3. STEP : " ;SMR
LOCATE 16,28:PRINT "4. DELAY : " ;DELAY
LOCATE 18,28:PRINT "5. START (Press ESC to stop)"
LOCATE 23,1:COLOR FGND2,BGND1:PRINT " SELECT ONE : ";
COLOR FGND2,BGND2
LOCATE 23,17:PRINT CHR$(15):LOCATE 23,17
A$ = INKEY$:IF A$ = "" THEN 1340
IF ASC(A$) < 49 OR ASC(A$) > 53 THEN 1340
LOCATE 23,17 :PRINT A$
ON ASC(A$)-48 GOTO 1380,1400,1420,1440,1460
LOCATE 10,42 :INPUT "",NMR
GOTO 1330
LOCATE 12,42 :INPUT "",XMR
GOTO 1330
LOCATE 14,42 : INPUT "", SMR
GOTO 1330
LOCATE 16,42 : INPUT "", DELAY
GOTO 1330
FOR I = NMR TO XMR STEP SMR
OUT &H306,0 : OUT &H307, I
FOR J = 1 TO DELAY : NEXT J
NEXT I
FOR I = XMR TO NMR STEP -SMR
OUT &H306,0 : OUT &H307, I
FOR J = 1 TO DELAY : NEXT J
NEXT I
A$ = INKEY$ : IF A$ = CHR$(27) THEN 1560
GOTO 1460
RETURN
'REad previous information of last sample and give a new information.
CLS : COLOR FGND2, BGND2
COLOR FGND1, BGND1: LOCATE 1,37: PRINT " MENU " : COLOR FGND2, BGND2
LOCATE 3,14 : PRINT "1.Material
MAT$
LOCATE 4,14 : PRINT "2.Treatment
TRT$
STO$
LOCATE 6,14 : PRINT "4.Data Name
DAT$
LOCATE 7,14 : PRINT "5.Initial Diameter (ins)
ID
LOCATE 8,14 : PRINT "6.Simulated Load (lbs)
PS
LOCATE 9,14 : PRINT "7.Time Interval (sec)
TI
LOCATE 10,14 : PRINT "8.Strain Rate (/sec)
EO
LOCATE 11,14 : PRINT "9.Span Set
SPT
LOCATE 12,13 : PRINT "10.LVDT Max. Length (ins)
LML
LOCATE 13,13 : PRINT "11.# of Sweeps (stroke)
SD
LOCATE 14,13 : PRINT "12.# OF DELAY
DLY
LOCATE 15,13 : PRINT "13.Initial Load (#)
OP
LOCATE 16,13 : PRINT "14.Simulated Load (#)
FP
LOCATE 17,13 : PRINT "15.Initial Diameter (#)
OD
LOCATE 18,13 : PRINT "16.Off set Load (#)
LD
LOCATE 19,13 : PRINT "17.Off set Diameter (#)
SD
LOCATE 20,13 :PRINT "18.CONTINUE"
COLOR FGND1,BGND1:LOCATE 23,1:PRINT " SELECT ONE ";CHRS(26)
COLOR FGND2,BGND2:LOCATE 23,16:PRINT CHRS(15);" "
LOCATE 23,16:INPUT "",NM
IF NM < 1 OR NM > 18 THEN 1790
TM$ = TIME$ :DT$ = DATE$
ON NM GOTO 1850, 1860, 1870, 1880, 1890, 1900, 1910,
1920, 1930, 1940, 1950, 2010, 2020, 2030, 2040, 2050,
2060, 2070
LOCATE 3,41 :PRINT ""
:LOCATE 3,41 :INPUT "", MAT$ :GOTO 1790
LOCATE 4,41:PRINT ""
:LOCATE 4,41 :INPUT "",TRT$ :GOTO 1790
LOCATE 5,41:PRINT ""
:LOCATE 5,41:INPUT "",STO$ :GOTO 1790
LOCATE 6,41:PRINT ""
:LOCATE 6,41:INPUT "",DAT$ :GOTO 1790
LOCATE 7,41:PRINT ""
:LOCATE 7,41:INPUT "",ID :GOTO 1790
LOCATE 8,41:PRINT ""
:LOCATE 8,41:INPUT "",PS :GOTO 1790
LOCATE 9,41:PRINT ""
:LOCATE 9,41:INPUT "",TI :GOTO 1790
LOCATE 10,41:PRINT ""
:LOCATE 10,41:INPUT "",EO :GOTO 1790
LOCATE 11,41:PRINT ""
:LOCATE 11,41:INPUT "",SPT :GOTO 1790
LOCATE 12,41:PRINT ""
:LOCATE 12,41:INPUT "",LML :GOTO 1790
LOCATE 13,41:PRINT ""
:LOCATE 13,41:INPUT "",NSD%
IF NSD% > 1 THEN 1790
LOCATE 14,41:PRINT "# of sweeps must be greater
than 1 "
LOCATE 15,41:PRINT "",NSD%
LOCATE 16,41:PRINT ""
:LOCATE 16,41:INPUT "",OP :GOTO 1790
LOCATE 17,41:PRINT ""
:LOCATE 17,41:INPUT "",FP :GOTO 1790
LOCATE 18,41:PRINT ""
:LOCATE 18,41:INPUT "",OD :GOTO 1790
LOCATE 19,41:PRINT ""
:LOCATE 19,41:INPUT "",LD :GOTO 1790
GOTO 1790
LOCATE 14,41:PRINT ""
:LOCATE 14,41:INPUT "",DLY :GOTO 1790
LOCATE 15,41:PRINT ""
:LOCATE 15,41:INPUT "",DP :GOTO 1790
LOCATE 16,41:PRINT ""
:LOCATE 16,41:INPUT "",FP :GOTO 1790
LOCATE 17,41:PRINT ""
:LOCATE 17,41:INPUT "",OD :GOTO 1790
LOCATE 18,41:PRINT ""
:LOCATE 18,41:INPUT
LOCATE 19,41: PRINT "": LOCATE 19,41: INPUT 
"": SD : GOTO 1790

' Get parameters of displacement and diameter 
reduction equations.

COLOR FGND3, BGND3 : CLS
COLOR FGND1, BGND1: LOCATE 3, 25: PRINT "LVDT AND DIAMETER FUNCTIONS"
COLOR FGND1, BGND1: LOCATE 7, 23: PRINT "1ST FUNCTION: 
Y = a + b*X + c*X^2"
COLOR FGND3, BGND3: LOCATE 10, 23: PRINT "2ND FUNCTION: Y = d + e*X"
COLOR FGND3, BGND3: LOCATE 14, 23: PRINT "1ST AND 2ND FUNCTION JOINT AT j"
COLOR FGND1, BGND1: LOCATE 16, 23: PRINT "a = "; A1 : LOCATE 16, 43: PRINT "b = "; A2
COLOR FGND1, BGND1: LOCATE 17, 23: PRINT "c = "; A3 : LOCATE 17, 43: PRINT "d = "; A4
COLOR FGND1, BGND1: LOCATE 18, 23: PRINT "e = "; A5 : LOCATE 18, 43: PRINT "j = "; A6
COLOR FGND1, BGND1: LOCATE 23, 27: PRINT "Is there any change <y/n>?"
A$: = INKEY$: IF A$ = "" THEN 2200
IF A$ = "N" OR A$ = "n" THEN 2300
IF A$ <> "y" AND A$ <> "y" THEN 2190
LOCATE 23, 27: PRINT "": LOCATE 16, 27: PRINT 
"": LOCATE 16, 27: INPUT 
"": A1
COLOR FGND1, BGND1: LOCATE 16, 47: PRINT "": LOCATE 16, 47: INPUT 
"": A2
COLOR FGND1, BGND1: LOCATE 17, 27: PRINT "": LOCATE 17, 27: INPUT 
"": A3
COLOR FGND1, BGND1: LOCATE 17, 47: PRINT "": LOCATE 17, 47: INPUT 
"": A4
COLOR FGND1, BGND1: LOCATE 18, 27: PRINT "": LOCATE 18, 27: INPUT 
"": A5
COLOR FGND1, BGND1: LOCATE 18, 47: PRINT "": LOCATE 18, 47: INPUT 
"": A6
CLS: COLOR FGND1, BGND1: LOCATE 23, 1
PRINT "Would you like to save this information <Y/N>?"
COLOR FGND3, BGND3: LOCATE 23, 52: PRINT CHR$(15); "": LOCATE 23, 52
A$: = INKEY$: IF A$ = "" THEN 2330
PRINT A$
IF A$ = "N" OR A$ = "n" THEN 2400
IF A$ <> "y" AND A$ <> "y" THEN 2320
OPEN "title" FOR OUTPUT AS #1
GOSUB 4900
CLOSE #1
RETURN
'Read load and diameter and calibrate load-cell.

CLS
LOCATE 13,29 :PRINT "INITIAL LOAD READING!"
LOCATE 21,29 :PRINT "Press any key to start."
A$ = INKEY$ :IF A$ = "" THEN 2500
GOSUB 4440 'Read load
OP = P%
COLOR FGND2,BGND2:CLS:LOCATE 13,28 :PRINT "INITIAL LOAD = ";OP
LOCATE 21,28 :PRINT "Press any key to continue."
A$ = INKEY$ :IF A$ = "" THEN 2550
RETURN

'Calibrated load
COLOR FGND3,BGND3 :CLS
LOCATE 12,32:PRINT "CALIBRATED LOAD!"
LOCATE 14,28:PRINT "<Install shunt resistance>"
LOCATE 21,29:PRINT "Press any key to start."
A$ = INKEY$ :IF A$ = "" THEN 2640
GOSUB 4440 'Read load
FP = P%
CLS :LOCATE 12,29:PRINT "SIMULATED LOAD = ";FP
LOCATE 14,28:PRINT "<Remove shunt resistance out>"
LOCATE 21,28:PRINT "Press any key to continue."
A$ = INKEY$ :IF A$ = "" THEN 2700
RETURN

'Read initial diameter
COLOR FGND2,BGND2 :CLS
LOCATE 13,28:PRINT "INITIAL DIAMETER READING!"
LOCATE 21,29:PRINT "Press any key to start."
A$ = INKEY$ :IF A$ = "" THEN 2780
GOSUB 4600 'Read diameter
OD = D%
CLS :LOCATE 13,28:PRINT "INITIAL DIAMETER = ";OD
LOCATE 21,28:PRINT "Press any key to continue."
A$ = INKEY$ :IF A$ = "" THEN 2830
RETURN

'Zero load cells.
COLOR FGND2,BGND2 :CLS
LOCATE 21,29 : PRINT "Press any key to start."
A$ = INKEY$ : IF A$ = "" THEN 2920
CLS
LOCATE 6,35 : PRINT "LOAD IN LBS"
GOSUB 4440 ' Read load
LOCATE 13,36 : PRINT ""
LD = -(P% - OP)*.6975*PS/(FP - OP)
LOCATE 13,36 : PRINT LD : Y%(1) = P%
LOCATE 21,31 : PRINT "Press ESC to finish!"
A$ = INKEY$ : IF A$ = CHR$(27) THEN 3020
GOTO 2950
GOSUB 4600 ' Read diameter
CLS : SD = D% : X%(1) = D% : LOCATE 13,28 : PRINT "STARTING DIAMETER = " ; SD
LOCATE 21,28 : PRINT "Press any key to continue."
A$ = INKEY$ : IF A$ = "" THEN 3050
RETURN
' -----------------------------------------------
' Calculate the diameter required for every set of displacement.
'
CLS
LOCATE 13,22 : INPUT "Expected min. diameter (#) = ", MND%
LOCATE 13,22 : PRINT ""
LOCATE 13,30 : PRINT "CALCULATING DIAMETER!"
I = 0 : Z%(1) = SD
I = I + 1
Z%(I+1) = SD * EXP(-E0*TI*I/2)
IF Z%(I+1) > MND% THEN 3170
LOCATE 13,30 : PRINT "CALCULATION COMPLETE!"
LOCATE 21,25 : PRINT "Print diameter on screen <y/n>?"
A$ = INKEY$ : IF A$ = "" THEN 3220
IF A$ = "n" OR A$ = "N" THEN 3330
IF A$ <> "y" AND A$ <> "Y" THEN 3210
CLS : CNTS = 1 : LOCATE 25,1 : PRINT "PRESS ANY KEY TO CONTINUE."
FOR J = 1 TO I
CNTS = CNTS + 1
IF CNTS < 21 THEN 3320
A$ = INKEY$ : IF A$ = "" THEN 3300
CNTS = 1 : CLS : LOCATE 25,1 : PRINT "PRESS ANY KEY TO CONTINUE."
NEXT J
RETURN
' -----------------------------------------------
' MTS closed loop control program.
'1ST step setup
CLS :X%(1) = SD
F% = OD - Z%(2) :H% = OD - X%(1)
R% = F%*(A2 - F%*A3) - H%*(A2 - H%*A3) + A1
SUM%=0 :K=1 :LV%(K)=0 :R%=INT(R%/(NSD%*2-2) )
LOCATE 12,20:INPUT "INPUT MAXIMUM LVDT (ins) : ", MAXX
LOCATE 14,20:INPUT "INPUT MAXIMUM LOAD (lbs) : ", MAXY
LOCATE 23,1
COLOR FGND1,BGND1:PRINT " Press any key to START or ESC to quit. "
COLOR FGND3,BGND3 :LOCATE 23,43
A$ = INKEY$ :IF A$ = "" THEN 3470
IF A$ = CHR$(27) THEN 80
GOSUB 6940
A$ = INKEY$ :IF A$ = "" THEN 3470
COLOR FGND3,BGND3 :LOCATE 23,43
OUT &H302,0 :ITM$ = TIME$ :LOCATE 1,1 :PRINT CHR$(7)
GOSUB 5490
PRINT CHR$(7):FTM$ = TIME$
OUT &H304,0 :OUT &H305,0 'Return LVDT to zero
IF TMON = 1 THEN GOSUB 440
SCREEN 0,0,0 :COLOR FGND2,BGND2 :TM0$=MID$(ITM$,4,1)
:TM7$=MID$(FTM$,4,1)
TM1$ = MID$(ITM$,5,1) :TM2$ = MID$(ITM$,7,1) :TM3$ = MID$(ITM$,8,1)
TM4$ = MID$(FTM$,5,1) :TM5$ = MID$(FTM$,7,1) :TM6$ = MID$(FTM$,8,1)
TME=( ASC(TM4$)  - ASC(TM1$))*60 + (ASC(TM5$) - ASC(TM2$))*10 + (ASC(TM6$) - ASC(TM3$)) + (ASC(TM7$) - ASC(TM0$))*600
CLS:LOCATE 13,35:PRINT"TEST DONE!
LOCATE 15,28 :PRINT "Each step take "; INT(TME*1Q00/K);  " msec"
LOCATE 21,28 :PRINT " Press any key to continue. 
A$ = INKEY$ :IF A$ = "" THEN 3650
RETURN

'Print data on screen
COLOR FGND2,BGND2 :CLS
M% = INT(K/16)
IF M% = 0 THEN 3860
LOCATE 3,10:PRINT "No.";LOCATE 3,25:PRINT "Diameter"
LOCATE 3,40:PRINT "Load";LOCATE 3,55:PRINT "LVDT"
FOR I = 0 TO M%-1
FOR J = 1 TO 16
NEXT J
LOCATE 22,9 : PRINT "Press any key to continue."
A$ = INKEY$ : IF A$ = "" THEN 3830
CLS
NEXT I
CLS: LOCATE 3,10 : PRINT "No." : LOCATE 3,25 : PRINT "Diameter"
LOCATE 3,40 : PRINT "Load" : LOCATE 3,55 : PRINT "LVDT"
FOR J = 1 TO K-M%*16
NEXT J
LOCATE 22,29 : PRINT "Press any key to continue."
A$ = INKEY$ : IF A$ = "" THEN 3930
'
'Take the uncollected data out
CLS
LOCATE 13,28 : INPUT "Number of unused data ", NT
LOCATE 13,28 : PRINT " "
IF NT = 0 THEN 4030
K = K - NT : GOTO 3720
CLS: LOCATE 6,35 : COLOR FGND1, BGND1 : PRINT " COMMENT "
COLOR FGND2, BGND2
FOR I = 1 TO 3 : LOCATE 9+I*2,2 : PRINT I; "." : NEXT I
FOR I = 1 TO 3 : LOCATE 9+I*2,9 : INPUT ", NT$(I): NEXT I
CLS: COLOR FGND1, BGND1
LOCATE 23,1 : PRINT " Would you like to save data <Y/N>? ">
COLOR FGND2, BGND2 : LOCATE 23,40 : PRINT CHR$(15); " ": LOCATE 23,40
A$ = INKEY$ : IF A$ = ", THEN 4150
PRINT A$
IF A$ = "N" OR A$ = "n" THEN 4370
IF A$ <> "Y" AND A$ <> ",y" THEN 4140
LOCATE 13,37 : COLOR FGND1+16, BGND1 : PRINT " WAIT " : COLOR FGND2, BGND2
OPEN DAT$+.dat" FOR OUTPUT AS #1
WRITE #1,0F,FP
WRITE #1,OD,ID
WRITE #1,SD,LD
WRITE #1,K,PS
FOR I = 1 TO K
WRITE #1,X%(I),Y%(I)
WRITE #1,Z%(I),LV%(I)
NEXT I
CLOSE #1
OPEN DAT$+.txt FOR OUTPUT AS #1
GOSUB 4900
FOR I = 1 TO 3
IF NT$(I) = "" THEN 4350
WRITE #1,NT$(I)
NEXT I
CLOSE #1
RETURN

'REad load subroutine
SMP = 0
FOR I = 1 TO 50
OUT &H302,0
OUT &H300,0
IF INP(&H308) >= 128 THEN 4480
P% = INP(&H300)/16 + INP(&H301)*16
SMP = SMP+P%
NEXT I
P% = INT(SMP/50)
RETURN

'REad diameter subroutine
D% = 2048
OUT &H343,&H92 'Initialized controled register
FOR J = 1 TO 25
GOSUB 4660
NEXT J
RETURN
FOR I = NMR TO XMR STEP SMR
OUT &H306,0 :OUT &H307,I
IF INP(&H341) < 128 THEN 4680
RD% = INP(&H340) + (INP(&H341)AND 127)*256
IF D% > RD% THEN D% = RD%
NEXT I
FOR I = XMR TO NMR STEP -SMR
OUT &H306,0:OUT &H307,I
IF INF(&H341) < 128 THEN 4740
RD% = INF(&H340) + (INF(&H341) AND 127) * 256
IF D% > RD% THEN D% = RD%
NEXT I
RETURN
COLOR FGND3,BGND3:CLS:LOCATE 23,64
COLOR FGND1,BGND1:PRINT " <ESC>_DONE "
OUT &H343,&H92
D% = 2048:LOCATE 13,37
GOSUB 4660
PRINT "":LOCATE 13,37:PRINT D%
A$ = INKEY$
IF A$ = CHR$(27) THEN 4880
GOTO 4820
RETURN

'Save title subroutine

WRITE #1,MAT$
WRITE #1,TRT$
WRITE #1,STO$
WRITE #1,DAT$
WRITE #1,DT$
WRITE #1,TM$
WRITE #1,ID
WRITE #1,PS
WRITE #1,TI
WRITE #1,E0
WRITE #1,SPT
WRITE #1,A1,A2,A3
WRITE #1,A4,A5,A6
WRITE #1,LML,NSD%
WRITE #1,OP
WRITE #1,FP
WRITE #1,OD
WRITE #1,SD
WRITE #1,LD
WRITE #1,DLY
WRITE #1,NMR,XMLR,SMR
RETURN

'REad from title.

OPEN "title" FOR INPUT AS #1
INPUT #1,MAT$
INPUT #1,TRT$

INPUT #1,ST0$
5250 INPUT #1,DAT$
5260 INPUT #1,DT$
5270 INPUT #1,TM$
5280 INPUT #1,ID
5290 INPUT #1,PS
5300 INPUT #1, TI
5310 INPUT #1,EO
5320 INPUT #1, SPT
5330 INPUT #1, A1, A2, A3
5340 INPUT #1, A4, A5, A6
5350 INPUT #1, LML, NSD$
5360 INPUT #1, OP
5370 INPUT #1, FP
5380 INPUT #1, OD
5390 INPUT #1, SD
5400 INPUT #1, LD
5410 INPUT #1, DLY
5420 INPUT #1, NMR, XMR, SMR
5430 CLOSE #1
5440 RETURN
5450 '
5460 '
5470 '
5480 '-----------------------------------------------
5490 'Control LVDT, read diameter scan up and down, read load
5500 '  
5510 FOR J = 1 TO NSD%-1
5520 OUT &H304, DLU%(J) : OUT &H305, DHU%(J)  'Control LVDT, D/A-0
5530 FOR I = NMR TO XMR STEP SMR
5540 OUT &H306,0 : OUT &H307, I  'Control Mirror, D/A-1
5550 IF INP(&H341) < 128 THEN 5560  'Check flag
5560 RD% = INP(&H340)+(INP(&H341) AND 127)*256 'Read diameter
5570 IF X%(K) > RD% THEN X%(K) = RD%  'Keep smallest diameter
5580 NEXT I
5590 FOR J = 1 TO NSD%-1
5600 OUT &H304, DLU%(J) : OUT &H305, DHU%(J)  'Control LVDT, D/A-0
5610 FOR I = XMR TO NMR STEP -SMR
5620 OUT &H306,0 : OUT &H307, I  'Control Mirror, D/A-1
5630 IF INP(&H341) < 128 THEN 5640  'Check flag
5640 RD% = INP(&H340)+(INP(&H341) AND 127)*256 'Read diameter
5650 IF X%(K) > RD% THEN X%(K) = RD%  'Keep smallest diameter
NEXT I
NEXT J
IF X%(K) < MND% THEN 6050
OUT &H304,DL% :OUT &H305,DH% 'Control LVDT, D/A-0
SUM%=0
FOR I = 1 TO 10
OUT &H300,0
IF INP(&H308) >= 128 THEN 5730
Y% = INP(&H300)/16 + INP(&H301)*16
SUMY=SUMY + Y%
NEXT I
Y%(K)=INT(SUMY/10)
X11=INT(LV%(K)*.1171875)+83
:X22=171-INT(((Y%(K)-OP)*111.6*PS/((OP-FP)*MAXY))
IF X11 < 83 THEN X11=83
IF X11 > 563 THEN X11=563
IF X22 < 11 THEN X22=11
IF X22 > 171 THEN X22=171
LINE -(X11,X22)
F% = OD-Z%(K+1) :H% = OD-X%(K)
FO% = OD-Z%(K+1) :H0% = OD-Z%(K)
IF F% > A6 THEN 5900
R% = F%*(A2 + F%*A3) - H%*(A2 + H%*A3) + 1
RO% = FO%*(A2 + FO%*A3) - H0%*(A2 + H0%*A3) + 1
GOTO 5920
R% = (F% - H%)*A5 + .5
RO% = (FO% - H0%)*A5 + .5
R% = INT((R%-R1%)/(2*NSD%-2) + .5)
RO% = INT((RO%/(2*NSD%-2) + .5)
IF R% < RO% THEN R% = RO%
IF R% > 3*RO% THEN R% = 3*RO%
IF R% < 1 THEN R%=1
FOR J = 1 TO NSD%-1
SUM%=SUM%+R% :DHU%(J)=INT(SUM%/16)
:DLU%(J)=(SUM%-16*DHU%(J))*16
SUM%=SUM%+R% :DHD%(J)=INT(SUM%/16)
:DLD%(J)=(SUM%-16*DHD%(J))*16
NEXT J
K = K+1 :LV%(K)=SUM% :X%(K)=X%(K-1)
FOR DLAY = 1 TO DLY :NEXT DLAY
GOTO 5520
RETURN
---------------
'MTS simulated closed loop control program.
'1ST step setup
COLOR FGND3,BGND3:CLS:X%(1)=SD:Y%(1)=OP
F% = OD - Z%(2):H% = OD - SD
R% = F%*(A2 - F%*A3) - H%*(A2 - H%*A3) + A1
SUM%=0:K=1:LV%(K)=0
R%=INT(R%/((NSD%*2-2)
LOCATE 12,20:INPUT "INPUT MAXIMUM LVDT (ins) : ",
MAXX
LOCATE 14,20:INPUT "INPUT MAXIMUM LOAD (lbs) : ",
MAXY
COLOR FGND1,BGND1:PRINT " Press any key to START or
ESC to quit. ",
COLOR FGND3,BGND3:LOCATE 23,43
A$ = INKEY$:IF A$ = "" THEN 6220
IF AS = CHR$(27) THEN 6220
A$ = INKEY$:IF A$ = "" THEN 6220
RETURN
'Control LVDT
OUT &H302,0 :ITM$ = TIME$ :LOCATE 1,1:PRINT CHR$(7)
GOSUB 6430
PRINT CHRS(7):FTMS = TIMES
OUT &H304,0:OUT &H305,0:OUT &H306,0:OUT &H307,0
Screen 0,0,0:COLOR FGND2,BGND2
'Calculate time interval
TM0$ = MID$(ITM$,4,1):TM7$ = MID$(FTM$,4,1)
TM1$ = MID$(ITM$,5,1):TM2$ = MID$(ITM$,7,1)
TM3$ = MID$(ITM$,8,1)
TM4$ = MID$(FTM$,5,1):TM5$ = MID$(FTM$,7,1)
TM6$ = MID$(FTM$,8,1)
TME = (ASC(TM4$) - ASC(TM1$))*60 + (ASC(TM5$) -
ASC(TM2$))*10 + (ASC(TM6$) - ASC(TM3$)) + (ASC(TM7$) -
ASC(TM0$))*600
CLS:LOCATE 13,35:PRINT"TEST DONE!"
LOCATE 15,28 :PRINT "Each step take ";
INT(TME*1000/K); " msec"
LOCATE 21,28 :PRINT " Press any key to continue. ",
A$ = INKEY$:IF A$ = "" THEN 6410
RETURN
'Control LVDT, read diameter scan up and down, read
load
FOR J = 1 TO NSD%-1
OUT &H304,DLU%( J ) :OUT &H305,DUH%( J )
Mirror, D/A-0
FOR I = NMR TO XMR STEP SMR
OUT &H306,0 :OUT &H307,I
IF INP(&H341) < 128 THEN 6500
'Check flag
RD% = INP(&H340) + (INP(&H341) AND 127) * 256 'Read diameter

IF X%(K) > RD% THEN X%(K) = RD% 'Keep smallest diameter

NEXT I

OUT &H304, DLD%(J) : OUT &H305, DHD%(J) 'Control LVDT, D/A-0

FOR I = XMR TO NMR STEP -SMR

OUT &H306, 0 : OUT &H307, I 'Control Mirror, D/A-1

IF INP(&H341) < 128 THEN 6570 'Check flag

RD% = INP(&H340) + (INP(&H341) AND 127) * 256 'Read diameter

IF X%(K) > RD% THEN X%(K) = RD% 'Keep smallest diameter

NEXT I

NEXT J

IF Z%(K) < MND% THEN 6930

OUT &H304, DL% : OUT &H305, DH% 'Control LVDT, D/A-0

SUMY = 0

FOR I = 1 TO 10

OUT &H300, 0

IF INP(&H308) >= 128 THEN 6670

Y% = INP(&H300)/16 + INP(&H301)*16

SUMY = SUMY + Y%

NEXT I

Y%(K) = INT(SUMY/10)

X11 = INT(LV%(K) * .1171875) + 83

:X22 = 171 - INT((Y%(K) - OP) * 111.6 * PS / ((OP - FP) * MAXY))

IF X11 < 83 THEN X11 = 83

IF X11 > 563 THEN X11 = 563

IF X22 < 11 THEN X22 = 11

IF X22 > 171 THEN X22 = 171

LINE -(X11, X22)

F% = OD - Z%(K+1) : H% = OD - Z%(K)

IF F% > A6 THEN 6820

R% = F% * (A2 + F% * A3) - H% * (A2 + H% * A3) + 1

GOTO 6830

R% = (F% - H%) * A5 + .5

R% = INT((R% - R1%) / (2 * NSD% - 2) + .5)

IF R% < 1 THEN R% = 1

FOR J = 1 TO NSD%-1

SUM% = SUM% + R% : DLU%(J) = INT(SUM%/16)

: DLU%(J) = (SUM% - 16 * DLU%(J)) * 16

SUM% = SUM% + R% : DHD%(J) = INT(SUM%/16)

: DLD%(J) = (SUM% - 16 * DHD%(J)) * 16

NEXT J

K = K+1 : LUV%(K) = SUM% : X%(K) = 2048

SUM% = SUM% + R% : DH% = INT(SUM%/16) : DL% = (SUM% - 16 * DH%) * 16

: R1% = R%
LOCATE 1,4: PRINT "PRINT ME" 7390
IF SY = 0 THEN 7400
LOCATE 22,7: PRINT "PRINT ME" 7370
IF SX = 0 THEN 7380
NEXT I 7350

7410 TLY = TLY + 10 7420
LOCATE 23,4+I*6: PRINT TLX 7330
LOCATE 24,4+I*2+3: PRINT TLY 7320
FOR I = 1 TO 11 7310
NEXT I 7300

(LINE (177,5) TO 39) 7290
NEXT I 7270

FOR I = 83 TO 59 STEP 48 7250
MAX = MAXX*10 7240
NEXT I 7230

FOR I = 10 TO SY+10 7220
IF I > 990 THEN 7240 7210
NEXT I 7200

MAXX = SX+TLY 7190
MAX = SY+10 7180

LINE (83,11) TO (63,17) 7150
"15 "LOCATE 16,1: PRINT TLY 7130
"15 "LOCATE 15,1: PRINT TLY 7120
"15 "LOCATE 14,1: PRINT TLY 7110
"15 "LOCATE 13,1: PRINT TLY 7100
"15 "LOCATE 12,1: PRINT TLY 7090
"15 "LOCATE 11,1: PRINT TLY 7080
"15 "LOCATE 10,1: PRINT TLY 7070
"15 "LOCATE 9,1: PRINT TLY 7060
"15 "LOCATE 8,1: PRINT TLY 7050
"15 "LOCATE 7,1: PRINT TLY 7040

CLS: SCREEN 2 7030
IF I = THEN GOSUB 340 7020
K=I+1: T=I 7010
R = INT(K/N) 7000
NEXT J 6990

6980 LOCAL: PRINT "CYU/NSD-16*DH%" 6970
RETURN 6960
GOTO 6460 6950
FOR I = 1 TO NSD-1 6940
LOCATE 1,33 : PRINT "LVDT VS. LOAD"

X11 = 83
:X22 = 171 - INT((Y(1) - OP) * 111.6 * PS / ((OP - FP) * MAXY))

IF X22 < 11 THEN X22 = 11
IF X22 > 171 THEN X22 = 171
PSET (X11, X22)
RETURN

COLOR FGND3, BGND3 : CLS : LOCATE 5, 37 : COLOR FGND1, BGND1
PRINT " MENU ": COLOR FGND3, BGND3
LOCATE 8, 28 : PRINT "1. Strain Rate Constant"
LOCATE 10, 28 : PRINT "2. Change in Strain Rate"
LOCATE 12, 28 : PRINT "3. External File"
LOCATE 23, 68 : PRINT "F1_Main Menu"
LOCATE 23, 1 : COLOR FGND1, BGND1 : PRINT "SELECT ONE : "
COLOR FGND3, BGND3
LOCATE 23, 17 : PRINT CHR$(15) : LOCATE 23, 17
A$ = INKEY$: IF A$ = "" THEN 7540
IF RIGHTS(A$, 1) = CHRS(59) THEN 7610
IF ASC(A$) < 49 OR ASC(A$) > 52 THEN 7540
PRINT A$
ON ASC(A$) - 48 GOSUB 3090, 8220, 8560
GOSUB 7640
GOTO 7460
RETURN
CLS : LOCATE 12, 23 : PRINT "Maximum Time (sec) : "; TIME
LOCATE 14, 23 : PRINT "Maximum Strain (in/in): "; 2 * LOG(OD / Z(I))
PRINT "Press any key to change maximum time and strain." : COLOR FGND3, BGND3
LOCATE 23, 51 : A$ = INKEY$: IF A$ = "" THEN 7680
LOCATE 12, 48 : PRINT "": LOCATE 12, 49 : INPUT "", MAXX
LOCATE 14, 48 : PRINT "": LOCATE 14, 49 : INPUT "", MAXY
IF TMON = 1 THEN GOSUB 340
CLS : SCREEN 2
LOCATE 6, 1 : PRINT "S"
LOCATE 7, 1 : PRINT "T"
LOCATE 8, 1 : PRINT "R"
LOCATE 9, 1 : PRINT "A"
LOCATE 10, 1 : PRINT "I"
LOCATE 11, 1 : PRINT "N"
LOCATE 12, 1 : PRINT "N"
LOCATE 13, 1 : PRINT "I"
LOCATE 14, 1 : PRINT "N"
LOCATE 15, 1 : PRINT "/"
LOCATE 16,1 :PRINT "I"
LOCATE 16,1 :PRINT "N"
LOCATE 17,1 :PRINT "."
LINE (83,11)-(563,171),B
SX=0 :SY=0 :TX=0 :TY=0: ITX=MAXX/10: ITY=MAXY/10
IF ITX <= 990 THEN 7920
ITX = ITX/10 :SX=SXX-1
GOTO 7990
IF ITY >= .1 THEN 7950
ITY = ITY*10 :SY=SYY+1
GOTO 7920
ITX = MAXX*10~SXX/10 :ITY = MAXY*10~SYY/10
FOR L = 83 TO 563 STEP 48
LINE (L,174)-(L,171)
NEXT L
FOR L = 11 TO 171 STEP 16
LINE (77,L)-(83,L)
NEXT L
FOR L = 1 TO I
LOCATE 24-L*2,3 :PRINT TY0
LOCATE 23,4+L*6 :PRINT TX0
TX0=TX0 + ITX :TY0 = TYO + ITY
NEXT L
IF SX = 0 THEN 8090
LOCATE 22,74 :PRINT "E";(-SX)
IF SY = 0 THEN 8110
LOCATE 1,9 :PRINT "E";(-SY)
LOCATE 1,32:PRINT "STRAIN VS. TIME"
PSET (83,171)
FOR L = 1 TO I
LINE -(X11,X22)
NEXT L
A$ = INKEY$:IF A$ = "" THEN 8170
IF RIGHT*(A$,1) <> CHR$(59) THEN 8170
IF TMON = 1 THEN GOSUB 440
IF TMON = 0 THEN SCREEN 0
RETURN
CLS:LOCATE 13,22 :INPUT "Second Strain Rate (/sec) = ",E1
CLS:LOCATE 13,17 :INPUT "Number of Step for First Strain Rate = ",SE0
CLS:LOCATE 13,17 :INPUT "Number of Step for Second Strain Rate = ",SE1
CLS:LOCATE 13,22 :INPUT "Expected min. diameter (#) = ",MND%
LOCATE 13,22 :PRINT "

233
LOCATE 13,30:PRINT "CACULATING DIAMETER!"
8330 I = 0 :Z%(1) = SD
8340 FOR J = 1 TO SE0
8350 Z%(I+1) = Z%(I) * EXP(-E0*TI/2)
8360 IF Z%(I+1) < MND% THEN 8420
8370 NEXT J
8380 FOR J = 1 TO SE1
8390 Z%(I+1) = Z%(I) * EXP(-E1*TI/2)
8400 IF Z%(I+1) < MND% THEN 8420
8410 NEXT J
8420 LOCATE 13,30:PRINT "CALCULATION COMPLETE!"
8430 LOCATE 21,25:PRINT "Print diameter on screen <y/n>?"
8440 A$ = INKEY$:IF A$ = "" THEN 8440
8450 IF A$ = "n" OR A$ = "N" THEN 8550
8460 IF A$ <>"y" AND A$<>"Y" THEN 8430
8470 CLS :CNTS = 1 :LOCATE 25,1:PRINT "PRESS ANY KEY TO CONTINUE."
8480 FOR J = 1 TO I
8490 CNTS = CNTS + 1
8500 LOCATE CNTS,30 :PRINT Z%(J) :LOCATE CNTS,50 :PRINT Z%(J) - Z%(J+1)
8510 IF CNTS < 21 THEN 8540
8520 A$ = INKEY$:IF A$ = "" THEN 8520
8530 CNTS = 1 :CLS:LOCATE 25,1:PRINT "PRESS ANY KEY TO CONTINUE."
8540 NEXT J
8550 RETURN
8560
8570 CLS:LOCATE 23,1:COLOR FGND1,BGND1
8580 PRINT " Input controlled file's name : ":COLOR FGND2,BGND2
8590 LOCATE 23,35 :PRINT CHR$(15):LOCATE 23,35:INPUT "", DATC$
8600 Z%(1) = SD : I = 1
8610 OPEN DATC$ FOR INPUT AS #1
8620 IF EOF(1) THEN 8680
8630 INPUT #1,ZD%
8640 IF ZD% > SD THEN 8620
8650 I = I + 1
8660 Z%(I) = ZD%
8670 GOTO 8620
8680 CLOSE #1
8690 RETURN
II. UTILITY PROGRAM

10 DIM X(1500), Y(1500), A(50), R(20,20), T(50), Z(1500), LV(1500), NT$(3)
20 CLS
30 GOSUB 9330 'Load screen control
40 ' Menu
50 ' Menu
60 ' Menu
70 COLOR FGND2, BGND2
80 FOR I = 2 TO 21 : LOCATE I, 1 : PRINT CHR$(179) : LOCATE I, 30 : PRINT CHR$(179) : NEXT
90 FOR I = 2 TO 29 : LOCATE 1,I : PRINT CHR$(196) : LOCATE 22,[1 : PRINT CHR$(196) : NEXT
100 LOCATE 1,1 : PRINT CHR$(218) : LOCATE 22,1 : PRINT CHR$(192) : LOCATE 1,30 : PRINT CHR$(191) : LOCATE 22,30 : PRINT CHR$(217)
110 COLOR FGND1, BGND1
120 FOR I = 2 TO 21 : LOCATE I, 2 : PRINT " " : NEXT I
130 LOCATE 3,5 : PRINT " F1_Menu or Exit Graph "
140 LOCATE 5,5 : PRINT " F2_Creat Data "
150 LOCATE 7,5 : PRINT " F3_Verify Data "
160 LOCATE 9,5 : PRINT " F4_Convert Data (MTS) "
170 LOCATE 11,5 : PRINT " F5_Get Parameter (MTS) "
180 LOCATE 13,5 : PRINT " F6_Linear Regression "
190 LOCATE 15,5 : PRINT " F7_Files List "
200 LOCATE 17,5 : PRINT " F8_Plot Graph "
210 LOCATE 19,5 : PRINT " F9_Print data "
220 LOCATE 21,4 : PRINT " F10_Exit "
230 LOCATE 21,40 : PRINT " P_Page advance L_Line advance "
240 COLOR FGND2, BGND2
250 A$ = INKEY$ : IF A$ = "" THEN 250
260 IF LEFT$(A$, 1) = "P" OR LEFT$(A$, 1) = "p" THEN LPRINT CHR$(12);
270 IF LEFT$(A$, 1) = "L" OR LEFT$(A$, 1) = "l" THEN LPRINT CHR$(10);
280 IF ASC(RIGHT$(A$, 1)) < 60 OR ASC(RIGHT$(A$, 1)) > 68 THEN 250
290 ACS = ASC(RIGHT$(A$, 1)) - 59
300 ON ACS GOSUB 3740, 4580, 6530, 550, 7020, 9570, 350, 1950, 320
310 GOTO 50
320 'End program
330 END
340 '-----------------------------------------------
350 'Plot graph from giving files
360 '
370 GOSUB 4710
380 A$ = INKEY$ : IF A$ = "" THEN 380
390 IF RIGHT$(A$,1) <> CHR$(59) THEN 380
400 IF TMON = 1 THEN GOSUB 9230
410 IF TMON = 0 THEN SCREEN 0
420 COLOR FGND2,BGND2 :CLS
430 LOCATE 23,1 :COLOR FGND1,BGND1:PRINT "PLOT THE SAME
GRAPH <Y/N>? ";
440 COLOR FGND2,BGND2 :PRINT " ";CHR$(15) :LOCATE 23,30
450 A$ = INKEY$:IF A$ = "" THEN 450
460 IF A$ = "N" OR A$ = "n" THEN 500
470 IF A$ <> "Y" AND A$ <> "y" THEN 450
480 GOSUB 5040
490 GOTO 380
500 RETURN
510 '
520 '
530 '
540 '------------------------------------------------------
550 'Get parameters for LVDT-diameter function
560 COLOR FGND3,BGND3:CLS:LOCATE 23,1 :COLOR FGND1,BGND1
:PRINT"FILE'S NAME : ";
570 COLOR FGND3,BGND3:LOCATE 23,18:PRINT CHR$(15)
580 LOCATE 23,18 :INPUT "",DATS
590 DATS=DATS+.Id" :AXS="DIAMETER" :AYS="LVDT"
:UX$="#COUNTS" :UY$=UX$
600 TITLE$ = "LVDT-DIAMETER"
610 GOSUB 4900 'Plot graph
620 A$ = INKEY$:IF A$ = "" THEN 620
630 IF RIGHT$(A$,1) <> CHR$(59) THEN 620
640 IF TMON = 1 THEN GOSUB 9230
650 IF TMON = 0 THEN SCREEN 0
660 '
670 '------------------------------------------------------
680 'Divided data into 2 files
690 '
700 COLOR FGND3,BGND3 :CLS :LOCATE 23,1 :COLOR
FGND1,BGND1
710 PRINT "FIRST AND SECOND EQUATIONS JOIN AT DIAMETER";
CHR$(26); :COLOR FGND3,BGND3 :PRINT " ";CHR$(15)
720 LOCATE 23,49:INPUT "",XJ
730 N = 0
740 N = N+1
750 IF X(N) < XJ THEN 740
760 '
770 '
780 '
790 '------------------------------------------------------
800 'First function
810 '
820 D=2
830 FOR I = 1 TO 5 :A(I) = 0:NEXT I
840 FOR I = 1 TO 4 :T(I) = 0:NEXT I
850  A(1) = N
860  FOR I = 1 TO N
870  FOR J = 2 TO 5
880  A(J) = A(J) + X(I)^*(J-1)
890  NEXT J
900  FOR K = 1 TO 3
910  R(K,4) = T(K) + Y(I)*X(I)^*(K-1)
920  T(K) = T(K) + Y(I)*X(I)^*(K-1)
930  NEXT K
940  T(4) = T(4) + Y(I)^2
950  NEXT I
960  GOSUB 7700
970  A0 = R(1,4): A1 = R(2,4): A2 = R(3,4)
980  '-------------------------------------------
990  'Second equation
1000  '-------------------------------------------
1010  D=1
1020  FOR I = 1 TO 3: A(I) = 0: T(I) = 0: NEXT I
1030  A(1) = M-N
1040  FOR I = N+1 TO M
1050  FOR J = 2 TO 3
1060  A(J) = A(J) + X(I)^*(J-1)
1070  NEXT J
1080  FOR K = 1 TO 2
1090  R(K,3) = T(K) + Y(I)*X(I)^*(K-1)
1100  T(K) = T(K) + Y(I)*X(I)^*(K-1)
1110  NEXT K
1120  T(3) = T(3) + Y(I)^2
1130  NEXT I
1140  GOSUB 7700
1150  B0 = R(1,3): B1 = R(2,3)
1160  '-------------------------------------------
1170  'Plot graph from raw data and calculated data
1180  '-------------------------------------------
1190  'Plot graph from raw data
1200  '-------------------------------------------
1210  '-------------------------------------------
1220  '-------------------------------------------
1230  '-------------------------------------------
1240  '-------------------------------------------
1250  GOSUB 5040  'Plot graph from raw data
1260  IBGN = INT(480*(X(1)-MINX)/(MAXX-MINX)) + 83
1270  IEND1 = INT(480*(X(N)-MINX)/(MAXX-MINX)) + 83
1280  IEND2 = INT(480*(X(M)-MINX)/(MAXX-MINX)) + 83
1290  IF IBGN < 83 THEN IBGN = 83
1300  IF IBGN > 563 THEN IBGN = 563
1310  IF IEND1 > 563 THEN IEND1 = 563
1320  IF IEND2 > 563 THEN IEND2 = 563
1330  IF IEND1 < 83 THEN IEND1 = 83
1340  IF IEND2 < 83 THEN IEND2 = 83
1350  FOR I = IBGN TO IEND2 STEP 2
XI = MINX + (I-83)*(MAXX-MINX)/480
IF I > IEND1 THEN 1400
W = A0 + A1*XI + A2*XI^2
GOTO 1410
W = B0 + B1*XI
IF W < MINY THEN W = MINY
X2 = 171 - INT(160*(W-MINY)/(MAXY-MINY))
IF X2 > 171 THEN X2 = 171
IF X2 < 11 THEN X2 = 11
PSET (I,X2)
NEXT I
A$ = INKEY$ :IF A$ = "" THEN 1470
IF RIGHT$(A$,1) <> CHR$(59) THEN 1470
'Print parameters
IF TMON = 1 THEN GOSUB 9230
IF TMON = 0 THEN SCREEN 0
COLOR FGND2,BGND2 :CLS
LOCATE 6,34 :PRINT "AO = ";AO
LOCATE 8,34 :PRINT "A1 = ";A1
LOCATE 10,34 :PRINT "A2 = ";A2
LOCATE 12,34 :PRINT "B0 = ";B0
LOCATE 14,34 :PRINT "B1 = ";B1
LOCATE 16,34 :PRINT "JOIN AT ",XJ
LOCATE 22,31 :PRINT "Recalculate <y/n>?"
A$ = INKEY$ :IF A$ = "" THEN 1650
IF A$ = "n" OR A$ = "N" THEN 1720
IF A$ <> "y" AND A$ <> "Y" THEN 1650
GOSUB 5040 'Plot graph
A$ = INKEY$ :IF A$ = "" THEN 1690
IF A$ <> "y" AND A$ <> "Y" THEN 1690
GOTO 640
COLOR FGND2,BGND2 :CLS :LOCATE 23,1 :COLOR FGND1,BGND1
PRINT " Save in COEFF file ";COLOR FGND2,BGND2
OPEN "coeff" FOR OUTPUT AS #1
WRITE #1,A0,A1,A2
WRITE #1,B0,B1
WRITE #1,XJ
CLOSE #1
CLS
LOCATE 12,24 :PRINT "Interpolation:(enter 0 to end)"
LOCATE 14,40:PRINT " 
LOCATE 14,36:INPUT "X = ";XI
IF XI = 0 THEN 1910
IF XI > XJ THEN 1870
YI = A0 + A1*XI + A2*XI^2
1860  GOTO 1880
1870  YI = B0 + B1*XI
1880  LOCATE 16,40 :PRINT "Y = " ;YI
1900  GOTO 1810
1910  RETURN
1920  ' Print out data
1930  ' COLOR FGND2,BGND2 :CLS
1940  COLOR FGND2,BGND2 :CLS
1950  COLOR FGND2,BGND2 :CLS
1960  COLOR FGND2,BGND2 :CLS
1970  LOCATE 11,30 :PRINT "1. Title"
1980  LOCATE 13,30 :PRINT "2. Test data"
1990  LOCATE 21,31 :PRINT "3. Sequential file"
2000  LOCATE 23,30 :PRINT "Select number :" ;CHR$(15)
2010  LOCATE 23,47 :PRINT "Fl_Main Menu"
2020  LOCATE 21,47 :A$ = INKEY$ :IF A$ = "" THEN 2040
2030  IF RIGHTS(A$,1) = CHR$(59) THEN 2100
2040  PRINT A$
2050  ON ASC(A$) - 48 GOSUB 2620,3080,3380
2060  GOTO 1970
2070  RETURN
2080  LOCATE 11,30:LOCATE 13,30:LOCATE 15,30:LOCATE 21,31
2090  LOCATE 23,68 :PRINT "FILE'S NAME "
2100  LOCATE 23,15 :COLOR FGND2,BGND2 :CLS
2110  PRINT " FILE'S NAME ":LOCATE 23,15 :COLOR FGND2,BGND2
2120  PRINT " FILE'S NAME ":LOCATE 23,15 :COLOR FGND2,BGND2
2130  PRINT " FILE'S NAME ":LOCATE 23,15 :COLOR FGND2,BGND2
2140  OPEN 23,15 :INPUT "",DATS
2150  OPEN DATS+.txt" FOR INPUT AS #1
2160  INPUT #1,MATS
2170  INPUT #1,TRTS
2180  INPUT #1,STOS
2190  INPUT #1,DATS
2200  INPUT #1,DT$
2210  INPUT #1,TM$
2220  INPUT #1,ID
2230  INPUT #1,PS
2240  INPUT #1,TI
2250  INPUT #1,EO
2260  INPUT #1,SPT
2270  INPUT #1,A1,A2,A3
2280  INPUT #1,A4,A5,A6
2290  INPUT #1,LMIL,NSD%
2300  INPUT #1,OP
2310  INPUT #1,FP
2320  INPUT #1,OD
2330  INPUT #1,SD
2340  INPUT #1,LD
2350  INPUT #1, DELAY
2360  INPUT #1, NMR, XMR, SMR
2370  FOR I = 1 TO 3
2380  IF EOF(1) THEN 2410
2390  INPUT #1, NT$(I)
2400  NEXT I
2410  CLOSE #1
2420  RETURN

2430  COLOR FGND2, BGND2 :CLS :LOCATE 23, 1 :COLOR FGND1, BGND1
2440  PRINT " FILE'S NAME ":LOCATE 23, 15 :COLOR FGND2, BGND2 :PRINT CHR$(15)
2450  LOCATE 23, 15:INPUT ",,.dat" FOR INPUT AS #1
2460  OPEN DAT$+".dat" FOR INPUT AS #1
2470  INPUT #1, OP, FP
2480  INPUT #1, OD, ID
2490  INPUT #1, SD, LD
2500  INPUT #1, M, PS
2510  FOR I = 1 TO M
2520  INPUT #1, X(I), Y(I)
2530  INPUT #1, Z(I), LV(I)
2540  NEXT I
2550  CLOSE #1
2560  RETURN

2570  GOSUB 2120
2580  FOR I = 1 TO 7:LPRINT :NEXT I
2590  LPRTCHR$(27);CHR$(71);
2600  LPRTCHR$(27);CHR$(69);
2610  LPRTTAB(16) "Material and Setup"
2620  LPRTCHR$(27);CHR$(70);:LPRINT
2630  LPRT " ":MAT$
2640  LPRT "":TRT$
2650  LPRT "":STO$
2660  LPRT "":DAT$
2670  LPRT "":ID
2680  LPRT "":LML
2690  LPRT "":PS
2760 LPRINT "Time interval(sec) : "
2770 LPRINT "Strain rate(/sec) : 
2780 LPRINT "Span set 
2790 LPRINT "Time delay 
2800 LPRINT "Number of LVDT/step 
2810 LPRINT CHR$(27);CHR$(69);:LPRINT
2820 LPRINT TAB(15) "LVDT Control"
2830 LPRINT CHR$(27);CHR$(70);:LPRINT
2840 LPRINT "First function 
2850 LPRINT "Second function 
2860 LPRINT "Two functions join at reduction of diameter = 
2870 LPRINT "Offset load (#) 
2880 LPRINT "Load factor (#) 
2890 LPRINT "Offset diameter (#) 
2900 LPRINT "Starting diameter (#) 
2910 LPRINT "Starting load (lbs) 
2920 LPRINT "Mirror move from ;NMR; to ;XMR; with increment ;SMR; ."
2930 LPRINT CHR$(27);CHR$(69);:LPRINT
2940 LPRINT TAB(15) "Note :"
2950 LPRINT CHR$(27);CHR$(70);:
2960 FOR I = 1 TO 3
2970 IF NT$(I) = "" THEN 3040
2980 LPRINT :LPRINT TAB(18) NT$(I)
2990 NEXT I
3000 RETURN
3010 'Print data
3020 GOSUB 2440
3030 MM% = INT(M/45)
3040 IF MM% < 1 THEN 3240
FOR J = 1 TO MM%
FOR IP = 1 TO 7 :LPRINT :NEXT IP
LPRINT CHR$(27);CHR$(69);
LPRINT TAB(17) "No." TAB(27) "Actual" TAB(41) "Load"
TAB(51) "Calculated" TAB(66) "LVDT"
LPRINT TAB(26) "Diameter" TAB(50) "Diameter"
LPRINT CHR$(27);CHR$(70);:LPRINT
FOR K = 1 TO 45
I = (J-l)*45 + K
LPRINT TAB(15) I TAB(27) X(I) TAB(39) Y(I) TAB(52)
Z(I) TAB(64) LV(I)
NEXT K
LPRINT TAB(17) "No." TAB(27) "Actual" TAB(41) "Load"
TAB(51) "Calculated" TAB(66) "LVDT"
LPRINT TAB(26) "Diameter" TAB(50) "Diameter"
LPRINT CHR$(27);CHR$(70);:LPRINT
FOR I = MM%*45+1 TO M
LPRINT TAB(15) I TAB(27) X(I) TAB(39) Y(I) TAB(52)
Z(I) TAB(64) LV(I)
NEXT I
LPRINT CHR$(12);
RETURN

'Print data from sequential files
COLOR FGND2,BGND2 :CLS :LOCATE 23,1 :COLOR
FGND1,BGND1
PRINT " FILE'S NAME ":LOCATE 23,15 :COLOR FGND2,BGND2
:PRINT CHR$(15)
LOCATE 23,15:INPUT "",DAT$
COLOR FGND2,BGND2 :CLS :LOCATE 23,1 :COLOR
FGND1,BGND1
PRINT " X - Label ":LOCATE 23,15 :COLOR FGND2,BGND2
:PRINT CHR$(15)
LOCATE 23,15:INPUT "",XLB$
COLOR FGND2,BGND2 :CLS :LOCATE 23,1 :COLOR
FGND1,BGND1
PRINT " Y - Label ":LOCATE 23,15 :COLOR FGND2,BGND2
:PRINT CHR$(15)
LOCATE 23,15:INPUT "",YLB$
LOCATE 13,37:COLOR FGND1+16,BGND1:PRINT " WAIT"
COLOR FGND2,BGND2
OPEN DAT$ FOR INPUT AS #1
M = 0
IF EOF(1) THEN 3480
M = M + 1
INPUT #1,X(M),Y(M)
GOTO 3450
CLOSE #1
MM% = INT(M/45)
IF MM% < 1 THEN 3610
FOR J = 1 TO MM%
FOR IP = 1 TO 7 :LPRINT :NEXT IP
LPRINT TAB(30)"File's name : ";DAT$
:LPRINT:LPRINT
LPRINT TAB(20) "No." TAB(30) XLB$ TAB(50) YLB$ :LPRINT
FOR K = 1 TO 45
I = (J-1)*45 + K
LPRINT TAB(19) I TAB(30) X(I) TAB(50) Y(I)
NEXT K
LPRINT CHR$(12);
NEXT J
IF MM%*45 = M THEN 3690
FOR IP = 1 TO 7 :LPRINT :NEXT IP
LPRINT TAB(30)"File's name : ";DAT$
:LPRINT:LPRINT
LPRINT TAB(20) "No." TAB(30) XLB$ TAB(50) YLB$ :LPRINT
FOR I = MM%*45+1 TO M
LPRINT TAB(19) I TAB(30) X(I) TAB(50) Y(I)
NEXT I
LPRINT CHR$(12);
RETURN
RETURN
'Creat sequential data files
COLOR FGND3,BGND3 :CLS :LOCATE 23,1 :COLOR FGND1,BGND1
PRINT " FILE'S NAME ":COLOR FGND3,BGND3 :LOCATE 23,16:PRINT CHR$(15)
LOCATE 23,16 :INPUT ",",DAT$ :LOCATE 23,1 :COLOR FGND1,BGND1
PRINT " INPUT # OF X-Y PAIRS ":COLOR FGND3,BGND3:LOCATE 23,22:PRINT " ";
PRINT CHR$(15) :LOCATE 23,24 :INPUT ",",M
IF M < 1500 THEN 3840
CLS :LOCATE 13,25 :PRINT "Data must be less than 1500"
GOTO 3760
CLS:LOCATE 23,1:COLOR FGND1,BGND1:PRINT "X-VALUE
GENERATED BY COMPUTER <Y/N>?":COLOR FGND3,BGND3
LOCATE 23,41:PRINT CHR$(15):LOCATE 23,41
A$ = INKEY$:IF A$ = "":THEN 3850
IF A$ = "N" OR A$ = "n" THEN 3900
IF A$ <> "Y" AND A$ <> "y" THEN 3850
GOSUB 9680
GOTO 4010
CLS
FOR I = 1 TO M
LOCATE 6,30:PRINT "No.":I
LOCATE 12,30:PRINT "Input X":
LOCATE 14,30:PRINT "Input Y":
LOCATE 12,42:INPUT ":,X(I)
LOCATE 14,42:INPUT ":,Y(I)
LOCATE 12,42:PRINT " 
LOCATE 14,42:PRINT " 
LOCATE 6,20:PRINT " 
NEXT I
COLOR FGND2,BGND2:CLS
MP = INT(M/16)
FOR I = 0 TO MP-1
CLS
LOCATE 3,15:PRINT "No." :LOCATE 3,35:PRINT "X"
LOCATE 3,55:PRINT "Y"
FOR J = 1 TO 16
LOCATE J+4,15:PRINT I*16+J :LOCATE J+4,34:PRINT X(I*16+J)
LOCATE J+4,54:PRINT Y(I*16+J)
NEXT J
LOCATE 23,29:PRINT "Is there any change <y/n>?"
A$ = INKEY$:IF A$ = "":THEN 4130
LOCATE 23,29:PRINT " 
IF A$ = "n" OR A$ = "N" THEN 4240
IF A$ <> "y" AND A$ <> "y" THEN 4120
LOCATE 23,25:INPUT "Input x-y pairs' number : ",CHG
LOCATE 23,25:PRINT " 
CHGI = INT((CHG-1)/16) :CHGJ = CHG - CHGI*16 + 4
LOCATE CHGJ,34:PRINT 
LOCATE CHGJ,35:INPUT ":,X(CHG)
LOCATE CHGJ,55:INPUT ":,Y(CHG)
GOTO 4120
NEXT I
CLS
LOCATE 3,15:PRINT "No." :LOCATE 3,35:PRINT "X"
LOCATE 3,55:PRINT "Y"
FOR J = 1 TO M-MP*16
LOCATE J+4,15:PRINT MP*16+J :LOCATE J+4,34:PRINT X(MP*16+J)
LOCATE J+4,54:PRINT Y(MP*16+J)
NEXT J
LOCATE 23,29 :PRINT "Is there any change <y/n>?"
A$ = INKEY$ :IF A$ = "" THEN 4330
LOCATE 23,29 :PRINT ""
IF A$ = "n" OR A$ = "N" THEN 4440
IF A$ <> "y" AND A$ <> "Y" THEN 4320
LOCATE 23,25 :INPUT "Input x-y pairs' number : ",CHG
LOCATE 23,25 :PRINT ""
CHGI = INT((CHG-1)/16) ;CHGJ = CHG - CHGI*16 + 4
LOCATE CHGJ,34 :PRINT ""
LOCATE CHGJ,35 :INPUT "",X(CHG)
LOCATE CHGJ,55 :INPUT "",Y(CHG)
GOTO 4320
CLS :LOCATE 23,29 :PRINT "Is there any change <y/n>?"
A$ = INKEY$ :IF A$ = "" THEN 4450
IF A$ = "Y" OR A$ = "y" THEN 4010
IF A$ <> "N" AND A$ <> "n" THEN 4450
OPEN DAT$ FOR OUTPUT AS #1
FOR I = 1 TO M
WRITE #1,X(I),Y(I)
NEXT I
CLOSE #1
RETURN
COLOR FGND3,BGND3 :CLS :LOCATE 23,1 :COLOR FGND1,BGND1
PRINT " FILE'S NAME ":COLOR FGND3,BGND3 :LOCATE 23,16:PRINT CHR$(15)
LOCATE 23,16 :INPUT "",DAT$
OPEN DAT$ FOR INPUT AS #1
M = 0
IF EOF(1) THEN 4670
M = M + 1
INPUT #1,X(M),Y(M)
GOTO 4630
CLOSE #1
GOSUB 4010
RETURN
'Plot stress-strain, strain-time, and LVDT-diameter curves.
'Title

COLOR FGND3,BGND3 :CLS
LOCATE 4,32 :PRINT "GRAPH PLOTTING"
LOCATE 8,25 :PRINT "Data files must be........."
LOCATE 10,28 :PRINT "1. sequencial data files"
LOCATE 12,28 :PRINT "2. maximum 1500 data pairs"
LOCATE 14,28 :PRINT "3. pairs of X-Y in a sequence"
COLOR FGND3,BGND3 :LOCATE 23,19 :PRINT "DATA FILE'S NAME ";CHR$(26);
COLOR FGND3,BGND3 :LOCATE 23,21 :INPUT ",",DAT$
OPEN DAT$ FOR INPUT AS #1
M = 0
IF EOF(1) THEN 4960
M = M + 1
INPUT #1,X(M),Y(M)
GOTO 4920
CLOSE #1
MAXX = X(1) :MAXY = Y(1) :MINX = X(1) :MINY = Y(1)
FOR I = 1 TO M
IF X(I) > MAXX THEN MAXX = X(I)
IF X(I) < MINX THEN MINX = X(I)
IF Y(I) > MAXY THEN MAXY = Y(I)
IF Y(I) < MINY THEN MINY = Y(I)
NEXT I
COLOR FGND2,BGND2 :CLS
LOCATE 2,7 :PRINT "1." :LOCATE 2,10 :COLOR FGND1,BGND1
PRINT "Title ";COLOR FGND2,BGND2 :PRINT " ";TITLE$
LOCATE 4,7 :PRINT "2." :LOCATE 4,10 :COLOR FGND1,BGND1
PRINT "X-lable ";COLOR FGND2,BGND2 :PRINT " ";AX$
LOCATE 6,7 :PRINT "3." :LOCATE 6,10 :COLOR FGND1,BGND1
PRINT "Y-lable ";COLOR FGND2,BGND2 :PRINT " ";AY$
LOCATE 8,7 :PRINT "4." :LOCATE 8,10 :COLOR FGND1,BGND1
PRINT "X-unit ";COLOR FGND2,BGND2 :PRINT " ";UX$
LOCATE 10,7 :PRINT "5." :LOCATE 10,10:COLOR FGND1,BGND1
PRINT " Y-unit ";:COLOR FGND2,BGND2 :PRINT " ";UY$
LOCATE 12,7 :PRINT "6." :LOCATE 12,10:COLOR FGND1,BGND1
PRINT " Maximum-X ";:COLOR FGND2,BGND2 :PRINT " ";MAXX :LOCATE 13,10
COLOR FGND1,BGND1:PRINT " Minimum-X ";:COLOR FGND2,BGND2:PRINT " ";MIXN
LOCATE 15,7 :PRINT "7." :LOCATE 15,10:COLOR FGND1,BGND1
PRINT " Maximum-Y ";:COLOR FGND2,BGND2 :PRINT " ";MAXY :LOCATE 16,10
COLOR FGND1,BGND1 :PRINT " Minimum-Y ";:COLOR FGND2,BGND2:PRINT " ";MINY
LOCATE 18,7 :PRINT "8." :LOCATE 18,10:COLOR FGND1,BGND1
PRINT " Grid <y/n> ";:COLOR FGND2,BGND2 :PRINT " ";GID$
LOCATE 20,7 :PRINT "9." :LOCATE 20,10:COLOR FGND1,BGND1
PRINT " CONTINUE ":COLOR FGND2,BGND2
LOCATE 23,24 :PRINT " ";MAXX :LOCATE 23,24:COLOR FGND1,BGND1 
PRINT "Select your choice. ";:CHR$(26);
LOCATE 23,22 :COLOR FGND2,BGND2 :PRINT " ";CHR$(15)
LOCATE 23,68 :PRINT "F1_Main Menu"
LOCATE 23,24
A$ = INKEY$:IF A$ = "" THEN 5300
IF RIGHTS(A$,1) « CHRS(59) THEN 50
IF ASC(A$) < 48 OR ASC(A$) > 57 THEN 5300
PRINT A$
ON ASC(A$) - 48 GOTO 5360, 5380, 5400, 5420, 5440, 5460, 5490, 5520, 5560
GOTO 5250
LOCATE 2,24 :PRINT " ";LOCATE 2,24:INPUT "",TITLE$
GOTO 5250
LOCATE 4,24 :PRINT " ";LOCATE 4,24:INPUT "",AX$
GOTO 5250
LOCATE 6,24 :PRINT " ";LOCATE 6,24:INPUT "",AY$
GOTO 5250
LOCATE 8,24 :PRINT " ";LOCATE 8,24:INPUT "",UX$
GOTO 5250
LOCATE 10,24 :PRINT " ";LOCATE 10,24:INPUT "",UY$
GOTO 5250
LOCATE 12,24 :PRINT " ";LOCATE 12,24:INPUT "",MAXX
LOCATE 13,24:PRINT "13,24:INPUT ",MINX
GOTO 5250
LOCATE 15,24:PRINT "15,24:INPUT ",MAXY
LOCATE 16,24:PRINT "16,24:INPUT ",MINY
GOTO 5250
LOCATE 18,24:PRINT "18,24:INPUT ",GID$
IF GID$ = "y" OR GID$ = "Y" THEN GRID = 1
IF GID$ = "n" OR GID$ = "N" THEN GRID = 0
GOTO 5250
LOCATE 15,24:PRINT "15,24:INPUT ",MAXY
LOCATE 16,24:PRINT "16,24:INPUT ",MINY
GOTO 5250
LOCATE 18,24:PRINT "18,24:INPUT ",GID$
IF UX$ = "" THEN AAX$ = AX$ ELSE AAX$ = AX$+4
+CHR$(4)+UX$+CHR$(4)
IF UY$ = "" THEN AAY$ = AY$ ELSE AAY$ = AY$+4
+CHR$(4)+UY$+CHR$(4)
IF TMON = 1 THEN GOSUB 9130
'Graph plot
CLS:SCREEN 2:CX = LEN(AAX$) :CY = LEN(AAY$)
CXP = 40 - INT(CX/2) :CYP = 11 - INT(CY/2)
FOR I = 1 TO CX
LOCATE 25,CXP+I :PRINT MID$(AAX$,1,1)
NEXT I
FOR I = 1 TO CY
LOCATE I+CYP,1 :PRINT MID$(AAY$,1,1)
NEXT I
LINE (83,11)-(563,171),,B
XI = INT(480*(X(I)-MINX)/(MAXX-MINX)) + 83
X2 = 171 - INT(160*(Y(I)-MINY)/(MAXY-MINY))
IF XI < 83 THEN XI = 83
IF XI > 564 THEN XI = 564
IF X2 > 171 THEN X2 = 171
IF X2 < 11 THEN X2 = 11
PSET (XI,X2)
FOR I = 2 TO M
XI = INT(480*(X(I)-MINX)/(MAXX-MINX)) + 83
X2 = 171 - INT(160*(Y(I)-MINY)/(MAXY-MINY))
IF XI < 83 THEN XI = 83
IF XI > 564 THEN XI = 564
IF X2 > 171 THEN X2 = 171
IF X2 < 11 THEN X2 = 11
LINE -(XI,X2)
NEXT I
'Make tick mark
SX = 0 :SY = 0
ITX = (MAXX-MINX)/10 :ITY = (MAXY-MINY)/10
5920 IF ITX >= .01 THEN 5950
5930 ITX = ITX * 10 : SX = SX + 1
5940 GOTO 5920
5950 IF ITX <= 990 THEN 5980
5960 ITX = ITX/10 : SX = SX - 1
5970 GOTO 5950
5980 IF ITY >= .01 THEN 6010
5990 ITY = ITY * 10 : SY = SY + 1
6000 GOTO 5980
6010 IF ITY <= 990 THEN 6040
6020 ITY = ITY/10 : SY = SY - 1
6030 GOTO 6010
6040 TX0 = MINX*10^-SX : TY0 = MINY*10^-SY
6050 ITX = (MAXX-MINX)*10^-SX/10 : ITY = (MAXY-MINY)*10^-SY/10
6060 FOR I = 83 TO 563 STEP 48
6070 LINE (I,174)-(I,171)
6080 IF GRID = 0 THEN 6120
6090 FOR J = 171 TO 11 STEP -2
6100 PSET (I,J)
6110 NEXT J
6120 NEXT I
6130 FOR I = 11 TO 171 STEP 16
6140 LINE (77,I)-(83,I)
6150 IF GRID = 0 THEN 6190
6160 FOR J = 83 TO 563 STEP 3
6170 PSET (J,I)
6180 NEXT J
6190 NEXT I
6200 FOR I = 1 TO 11
6210 IF SY < 0 THEN 6280
6220 IF MAXY > 99.99 OR ABS(MINY) > 99.99 THEN 6280
6230 IF MAXX > 9.99 OR ABS(MINX) > 9.99 THEN 6260
6240 LOCATE 24-I*2,4 : PRINT USING "#.##"; TY0
6250 GOTO 6290
6260 LOCATE 24-I*2,4 : PRINT USING "###.##"; TY0
6270 GOTO 6290
6280 LOCATE 24-I*2,4 : PRINT USING "####.##"; TY0
6290 IF SX < 0 THEN 6360
6300 IF MAXX > 99.99 OR ABS(MINX) > 99.99 THEN 6360
6310 IF MAXX > 9.99 OR ABS(MINX) > 9.99 THEN 6340
6320 LOCATE 23,4+I*6 ; PRINT USING "#.##"; TX0
6330 GOTO 6370
6340 LOCATE 23,3+I*6 ; PRINT USING "#.##"; TX0
6350 GOTO 6370
6360 LOCATE 23,4+I*6 ; PRINT TX0
6370 TX0 = TX0 + ITX : TY0 = TY0 + ITY
6380 NEXT I
6390 ' Label unit and title
6400 IF SX = 0 THEN 6420
6410 LOCATE 22,74 ; PRINT "E"; LOCATE 22,76; PRINT USING "*#"; (-SX)
IF SY = 0 THEN
LOCATE 1,9 :PRINT "E" :LOCATE 1,11:PRINT USING
"##":(-SY)
TLE = LEN(TITLE$):TLEX = 40 - INT(TLE/2)
LOCATE 1,TLEX :PRINT TITLE$
RETURN

'This program will read data files and convert to
1. stress-strain file (se),
2. strain-time file (et),
3. LVDT-diameter file (ld),
4. LVDT-load (lp).

'Get file
GOSUB 2120
GOSUB 2470
CLS: LOCATE 10,22 :PRINT "STRESS-STRAIN SAVE IN"
";DAT$;".SE FILE"
LOCATE 12,22 :PRINT "STRAIN-TIME SAVE IN ";DAT$;".ET FILE"
LOCATE 14,22 :PRINT "LVDT-DIAMETER SAVE IN"
";DAT$;".LD FILE"
LOCATE 16,22 :PRINT "LVDT-LOAD SAVE IN ";DAT$;".LP FILE"
LOCATE 18,22 :PRINT "LVDT-STRAIN SAVE IN ";DAT$;".LE FILE"
OPEN DAT$+.se FOR OUTPUT AS #1
OPEN DAT$+.lp FOR OUTPUT AS #2
OPEN DAT$+.LE FOR OUTPUT AS #3
FOR I = 1 TO M
P = -(Y(I)-OP)*.6975*PS/(FP-OP)
A = .7853982*(X(I)*ID/OD)^2
S = P/A
E = 2*LOG(OD/X(I))
WRITE #1,E,S
WRITE #2,LVII,P
WRITE #3,LVII,E
NEXT I
CLOSE #1
CLOSE #2
CLOSE #3
OPEN DAT$+.et FOR OUTPUT AS #1
6870 FOR I = 1 TO M
6880 E = 2*LOG(OD/X(I))
6890 WRITE #1,I*TI,E
6900 NEXT I
6910 CLOSE #1
6920 OPEN DAT$+".ld" FOR OUTPUT AS #1
6930 FOR I = 1 TO M
6940 D = OD - X(I)
6950 WRITE #1,D,LV(I)
6960 NEXT I
6970 CLOSE #1
6980 RETURN

6990 1
7000 1
7010 1

7020 'N/th order regression, data must be in the sequential data files

7030 1
7040 1
7050 'Title
7060 1
7070 COLOR FGND2,BGND2 :CLS
7080 LOCATE 13,31 :PRINT "LINEAR REGRESSION"
7090 LOCATE 15,30 :PRINT "<Maximum 18 degree>"
7100 LOCATE 23,1 :COLOR FGND1,BGND1 :PRINT " FILE'S NAME "
7110 COLOR FGND2,BGND2 :LOCATE 23,16 :PRINT CHR$(15)
7120 LOCATE 23,16 :INPUT "",DAT$
7130 LOCATE 23,1 :COLOR FGND1,BGND1 :PRINT " DEGREE OF EQUATION "
7140 LOCATE 23,21 :PRINT " "
7150 LOCATE 23,23 :PRINT CHR$(15) :LOCATE 23,23 :INPUT "",D
7160 1
7170 1
7180 1

7200 'Initialize the variable
7210 1
7220 1
7230 1
7240 FOR I = 1 TO 2*D+1
7250 A(I)=0
7260 NEXT I
7270 FOR I = 1 TO D+2
7280 T(I)=0
7290 NEXT I
7300 1
7310 1
7320 1
7330 1

7340 'Get data from sequential data files
7350 1
7360 OPEN DAT$ FOR INPUT AS #1
N = 0
IF EOF(1) THEN 7420
N = N + 1
INPUT #1,X(N),Y(N)
GOTO 7380
CLOSE #1
M = N

'Calculation

A(1) = N
FOR I = 1 TO N
FOR J = 2 TO 2*D+1
A(J) = A(J) + X(I)^(J-1)
NEXT J
FOR K = 1 TO D+1
R(K,D+2) = T(K) + Y(I)*X(I)^(K-1)
T(K) = T(K) + Y(I)*X(I)^(K-1)
NEXT K
T(D+2) = T(D+2) + Y(I)^2
NEXT I
GOSUB 7700
GOSUB 8880
GOSUB 8090
RETURN

'Solve the system of equations in the matrices

FOR J = 1 TO D+1
FOR K = 1 TO D+1
R(J,K) = A(J+K-1)
NEXT K
NEXT J
FOR J = 1 TO D + 1
FOR K = J TO D + 1
IF R(K, J) <> 0 THEN 7850
NEXT K
NEXT K
CLS
LOCATE 13,30 : PRINT "NO UNIQUE SOLUTION!"
PRINT CHR$(7): PRINT CHR$(7) : FOR I = 1 TO 500 : NEXT I
GOTO 50
FOR I = 1 TO D + 2
S = R(J,I)
R(J,I) = R(K,I)
253

7880 R(K,I)=S
7890 NEXT I
7900 Z=1/R(J,J)
7910 FOR I = 1 TO D+2
7920 R(J,I)=Z*R(J,I)
7930 NEXT I
7940 FOR K = 1 TO D+1
7950 IF K = J THEN 8000
7960 Z=-R(K,J)
7970 FOR I = 1 TO D+2
7980 R(K,I)=R(K,I)+Z*R(J,I)
7990 NEXT I
8000 NEXT K
8010 NEXT J
8020 "
8030 "
8040 "
8050 RETURN
8060 "
8070 "
8080 "
8090 'Printing results
8100 IF TMON = 1 THEN GOSUB 9230
8110 IF TMON = 0 THEN SCREEN 0
8120 COLOR FGND3,BGND3 :CLS
8130 LOCATE 3,24 :PRINT "Constant : ":R(1,D+2)
8140 'Print equation coefficients
8150 FOR J = 1 TO D
8160 LOCATE 3+J,23 :PRINT J:"Degree Coeff. : ";R(J+1,D+2)
8170 NEXT J
8180 LOCATE 22,28 :PRINT "Press any key to continue."
8190 A$ = INKEY$ :IF A$ = "" THEN 8190
8200 "
8210 "
8220 "
8230 "
8240 'Compute regression analysis
8250 "
8260 P=0
8270 FOR J = 2 TO D+1
8280 P=P+R(J,D+2)*(T(J)-A(J)*T(1)/N)
8290 NEXT J
8300 Q=T(D+2)-T(1)^2/N
8310 Z=Q-P
8320 ICD=N-D-1
8325 IF ICD < 1 THEN ICD = 1
8330 JC=P/Q
8340 COLOR FGND3,BGND3 :CLS
8350 LOCATE 8,23 :PRINT "Correlation coeff. : ":SQR(JC)
LOCATE 12,23 :PRINT "Standard error : ",SQR(Z/ICD)

LOCATE 21,28 :PRINT "Press any key to continue."

LOCATE 23,19 :PRINT "P-Print out R-Recalculate S-Save curve fit"

LOCATE 23,68 :PRINT "F1_Main Menu"

A$ = INKEY$ : IF A$ = "" THEN 8400

IF RIGHTS(A$,1) = CHRS(59) THEN 8740

IF AS = "P" OR AS = "p" THEN GOSUB 9480

IF AS = "P" OR AS = "p" THEN 8400

IF AS = "S" OR AS = "s" THEN GOSUB 8760

IF AS = "S" OR AS = "s" THEN 8340

IF AS <> "r" AND AS <> "R" THEN 8590

CLS : LOCATE 23,1 : COLOR FGND1,BGND1 : PRINT " DEGREE OF EQUATION "

COLOR FGND3,BGND3 : LOCATE 23,23 : PRINT CHR$(15)

FOR I = 1 TO 2*D+1
  A(I) = 0
NEXT I

FOR I = 1 TO D+2
  T(I) = 0
NEXT I

GOTO 7470

'Compute y-coordinate from entered x-coordinate

CLS

LOCATE 12,24 : PRINT "Interpolation: (enter 0 to end) "

P=R(1,D+2)

LOCATE 14,40 : PRINT " "

LOCATE 14,36 : INPUT "x = ",X

IF X = 0 THEN 8740

FOR J = 1 TO D
  P=P+R(J+1,D+2)*X^J
NEXT J

LOCATE 16,40 : PRINT " 

LOCATE 16,36 : PRINT "y = ",P

PRINT

GOTO 8630

RETURN

CLS : LOCATE 23,1 : COLOR FGND1,BGND1 : PRINT " FILE'S NAME OF CURVE FIT "

COLOR FGND2,BGND2 : LOCATE 23,29 : PRINT CHR$(15)

LOCATE 23,29 : INPUT 

LOCATE 13,37:COLOR FGND1+16,BGND1:PRINT " WAIT ":COLOR FGND2,BGND2
OPEN "linear.fit" FOR INPUT AS #1
OPEN DOUT$ FOR OUTPUT AS #2
IF EOF(1) THEN 8840
INPUT #1, XI, P
WRITE #2, XI, P
GOTO 8815
CLOSE
RETURN

';

Plot graph from raw data and calculated data

GOSUB 4970 'Plot graph from raw data
OPEN "linear.fit" FOR OUTPUT AS #1
IBGN = INT(480*(X(1)-MINX)/(MAXX-MINX))+83
IEND = INT(480*(X(N)-MINX)/(MAXX-MINX))+83
IF IBGN < 83 THEN IBGN = 83
IF IBGN > 563 THEN IBGN = 563
IF IEND > 563 THEN IEND = 563
IF IEND < 83 THEN IEND = 83
FOR I = IBGN TO IEND STEP 2
XI = MINX + (1-83)*(MAXX-MINX)/480
P = R(1,D+2)
FOR J = 1 TO D
P = P + R(J+1,D+2)*XI^J
NEXT J
X2 = 171-INT(160*(P-MINY)/(MAXY-MINY))
IF X2 > 171 THEN X2 = 171
IF X2 < 11 THEN X2 = 11
PSET (I,X2)
NEXT I
CLOSE #1
A$ = INKEY$: IF A$ = "" THEN 9080
IF RIGHT$(A$,1) <> CHR$(59) THEN 9080
RETURN

Switching Display to Color

DEF SEG = 0
POKE &H410, (PEEK(&H410) AND &HCF) OR &H10
SCREEN 1,0,0,0
SCREEN 0
WIDTH 40
WIDTH 80
LOCATE ,,1,6,7
RETURN
'Switching Display to Monochrome

DEF SEG = 0
POKE &H410,(PEEK(&H410) OR &H30)
SCREEN 0
WIDTH 40
WIDTH 80
LOCATE ,,1,12,13
RETURN
'Screen control
ON ERROR GOTO 9460
OPEN "display" FOR INPUT AS #1
INPUT #1,A$
CLOSE #1
BGND2 = ASC(LEFT$(A$,1))-1
FGND2 = ASC(MID$(A$,2,1))-1
TMON = ASC(MID$(A$,3,1))-1
BGND3 = BGND2
FGND3 = FGND2
FGND1 = ASC(MID$(A$,6,1))-8
BGND1 = ASC(MID$(A$,7,1))-1
RETURN
LPRINT TAB(24) "Constant" TAB(45) ":" TAB(50)
R(1,D+2)
FOR J = 1 TO D
LPRINT TAB(23) J;"Degree Coeff." TAB(45) ":" TAB(50)
R(J+1,D+2)
NEXT J
LPRINT TAB(24) "Correlation coeff." TAB(45) ":"
TAB(50) SQR(JC)
LPRINT TAB(24) "Standard error" TAB(45) ":" TAB(50)
SQR(Z/ICD)
RETURN
COLOR FGND2,BGND2 :CLS :LOCATE 23,1 :COLOR
FGND1,BGND1
PRINT " Files in Drive ";CHR$(26)
COLOR FGND2,BGND2 :LOCATE 23,20 :PRINT CHR$(15)
LOCATE 23,20 :INPUT ":",A$
COLOR FGND1,BGND1 :CLS
FILES A$+".*"
LOCATE 23,68 :PRINT "Fl_Main Menu"
A$ = INKEY$ :IF A$ = "" THEN 9640
IF RIGHTS(A$,1) <> CHR$(59) THEN 9640
COLOR FGND2,BGND2 :CLS
RETURN
CLS :LOCATE 23,1 :COLOR FGND1,BGND1 :PRINT " MINIMUM X "
COLOR FGND3,BGND3 :LOCATE 23,14:PRINT CHR$(15)
LOCATE 23,14 :INPUT ":",X(1)
CLS:LOCATE 23,1:COLOR FGND1,BGND1:PRINT "X_INCREMENT"
COLOR FGND3,BGND3:LOCATE 23,16:PRINT CHR$(15)
LOCATE 23,16:INPUT "",DXG
CLS
FOR I = 1 TO M
LOCATE 6,30:PRINT "No.":I
LOCATE 12,30:PRINT "Input X:"
LOCATE 14,30:PRINT "Input Y:"
LOCATE 12,41:PRINT X(I)
LOCATE 14,42:INPUT "",Y(I)
LOCATE 12,42:PRINT ""
LOCATE 14,42:PRINT ""
LOCATE 6,20:PRINT ""
X(I+1) = X(I) + DXG
NEXT I
RETURN
III. NONLINEAR ANALYSIS PROGRAM

10 DIM X(700), Y(700), B(4), Z(600,4), ZPY(4), DB(4), HMX(4,4), HMXI(4,4), Y0(700), C(4)
20 DEFDBL H
30CLS
40GOSUB 3510 'Load screen command 'Help command
50 COLOR FGNDD2, BGNDD2
60 FOR I = 2 TO 21 :LOCATE I,1 :PRINT CHR$(179) :LOCATE I,30 :PRINT CHR$(179) :NEXT
70 FOR I = 2 TO 29 :LOCATE 1,I :PRINT CHR$(196) :LOCATE 22,I :PRINT CHR$(196) :NEXT
80 LOCATE 1,1 :PRINT CHR$(218) :LOCATE 22,1 :PRINT CHR$(192) :LOCATE 1,30 :PRINT CHR$(191) :LOCATE 22,30 :PRINT CHR$(217)
90 POWER = 0:COLOR FGNDD1, BGNDD1
100 FOR I = 2 TO 21 :LOCATE I,2 :PRINT "F" .NEXT I
110 LOCATE 3,5:PRINT "F1_Menu or Exit Graph "
120 LOCATE 5,5 :PRINT "F2_Load Data"
130 LOCATE 7,5:PRINT "F3_Unit Changed"
140 LOCATE 9,5:PRINT "F4_Print/Save Data"
150 LOCATE 11,5:PRINT "F5_Mergs and Sort Data"
160 LOCATE 13,5:PRINT "F6_Power (n=0)"
170 LOCATE 15,5:PRINT "F7_Power and Power"
180 LOCATE 17,5:PRINT "F8_File's list"
190 LOCATE 19,5:PRINT "F9_Plot Graph"
200 LOCATE 21,5 :PRINT "F10_Exit"
210 COLOR FGNDD2, BGNDD2
220 LOCATE 21,40 :COLOR FGNDD2, BGNDD2 :PRINT "P_Page Advance " :COLOR FGNDD2, BGNDD2
230 LOCATE 23,64 :A$ = INKEY$ :IF A$ = "" THEN 260
240 IF A$ = "P" OR A$ = "p" THEN LPRINT CHR$(12);
250 IF A$ = "L" OR A$ = "l" THEN LPRINT CHR$(10);
260 A$ = RIGHTS(A$,1) :ACS = ASC(A$)
270 IF ACS < 60 OR ACS > 68 THEN 260
280 ON ACS-59 GOSUB 2110, 3770, 9650, 8630, 9000, 8070, 3660, 3220, 330
290 GOTO 60
300 'End program
310 END
320 COLOR FGNDD3, BGNDD3 :CLS :COLOR FGNDD1, BGNDD1 :LOCATE 23, 1
330 PRINT "DATA START FROM NO.";CHR$(26)
340 COLOR FGNDD3, BGNDD3 :LOCATE 23, 24 :PRINT CHR$(15)
350 LOCATE 23, 24 :INPUT "", DBGN
COLOR FGND3,BGND3 :CLS :COLOR FGND1,BGND1 :LOCATE 23,1
PRINT " TO NO.";CHR$(26)
COLOR FGND3,BGND3 :LOCATE 23,11 :PRINT CHR$(15)
LOCATE 23,11 :INPUT "",DEND
RETURN
'
COLOR FGND2,BGND2 :CLS
LOCATE 12,25 :PRINT "Stress at Maximum Load = ";SM
LOCATE 14,25 :PRINT "Strain at Maximum Load = ";EM
LOCATE 23,1 :COLOR FGND1,BGND1 :PRINT " Press any key to continue. "
COLOR FGND2,BGND2 :LOCATE 23,31 :PRINT CHR$(15)
LOCATE 23,31
A$ = INKEY$ :IF A$ = "" THEN 530
MP = INT(M/16)
IF MP = 0 THEN 850
FOR I = 0 TO MP-1
CLS
LOCATE 3,15 :PRINT "No." :LOCATE 3,35 :PRINT "X"
LOCATE 3,55 :PRINT "Y"
FOR J = 1 TO 16
LOCATE J+4,15:PRINT I*16+J :LOCATE J+4,34 : PRINT X(I*16+J)
LOCATE J+4,54:PRINT Y(I*16+J)
NEXT J
LOCATE 23,29 : PRINT "Is there any change <y/n>?"
A$ = INKEY$ :IF A$ = "" THEN 650
LOCATE 23,29 :PRINT ""
IF A$ = "n" OR A$ = "N" THEN 840
IF A$ <> "y" AND A$ <> "Y" THEN 640
LOCATE 23,25 :INPUT "Input x-y pairs' number : ",CHG
LOCATE 23,25 :PRINT ""
CHGI = INT((CHG-1)/16) :CHGJ = CHG - CHGI*16 + 4
LOCATE 23,25 :PRINT "X or Y will be changed? : "
LOCATE 23,53
A$ = INKEY$:IF A$ = "" THEN 730
LOCATE 23,25 :PRINT ""
IF A$ = "X" OR A$ = "x" THEN 780
IF A$ = "Y" OR A$ = "y" THEN 810
GOTO 720
LOCATE CHGJ,34 :PRINT ""
LOCATE CHGJ,35 :INPUT ",X(CHG)
GOTO 640
LOCATE CHGJ,54 :PRINT ""
LOCATE CHGJ,55 :INPUT ",Y(CHG)
GOTO 640
NEXT I
CLS
LOCATE 3,15 :PRINT "No." :LOCATE 3,35 :PRINT "X"
LOCATE 3,55 : PRINT "Y"
FOR J = 1 TO M-MP*16
  LOCATE J+4,15 : PRINT MP*16+J : LOCATE J+4,34 : PRINT X(MP*16+J)
  LOCATE J+4,54 : PRINT Y(MP*16+J)
NEXT J
LOCATE 23,29 : PRINT "Is there any change <y/n>?"
A$ = INKEY$ : IF A$ = "" THEN 930
LOCATE 23,29 : PRINT ""
IF A$ = "n" OR A$ = "N" THEN 1120
IF A$ <> "y" AND A$ <> "Y" THEN 920
LOCATE 23,25 : INPUT "Input x-y pairs' number : ", CHG
LOCATE 23,25 : PRINT ""
CHGI = INT((CHG-1)/16) : CHGJ = CHG - CHGI*16 + 4
LOCATE 23,25 : PRINT "X or Y will be changed? : ": LOCATE 23,53
A$ = INKEY$: IF A$ = "" THEN 1010
LOCATE 23,25 : PRINT ""
IF A$ = "X" OR A$ = "x" THEN 1060
IF A$ = "Y" OR A$ = "y" THEN 1090
GOTO 1000
LOCATE CHGJ,34 : PRINT ""
LOCATE CHGJ,35 : INPUT ",X(CHG)
GOTO 920
LOCATE CHGJ,54 : PRINT ""
LOCATE CHGJ,55 : INPUT ",Y(CHG)
GOTO 920
CLS : LOCATE 23,29 : PRINT "Check all data again <y/n>?"
A$ = INKEY$: IF A$ = "" THEN 1130
IF A$ = "Y" OR A$ = "y" THEN 480
IF A$ <> "N" AND A$ <> "n" THEN 1130
RETURN
COLOR FGND3,BGND3 : CLS : LOCATE 23,1 : COLOR FGND1,BGND1
PRINT "FILE'S NAME ": COLOR FGND3,BGND3 : LOCATE 23,16
: PRINT CHR$(15)
LOCATE 23,16 : INPUT ",DAT$
OPEN DAT$+".dat" FOR INPUT AS #1
FOR I = 1 TO M
  INPUT #1,OP,FP
  INPUT #1,OD,ID
  INPUT #1,SD,LD
  INPUT #1,M,PS
FOR I = 1 TO M
  INPUT #1,X(I),Y(I)
INPUT #1,Y11,Y0(I)
NEXT I
CLOSE #1
1340  M5 = 1 : M6 = M
1350  GOSUB 4490
1360  GOSUB 4280
1370  GOSUB 480
1380  GOSUB 350
1390  RETURN
1400  
1410  'Title
1420  
1430  COLOR FGND3,BGND3 : CLS: COLOR FGND1,BGND1
1440  LOCATE 5,37 : PRINT " MENU " : COLOR FGND3,BGND3
1450  LOCATE 23,68 : PRINT "F1_Main Menu"
1460  LOCATE 10,28 : PRINT "1. Stress at maximum load: ": SM
1470  LOCATE 12,28 : PRINT "2. Strain at maximum load: ": EM
1480  LOCATE 14,28 : PRINT "3. Constant N
1490  LOCATE 16,28 : PRINT "4. Number of Iteration ": XITER
1500  LOCATE 18,28 : PRINT "5. Continue"
1510  LOCATE 23,1 : COLOR FGND1,BGND1 : PRINT " SELECT ONE
1520  ":CHR$(26)
1530  COLOR FGND3,BGND3 : LOCATE 23,16 : PRINT CHR$(15)
1540  LOCATE 23,16 : A$ = INKEY$ : IF A$ = "" THEN 1530
1550  IF RIGHTS(A$,1) = CHR$(59) THEN 1670
1560  IF ASC(A$) = 53 THEN 1670
1570  IF ASC(A$)<49 OR ASC(A$)>52 THEN 1530
1580  PRINT A$
1590  ON ASC(A$) =48 GOTO 1590,1610,1630,1650
1600  GOTO 1510
1610  LOCATE 10,56 : PRINT " 
:LOCATE 10,57
1620  LOCATE 12,56 :PRINT 
:LOCATE 12,57
1630  LOCATE 14,56 :PRINT 
:LOCATE 14,57
1640  LOCATE 16,56 : PRINT 
:LOCATE 16,57
1650  GOTO 1510
1660  RETURN
1670  
1680  
1690  GOSUB 1410
1700  MAXX = X(DBGN) : MAXY = Y(DBGN) : MINX = X(DBGN) : MINY
1710  FOR I = DBGN TO DEND
1720  IF X(I) > MAXX THEN MAXX = X(I)
1730  IF X(I) < MINX THEN MINX = X(I)
1740  IF Y(I) > MAXY THEN MAXY = Y(I)
1750  IF Y(I) < MINY THEN MINY = Y(I)
1760  NEXT I
1770  COLOR FGND2,BGND2 : CLS
1780 LOCATE 2,7 :PRINT "1." :LOCATE 2,10 :COLOR FGND1,BGND1
1790 PRINT " Title " ;COLOR FGND2,BGND2 :PRINT " ":TITLE$
1800 LOCATE 4,7 :PRINT "2." :LOCATE 4,10 :COLOR FGND1,BGND1
1810 PRINT " X-lable " ;COLOR FGND2,BGND2 :PRINT " ":AX$
1820 LOCATE 6,7 :PRINT "3." :LOCATE 6,10 :COLOR FGND1,BGND1
1830 PRINT " Y-lable " ;COLOR FGND2,BGND2 :PRINT " ":AY$
1840 LOCATE 8,7 :PRINT "4." :LOCATE 8,10 :COLOR FGND1,BGND1
1850 PRINT " X-unit " ;COLOR FGND2,BGND2 :PRINT " ":UX$
1860 LOCATE 10,7 :PRINT "5." :LOCATE 10,10 :COLOR FGND1,BGND1
1870 PRINT " Y-unit " ;COLOR FGND2,BGND2 :PRINT " ":UY$
1880 LOCATE 12,7 :PRINT "6." :LOCATE 12,10 :COLOR FGND1,BGND1
1890 PRINT " Maximum-X " ;COLOR FGND2,BGND2 :PRINT " ":MAX $MAXX :LOCATE 13,10
1900 COLOR FGND1,BGND1 :PRINT " Minmum-X " ;COLOR FGND2,BGND2 :PRINT " ":MINX
1910 LOCATE 15,7 :PRINT "7." :LOCATE 15,10 :COLOR FGND1,BGND1
1920 PRINT " Maximum-Y " ;COLOR FGND2,BGND2 :PRINT " ":MAXY :LOCATE 16,10
1930 COLOR FGND1,BGND1 :PRINT " Minimum-Y " ;COLOR FGND2,BGND2 :PRINT " ":MINY
1940 LOCATE 18,7 :PRINT "8." :LOCATE 18,10 :COLOR FGND1,BGND1
1950 PRINT " Grid <y/n>" ;COLOR FGND2,BGND2 :PRINT " ":GID$
1960 LOCATE 20,7 :PRINT "9." :LOCATE 20,10 :COLOR FGND1,BGND1
1970 PRINT " CONTINUE " ;COLOR FGND2,BGND2
1980 LOCATE 23,24 :PRINT " ">
1990 LOCATE 23,1 :COLOR FGND1,BGND1 :PRINT "Select your choice. ";CHR$(26);
2000 LOCATE 23,22 :COLOR FGND2,BGND2 :PRINT " ";CHR$(15)
2010 LOCATE 23,73 :PRINT "F1_Help"
2020 LOCATE 23,24
2030 A$ = INKEY$ :IF A$ = "" THEN 2030
2040 IF RIGHTS(A$,1) = CHR$(59) THEN 60
2050 IF ASC(A$) < 49 OR ASC(A$) > 57 THEN 2030
2060 PRINT A$
2070 ON ASC(A$) - 48 GOTO 2090, 2110, 2130, 2150, 2170, 2190, 2220, 2250, 2290
2080 GOTO 1980
2090 LOCATE 2,24 :PRINT "":LOCATE 2,24:INPUT "",TTL$ "
2100 GOTO 1980
2110 LOCATE 4,24 :PRINT "":LOCATE 4,24:INPUT "",AX$ "
2120 GOTO 1980
2130 LOCATE 6,24 :PRINT "":LOCATE 6,24:INPUT "",AY$ "
2140 GOTO 1980
2150 LOCATE 8,24 :PRINT "":LOCATE 8,24:INPUT "",UX$ "
2160 GOTO 1980
2170 LOCATE 10,24 :PRINT "":LOCATE 10,24:INPUT "",UY$ "
2180 GOTO 1980
2190 LOCATE 12,24 :PRINT "":LOCATE 12,24:INPUT "",MAX$ "
2200 LOCATE 13,24 :PRINT "":LOCATE 13,24:INPUT "",MIN$ "
2210 GOTO 1980
2220 LOCATE 15,24 :PRINT "":LOCATE 15,24:INPUT "",MAXY "
2230 LOCATE 16,24 :PRINT "":LOCATE 16,24:INPUT "",MINY "
2240 GOTO 1980
2250 LOCATE 18,24 :PRINT "":LOCATE 18,24:INPUT "",GRID$ "
2260 IF GID$ = "Y" OR GID$ = "y" THEN GRID = 1
2270 IF GID$ = "N" OR GID$ = "n" THEN GRID = 0
2280 GOTO 1980
2290 IF UX$ = "" THEN AAX$ = AX$ ELSE AAX$ = AX$ + " " + CHR$(4) + UX$ + CHR$(4)
2300 IF UY$ = "" THEN AAY$ = AY$ ELSE AAY$ = AY$ + " " + CHR$(4) + UY$ + CHR$(4)
2310 IF TMON = 1 THEN GOSUB 3310
2320 'Graph plot
2330 'CLS:SCREEN 2:CX = LEN(AAX$) :CY = LEN(AAY$)
2340 CXP = 40 - INT(CX/2) :CYP = 11 - INT(CY/2)
2350 FOR I = 1 TO CX
2360 LOCATE 25,CXP+I :PRINT Mid$(AAX$,I,1)
2370 NEXT I
2380 LOCATE 25,CXP+I :PRINT Mid$(AAX$,I,1)
2390 NEXT I
2400 FOR I = 1 TO CY
2410 LOCATE I+CYP,1 :PRINT Mid$(AAY$,I,1)
2420 NEXT I
2430 LINE (83,11)-(563,171),B
2440 X1 = INT(480*(X(DBG)-MINX)/(MAXX-MINY)) + 83
2450 X2 = 171 - INT(160*(Y(DBG)-MINY)/(MAXY-MINY))
2460 IF X1 < 83 THEN X1 = 83
2470 IF X1 > 563 THEN X1 = 563  
2480 IF X2 > 171 THEN X2 = 171  
2490 IF X2 < 11 THEN X2 = 11  
2500 PSET (X1,X2)  
2510 FOR I = DBGN+1 TO DEND  
2520 X1 = INT(480*(X(I)-MINX)/(MAXX-MINX)) + 83  
2530 X2 = 171 - INT(160*(Y(I)-MINY)/(MAXY-MINY))  
2540 IF X1 < 83 THEN X1 = 83  
2550 IF X1 > 563 THEN X1 = 563  
2560 IF X2 > 171 THEN X2 = 171  
2570 IF X2 < 11 THEN X2 = 11  
2580 PSET (X1,X2)  
2590 NEXT I  
2600 '  
2610 '  
2620 'Make tick mark  
2630 SX = 0 : SY = 0  
2640 ITX = (MAXX-MINX)/10 : ITY = (MAXY-MINY)/10  
2650 IF ITX >= .01 THEN 2680  
2660 ITX = ITX * 10 : SX = SX + 1  
2670 GOTO 2650  
2680 IF ITX <= 990 THEN 2710  
2690 ITX = ITX/10 : SX = SX - 1  
2700 GOTO 2680  
2710 IF ITY >= .01 THEN 2740  
2720 ITY = ITY * 10 : SY = SY + 1  
2730 GOTO 2710  
2740 IF ITY <= 990 THEN 2770  
2750 ITY = ITY/10 : SY = SY - 1  
2760 GOTO 2740  
2770 TX0 = MINX*10^SX : TY0 = MINY*10^SY  
2780 ITX = (MAXX-MINX)*10^SX/10 : ITY = (MAXY-MINY)*10^SY/10  
2790 FOR I = 83 TO 563 STEP 48  
2800 LINE (I,174)-(I,171)  
2810 IF GRID = 0 THEN 2850  
2820 FOR J = 171 TO 11 STEP -2  
2830 PSET (I,J)  
2840 NEXT J  
2850 NEXT I  
2860 FOR I = 11 TO 171 STEP 16  
2870 LINE (77,I)-(83,I)  
2880 IF GRID = 0 THEN 2920  
2890 FOR J = 83 TO 563 STEP 3  
2900 PSET (J,I)  
2910 NEXT J  
2920 NEXT I  
2930 FOR I = 1 TO 11  
2940 IF SY < 0 THEN 3010  
2950 IF MAXY > 99.99 OR ABS(MINY) > 99.99 THEN 3010  
2960 IF MAXY > 9.99 OR ABS(MINY) > 9.99 THEN 2990
LOCATE 24-I*2,4 :PRINT USING "##.##";TY0
GOTO 3020
LOCATE 24-I*2,4 :PRINT USING "###.#";TY0
GOTO 3020
LOCATE 24-I*2,4 :PRINT USING "#####";TY0
IF SX < 0 THEN 3090
IF MAXX > 99.99 OR ABS(MINX) > 99.99 THEN 3090
IF MAXX > 9.99 OR ABS(MINX) > 9.99 THEN 3070
LOCATE 23.4+I*6 :PRINT USING "####.#";TX0
GOTO 3100
LOCATE 23.3+I*6 :PRINT USING "####.#";TX0
GOTO 3100
LOCATE 23.4+I*6 :PRINT TX0
TX0 = TX0 + ITX :TY0 = TY0 + ITY
NEXT I
'Label unit and title
IF SX = 0 THEN 3150
LOCATE 22,74 :PRINT "E":LOCATE 22,75 :PRINT USING "+#";(-SX)
IF SY = 0 THEN 3170
LOCATE 1.9 :PRINT "E":LOCATE 1.10 :PRINT USING "+#";(-SY)
TLE = LEN(TITLE$):TLEX = 40 - INT(TLE/2)
LOCATE 1,TLEX :PRINT TITLE$
RETURN
'Plot graph on raw data
GOSUB 1700
A$ = INKEY$ :IF A$ = "" THEN 3240
IF RIGHT$(A$,1) <> CHR$(59) THEN 3240
IF TMON = 0 THEN SCREEN 0
IF TMON = 1 THEN GOSUB 3410
RETURN
' Switching Display to Color
DEF SEG = 0
POKE &H410, (PEEK(&H410) AND &HCF) OR &H10
SCREEN 1,0,0,0
SCREEN 0
WIDTH 40
WIDTH 80
LOCATE ,,1,6,7
RETURN
'Switching Display to Monochrome
DEF SEG = 0
POKE &H410,(PEEK(&H410) OR &H30)
SCREEN 0
3460 WIDTH 40
3470 WIDTH 80
3480 LOCATE ,,1,12,13
3490 RETURN
3500 'Screen command
3510 'ON ERROR GOTO 3640
3520 OPEN "display" FOR INPUT AS #1
3530 INPUT #1,A$
3540 CLOSE #1
3550 BGND2 = ASC(LEFT$(A$,1))-1
3560 FGND2 = ASC(MID$(A$,2,1))-1
3570 TMON = ASC(MID$(A$,3,1))-1
3580 BGND3 = BGND2
3590 FGND3 = FGND2
3600 BGND1 = ASC(MID$(A$,6,1))-8
3610 FGND1 = ASC(MID$(A$,7,1))-1
3620 RETURN
3630 'COLOR FGND2,BGND2 :CLS :LOCATE 23,1 :COLOR
3640 FGND1,BGND1
3650 'COLOR FGND2,BGND2 :LOCATE 23,20 :PRINT CHR$(15)
3660 'COLOR FGND1,BGND1 :CLS
3670 FILES A$"*."
3680 LOCATE 23,68 :PRINT "Files in Drive ":CHR$(26)
3690 COLOR FGND2,BGND2 :LOCATE 23,20 :PRINT CHR$(15)
3700 COLOR FGND1,BGND1 :CLS
3710 A$ = INKEY$:IF A$ = "" THEN 3730
3720 IF RIGHT$(A$,1) <> CHR$(59) THEN 3730
3730 COLOR FGND2,BGND2 :CLS
3740 RETURN
3750 'COLOR FGND3,BGND3 :CLS :COLOR FGND1,BGND1 :LOCATE 5,38:PRINT "MENU"
3760 COLOR FGND3,BGND3:LOCATE 10,30 :PRINT "1. PSI to KSI"
3770 COLOR FGND3,BGND3 :LOCATE 23,1:PRINT "2. KSI to PSI"
3780 LOCATE 12,30 :PRINT "3. PSI to MPA"
3790 LOCATE 16,30 :PRINT "4. MPA to PSI"
3800 LOCATE 23,17 :PRINT "F1_Main Menu"
3810 COLOR FGND1,BGND1 :LOCATE 23,1:PRINT " SELECT ONE : "
3820 COLOR FGND3,BGND3 :LOCATE 23,17:PRINT CHR$(15)
3830 A$ = INKEY$:IF A$ = "" THEN 3870
3840 IF RIGHT$(A$,1) = CHR$(59) THEN RETURN
3850 LOCATE 23,17 :PRINT A$
3860 IF ASC(A$) < 49 OR ASC(A$) > 52 THEN 3860
3870 A$ = INKEY$:IF A$ = "" THEN 3870
3880 IF RIGHT$(A$,1) = CHR$(59) THEN RETURN
3890 LOCATE 23,17 :PRINT A$
3900 IF ASC(A$) < 49 OR ASC(A$) > 52 THEN 3860
3910 CLS :COLOR FGND1,BGND1:LOCATE 23,1 :PRINT " X or Y will be changed? "
COLOR FGND3,BGND3 :LOCATE 23,28:PRINT CHR$(15):TPE= 0
LOCATE 23,28 :B$ = INKEY$ :IF B$ = "" THEN 3930
LOCATE 23,28 :PRINT B$
IF B$ = "X" OR B$ = "x" THEN TPE = 1
IF B$ = "Y" OR B$ = "y" THEN TPE = 2
IF TPE = 0 THEN 3920
ON ASC(A$)-48 GOTO 3990,4060,4130,4200
FOR I = DBGN TO DEND
IF TPE = 1 THEN X(I)=X(I)/1000
IF TPE = 2 THEN Y(I)=Y(I)/1000
NEXT I
IF TPE = 1 THEN EM=EM/1000
IF TPE = 2 THEN SM=SM/1000
GOTO 3770
FOR I = DBGN TO DEND
IF TPE = 1 THEN X(I)=X(I)*1000
IF TPE = 2 THEN Y(I)=Y(I)*1000
NEXT I
IF TPE = 1 THEN EM=EM*1000
IF TPE = 2 THEN SM=SM*1000
GOTO 3770
FOR I = DBGN TO DEND
IF TPE = 1 THEN X(I)=X(I)/145
IF TPE = 2 THEN Y(I)=Y(I)/145
NEXT I
IF TPE = 1 THEN EM = EM/145
IF TPE = 2 THEN SM = SM/145
GOTO 3770
RETURN
MXLOAD = 0
FOR I = M5 TO M6
P = -(Y(I)-OP) *.6975*PS/(FP-OP)
A = .7853982*(X(I)*ID/OD)^2
S = P/A :E = 2*LOG(OD/X(I))
IF DWRK = 1 THEN X(I) = I
IF DWRK = 1 THEN Y(I) = E
IF DWRK = 2 THEN X(I) = X(I)
IF DWRK = 2 THEN Y(I) = Y0(I)
IF DWRK = 3 THEN X(I) = Y0(I)
IF DWRK = 3 THEN Y(I) = P
IF DWRK = 4 THEN X(I) = E
IF DWRK = 4 THEN Y(I) = S
IF DWRK = 5 THEN X(I) = Y0(I)
IF DWRK = 5 THEN Y(I) = S
IF MXLOAD > P THEN
MXLOAD = P : EM = E : SM = S
NEXT I
RETURN

CLS
LOCATE 6,30 : PRINT "1. Strain and Time"
LOCATE 8,30 : PRINT "2. LVDT and Diameter"
LOCATE 10,30 : PRINT "3. Load and LVDT"
LOCATE 12,30 : PRINT "4. Stress and Strain"
LOCATE 14,30 : PRINT "5. Strain and LVDT"
LOCATE 23,1 : COLOR FGND1, BGND1 : PRINT "SELECT ONE : "
COLOR FGND3, BGND3 : LOCATE 23,17 : PRINT CHR$(15)
LOCATE 23,17
A$ = INKEY$ : IF A$ = "" THEN
IF ASC(A$) < 49 OR ASC(A$) > 53 THEN
PRINT A$
DWRK = ASC(A$) - 48
RETURN

'Plot graph on raw data and predicted curve to specify point.
GOSUB 1690
OPEN "curvefit" FOR OUTPUT AS #1
IBGN = INT(480*(X(DBGN)-MINX)/(MAXX-MINX)) + 83
IF IBGN < 83 THEN IBGN = 83
IF IBGN > 560 THEN IBGN = 560
IMID = INT(480*(X(DMID)-MINX)/(MAXX-MINX)) + 83
XI = MINX + (IBGN - 83)*(MAXX-MINX)/480
P = SM*(XI/EM)^EM
X2 = 171 - INT(160*(P-MINY)/(MAXY-MINY))
IF X2 > 171 THEN X2 = 171
IF X2 < 11 THEN X2 = 11
PSET (IBGN, X2)
FOR I = IBGN TO IMID STEP 2
XI = MINX + (I-83)*(MAXX-MINX)/480
P = SM*(XI/EM)^EM
X2 = 171 - INT(160*(P-MINY)/(MAXY-MINY))
IF X2 > 171 THEN X2 = 171
IF X2 < 11 THEN X2 = 11
LINE -(I, X2)
WRITE #1, XI, P
NEXT I
IEND = 560
XI = MINX + (IMID-83)*(MAXX-MINX)/480
US = (EM/NN)*((XI/EM)^NN-1)
VS = EXP(US)
4910  P = SM*VS
4920  X2 = 171-INT(160*(P-MINY)/(MAXY-MINY))
4930  IF X2 > 171 THEN X2 = 171
4940  IF X2 < 11 THEN X2 = 11
4950  PSET (IMID,X2)
4960  FOR I = IMID TO IEND STEP 2
4970  XI = MINX + (I-83)*(MAXX-MINX)/480
4980  US = (EM/NN)*((XI/EM)^NN-1)
4990  VS = EXP(US)
5000  P = SM*VS
5010  X2 = 171-INT(160*(P-MINY)/(MAXY-MINY))
5020  IF X2 > 171 THEN X2 = 171
5030  IF X2 < 11 THEN X2 = 11
5040  LINE -(I,X2)
5050  IF I = IMID THEN 5070
5060  WRITE #1,XI,P
5070  NEXT I
5080  CLOSE #1
5090  A$ = INKEY$ :IF A$ = "" THEN 5090
5100  IF RIGHTS(A$,1) <> CHR$(59) THEN 5090
5110  IF TMON = 0 THEN SCREEN 0
5120  IF TMON = 1 THEN GOSUB 3410
5130  COLOR FGND2,BGND2:CLS:LOCATE 23,1:COLOR FGND1,BGND1
5140  PRINT " PLOT GRAPH AGAIN <Y/N>? ":COLOR FGND2,BGND2
5150  :LOCATE 23,28
5160  PRINT CHR$(15):LOCATE 23,28
5170  A$ = INKEY$ :IF A$ = "" THEN 5160
5180  IF A$ = "N" OR A$ = "n" THEN 5200
5190  GOTO 4650
5200  RETURN
5210  
5220  'Modified Gauss-Newton
5230  GOSUB 1410
5240  IF RIGHTS(A$,1) = CHR$(59) THEN 6410
5250  CLS:LOCATE 23,1:COLOR FGND1,BGND1
5260  PRINT " Press -T- to turn trace on or any key to continue. ":COLOR FGND2,BGND2
5270  LOCATE 23,55 :COLOR FGND3,BGND3 :PRINT CHR$(15)
5280  LOCATE 23,55 :A$ = INKEY$ :IF A$ = "" THEN 5290
5290  IF A$ = "T" OR A$ = "t" THEN TRCE = 1 ELSE TRCE = 0
5300  CLS
5310  IF TRCE = 1 THEN 5350
5320  LOCATE 13,37 :COLOR FGND1+16,BGND1:PRINT " WAIT ":COLOR FGND3,BGND3
5330  IF POWER = 0 THEN 5380
5340  B(1) = NN :B(2) = SM :B(3) = EM
5350  GOTO 5390
5360  B(3) = SM:B(1) = NN:B(2) = EM
5370  GOTO 5390
5380  IF POWER = 0 THEN 5420
5400 GOSUB 8290
5410 GOTO 5430
5420 GOSUB 6420 'Get matrix of (Y - F), Y(n)
5430 FOR ITER = 1 TO XITER
5440 IF POWER = 0 THEN 5470
5450 GOSUB 8420
5460 GOTO 5480
5470 GOSUB 6500 'Get Z-matrix, Z(n,4)
5480 GOSUB 6650 'Get ZPY-matrix, ZPY(4)
5490 GOSUB 6740 'Get ZPZ-matrix, MX(4,4)
5500 GOSUB 7650 'Get inv(ZPZ), MXI(4,4)
5510 IF CHK = 0 THEN 6410
5520 GOSUB 6380 'Get parameters changed, DB(4)
5530 GOSUB 6920 'Get SSE, SSE
5540 CHK = 1 : SSE0 = SSE
5550 FOR I = 1 TO TPE : C(I) = B(I) : NEXT I
5560 FOR I = 1 TO TPE
5570 IF ABS(B(I)) < .00001 THEN B(I) = .00001
5580 F = DB(I)/B(I) : B(I) = B(I) + DB(I)
5590 IF ABS(F) > .000001 THEN CHK = 0
5600 NEXT I
5610 IF POWER = 0 THEN 5640
5620 GOSUB 8290
5630 GOTO 5650
5640 GOSUB 6420 'Get new Y0(n)
5650 GOSUB 6920 'Get SSE, SS
5660 SSE1 = SSE
5670 GOSUB 6990 'Print results
5680 IF CHK = 1 THEN 6160
5690 IF SSE0 < SSE1 THEN 5720
5700 NEXT ITER
5710 IF SSE0 > SSE1 THEN 6410
5720 GOSUB 7050 'DB0 = DB0/2
5730 GOSUB 7110 'BO = BO - DB0
5740 IF POWER = 0 THEN 5770
5750 GOSUB 8290
5760 GOTO 5780
5770 GOSUB 6420 'Get new Y0(n)
5780 GOSUB 6920 'Get SSE, SS
5790 SSE1 = SSE
5800 GOSUB 6990 'Print results
5810 A$ = INKEY$: IF A$ = CHR$(27) THEN 6160
5820 CHK = 1
5830 FOR I = 1 TO TPE
5840 IF ABS(C(I)) < .00001 THEN C(I) = .00001
5850 F = (C(I) - B(I))/C(I)
5860 IF ABS(F) > .000001 THEN CHK = 0
5870 NEXT I
5880 IF CHK = 1 THEN 6160
5890 IF SSE1 > SSE0 THEN 5720
5900 GOSUB 7050 'DB0 = DB0/2
5910  GOSUB 7110  'B0  =  B0  -  DB0
5920  IF  POWER  =  0  THEN  5950
5930  GOSUB 8290
5940  GOTO 5960
5950  GOSUB 6420  'Get new Y0(n)
5960  GOSUB 6920  'Get SSE, SS
5970  SSE0 = SSE1
5980  SSE1 = SSE
5990  GOSUB 6990  'Print results
6000  A$ = INKEY$ : IF A$ = CHR$(27) THEN 6160
6010  CHK = 1
6020  FOR I = 1 TO TPE
6030  IF ABS(C(I)) < .00001 THEN C(I) = .00001
6040  F = (C(I) - B(I))/C(I)
6050  IF ABS(F) > .000001 THEN CHK=0
6060  NEXT I
6070  IF CHK = 1 THEN 6160
6080  IF SSE1 < SSE0 THEN 5900
6090  GOSUB 7170  'B0 = B0 + DB0
6100  I = 1
6110  IF DB(I)/B(I) < .05 THEN 6150
6120  I = I+1
6130  IF I <= TPE THEN 6110
6140  GOTO 5900
6150  GOTO 5390
6200  SE = SSE1 : TOT = 0
6210  FOR I = DBGN TO DEND
6220  TOT = TOT + Y(I)*Y(I)
6230  NEXT I
6240  MSE = SE/(DEND-DBGN-TPE+1)
6250  REG = TOT - SE
6260  IF POWER = 0 THEN 6250
6270  GOSUB 8420
6280  GOTO 6260
6290  GOSUB 7650
6300  FOR I = 1 TO TPE
6310  C(I) = 1.96*(HMXI(1,1)*MSE)*.5
6320  NEXT I
6330  GOSUB 7210
6340  COLOR FGND2, BGND2: CLS: LOCATE 23, 1: COLOR FGND1, BGND1
6350  PRINT " PLOT GRAPH <Y/N>? ": COLOR FGND2, BGND2: LOCATE 23, 22: PRINT CHR$(15)
6360  LOCATE 23, 22: A$ = INKEY$: IF A$ = "" THEN 6360
6370  IF A$ = "N" OR A$ = "n" THEN 6410
6380  IF A$ <> "y" AND A$ <> "y" THEN 6360
6390  PRINT A$
6400  GOSUB 4650
SSE = 0
FOR I = DBGN TO DEND
SSE = SSE + Y0(I)*Y0(I)
NEXT I
RETURN

IF TRCE = 0 THEN 7040
PRINT "Parameters => ";:LOCATE,15:PRINT B(1);:LOCATE,30:PRINT B(2);:LOCATE,45:PRINT B(3)
PRINT "SSEO => ",SSE0
PRINT "SSE1 => ",SSE1:PRINT:PRINT
RETURN

FOR I = 1 TO TPE
DB(I) = DB(I)/2
NEXT I
RETURN

FOR I = 1 TO TPE
B(I) = B(I) - DB(I)
NEXT I
RETURN

FOR I = 1 TO TPE
B(I) = B(I) + DB(I)
NEXT I
RETURN

IF POWER = 0 THEN 7250
:DNN=C(1)
GOTO 7260

:DNN=C(1)
COLOR FGND3, BGND3:CLS:COLOR FGND1, BGND1
LOCATE 3,37:PRINT " ANOVA ":COLOR FGND3, BGND3
LOCATE 5,5:PRINT "Source of Variation" TAB(20) "df"
TAB(40) "SSE" TAB(55) "MSE" TAB(70) "F"
LOCATE 7,5:PRINT "Total" TAB(27) DEND-DBGN+1
TAB(35) TOT
LOCATE 9,5:PRINT "Regression" TAB(27) TPE TAB(35)
REG TAB(50) REG/TPE TAB(65) REG/(MSE*TPE)
LOCATE 11,5:PRINT "Residual " TAB(27)
DEND-DBGN-TPE+1 TAB(35) SE TAB(50) MSE
LOCATE 14,52:PRINT "95% Confidence Interval"
LOCATE 17,5:PRINT "Stress at maximum load" TAB(35)
SM TAB(50) SM-DSM TAB(65) SM+DSM
LOCATE 18,5:PRINT "Strain at maximum load" TAB(35)
EM TAB(50) EM-DEM TAB(65) EM+DEM
LOCATE 19,5:PRINT "Material constant N" TAB(35) NN
TAB(50) NN-DNN TAB(65) NN+DNN
LOCATE 23,1:COLOR FGND1,BGND1
PRINT " PRESS <P> FOR PRINT OUT OR ANY KEY TO CONTINUE:" "
COLOR FGND3,BGND3:LOCATE 23,53:PRINT CHR$(15)
IF A$ <> "p" AND A$ <> "P" THEN 7640
CLS:COLOR FGND1,BGND1:LOCATE 23,1:PRINT " TITLE:
COLOR FGND3,BGND3:LOCATE 23,12:PRINT
CLS:LOCATE 13,37,0:COLOR FGND1+16,BGND1:PRINT " WAIT"
COLOR FGND3,BGND3
TLE = LEN(TITLE$):TLE = 45-TLE/2
LPRINT CHR$(27);CHR$(69);CHR$(27);CHR$(71);
LPRINT TAB(TLE) TITLE$ :LPRINT LPRINT
LPRINT TAB(14) "Source of" TAB(30) "df" TAB(36) "SSE"
TAB(54) "MSE" TAB(69) "F"
LPRINT TAB(14) "Variation":LPRINT :LPRINT
LPRINT CHR$(27);CHR$(70);
LPRINT TAB(15) "Total" TAB(30) DEND-DBGN+1 TAB(35) TOT
LPRINT TAB(14) "Regression" TAB(29) TPE TAB(34) REG
TAB(50) REG/TPE TAB(65) REG/(MSE*TPE)
LPRINT TAB(14) "Residual " TAB(29) DEND-DBGN-TPE+1
TAB(34) SE TAB(50) MSE :LPRINT
LPRINT CHR$(27);CHR$(69);
LPRINT TAB(15) "95% Confidence Interval"
LPRINT CHR$(27);CHR$(70);
LPRINT:LPRINT TAB(14) "Stress at maximum load"
SM TAB(54) SM-DSM TAB(66) SM+DSM
LPRINT TAB(14) "Strain at maximum load" TAB(40) EM
TAB(54) EM-DEM TAB(66) EM+DEM
LPRINT TAB(14) "Material constant N" TAB(40) NN
TAB(54) NN-DNN TAB(66) NN+DNN
LPRINT CHR$(27);CHR$(72);
RETURN
'Subroutine Matrix inversion by Gauss-Jordan elimination method.
'MX and MXI are matrix X and inverse of X.
'Dimensions = 4
FOR I = 1 TO TPE
FOR J = 1 TO TPE
HMX(I,J) = 0
NEXT J
FOR I = 1 TO TPE
HMX(I,I) = 1
NEXT I
FOR I = 1 TO TPE
FOR J = I TO TPE
IF HMX(J,I) <> 0 THEN 7860
NEXT J
COLOR FGND3, BGND3:CLS:LOCATE 13,22:COLOR FGND1, BGND1
PRINT " Matrix is not a nonsigular matrix. ":COLOR FGND3,BGND3
LOCATE 23,1 :COLOR FGND1,BGND1
PRINT " Press any key to continue : ":COLOR FGND3,BGND3
LOCATE 23,32 :PRINT CHR$(15)
A$ = INKEY$:IF A$ = "" THEN 7830
CHK = 0
GOTO 8050
FOR K = 1 TO TPE
HMS = HMX(I,K) :HMX(I,K) = HMX(J,K) :HMX(J,K) = HMS
HMS = HMXI(I,K):HMXI(I,K) = HMXI(J,K) :HMXI(J,K) = HMS
NEXT K
HMT = 1/HMX(I,I)
FOR K = 1 TO TPE
HMX(I,K) = HMX(I,K) + HMT*HMX(J,K)
HMXI(I,K) = HMXI(I,K) + HMT*HMXI(J,K)
NEXT K
FOR L = 1 TO TPE
IF L = I THEN 8020
HMT = -1*HMX(L,I)
FOR K = 1 TO TPE
HMX(L,K) = HMX(L,K) + HMT*HMX(I,K)
HMXI(L,K) = HMXI(L,K) + HMT*HMXI(I,K)
NEXT K
NEXT L
NEXT I
RETURN
'Power and Power
COLOR FGND2, BGND2 :CLS
LOCATE 23,1 :COLOR FGND1,BGND1 :PRINT " Select one : ":COLOR FGND2,BGND2
LOCATE 23,17 :PRINT CHR$(15)
:LOCATE 23,17
A$ = INKEY$: IF A$ = "" THEN 8150
IF ASC(A$) < 49 OR ASC(A$) > 52 THEN 8150
PRINT A$
ON ASC(A$)-48 GOTO 8190, 8210, 8230, 8250
POWER=0 : TPE=2
GOTO 8260
POWER=1 : TPE=2
GOTO 8260
POWER=0 : TPE=1
GOTO 8260
POWER=0 : TPE=3
GOSUB 8580
GOSUB 5240
RETURN
'Subroutine
FOR I = DBGN TO DMID
YO(I) = Y(I) - B(2)*(X(I)/B(3))^B(3)
NEXT I
FOR I = DMID+1 TO DEND
U = (B(3)/B(1))*((X(I)/B(3))^(B(1)-1)
V = EXP(U)
YO(I) = Y(I) - B(2)*V
NEXT I
RETURN
'Subroutine
FOR I = DBGN TO DMID
V = (X(I)/B(3))^(B(3)
Z(I,2) = V
Z(I,3) = -B(2)*V
Z(I,1) = 0
NEXT I
FOR I = DMID + 1 TO DEND
U = (B(3)/B(1))*((X(I)/B(3))^(B(1)-1)
V = EXP(U)
Z(I,1) = B(2)*((B(3)/B(1))*((X(I)/B(3))^(B(1)))*LOG(X(I)/B(3))-(U/B(1)))*V
Z(I,2) = B(2)*((U/B(3))-(X(I)/B(3))^(B(1)))*V
Z(I,3) = V
NEXT I
RETURN
'Power and Saturation Type Equation
COLOR FGND2,BGND2 :CLS
LOCATE 23,1 : COLOR FGND1,BGND1: PRINT " TOW EQUATIONS JOIN AT DATA # ":
COLOR FGND2,BGND2 : INPUT " ", DMID
RETURN
COLOR FGND3, BGND3 :CLS : M5 = 1 : EM = 0 : SM = 0 : MXLOAD = 0 : LOCATE 23, 1
COLOR FGND1, BGND1 : PRINT " Input numbers of files to be merged : "
COLOR FGND3, BGND3 : LOCATE 23, 42 : PRINT CHR$(15)
LOCATE 23, 42 : INPUT "", NF
FOR J = 1 TO NF
CLS : LOCATE 23, 1 : COLOR FGND1, BGND1 : PRINT " Input file's # " ; J ; " "
COLOR FGND3, BGND3 : LOCATE 23, 23 : PRINT CHR$(15)
LOCATE 23, 23 : INPUT "", DAT$ OPEN DAT$ + ".dat" FOR INPUT AS # 1
INPUT #1, OP, FP INPUT #1, OD, ID INPUT #1, SD, LD INPUT #1, M, PS
M6 = M5 + M - 1 FOR K = M5 TO M6
INPUT #1, X(K), Y(K)
INPUT #1, Yll, YO(K)
NEXT K CLOSE #1 GOSUB 4490 GOSUB 4310 RETURN COLOR FGND2, BGND2 :CLS : LOCATE 13, 37
COLOR FGND1 + 16, BGND1 : PRINT " WAIT " FOR I = 1 TO M5 - 2
FOR J = I + 1 TO M5 - 1
IF X(I) <= X(J) THEN 8940
XT = X(I) : YT = Y(I)
X(I) = X(J) : Y(I) = Y(J)
X(J) = XT : Y(J) = YT
NEXT J
NEXT I
M = M5 - 1 : COLOR FGND2, BGND2 :CLS
GOSUB 480 GOSUB 350 RETURN COLOR FGND2, BGND2 :CLS : LOCATE 13, 37 : COLOR FGND1 + 16, BGND1 : PRINT " WAIT " COLOR FGND2, BGND2
FOR I = DBGN TO DEND
Z(I, 1) = 1 : Z(I, 2) = LOG(X(I)) : Y0(I) = LOG(Y(I))
NEXT I
TPE = 2 GOSUB 6650 ' Get XPY GOSUB 6740 ' Get XPX GOSUB 7650 ' Get inv(XPX)
IF CHK = 0 THEN 9640
GOSUB 6830 'Get parameters
GOSUB 6920 'Get SST
REG = 0
FOR I = 1 TO TPE
REG = REG + DB(I)*ZPY(I)
NEXT I
SE = SSE-REG
MSE = SE/(DEND-DBGN-TPE+1)
TOT = SSE
FOR I = 1 TO TPE
C(I) = 1.96*(HMXI(I,I)*MSE)^.5
NEXT I
NN = 0 :DNN = 0 :DEM = C(2) :EM = DB(2)
SM = EXP(DB(1))*EM^EM :DSM = EXP(C(3))*C(2)^C(2)
GOSUB 7260
COLOR FGND2,BGND2:CLS:LOCATE 23,1:COLOR FGND1,BGND1
PRINT " PLOT GRAPH <Y/N>? ":COLOR FGND2,BGND2 : LOCATE 23,22 :PRINT CHR$(15)
LOCATE 23,22 :A$ = INKEY$:IF A$ = "" THEN 9270
IF A$ = "N" OR A$ = "n" THEN 9640
IF A$ <> "Y" AND A$ < > "y" THEN 9250
PRINT A$
GOSUB 1690
OPEN "curvefit" FOR OUTPUT AS #1
IBGN = INT(480*(X(DBGN)-MINX)/(MAXX-MINX))+83
IF IBGN < 83 THEN IBGN = 83
IF IBGN > 560 THEN IBGN = 560
IEND = INT(480*(X(DEND)-MINX)/(MAXX-MINX))+83
XI = MINX + (IBGN-83)*(MAXX-MINX)/480
P = SM*(XI/EM)^EM
X2 = 171-INT(160*(P-MINY)/(MAXY-MINY))
IF X2 > 171 THEN X2 = 171
IF X2 < 11 THEN X2 = 11
PSET (IBGN,X2)
FOR I = IBGN TO IEND STEP 2
XI = MINX + (I-83)*(MAXX-MINX)/480
P = SM*(XI/EM)^EM
X2 = 171-INT(160*(P-MINY)/(MAXY-MINY))
IF X2 > 171 THEN X2 = 171
IF X2 < 11 THEN X2 = 11
LINE -(I,X2)
WRITE #1,XI,P
NEXT I
CLOSE #1
A$ = INKEY$:IF A$ = "" THEN 9530
IF RIGHT$(A$,1) <> CHR$(59) THEN 9530
IF TMON = 0 THEN SCREEN 0
IF TMON = 1 THEN GOSUB 3410
COLOR FGND2,BGND2:CLS:LOCATE 23,1:COLOR FGND1,BGND1
PRINT " PLOT GRAPH AGAIN <Y/N>? ":COLOR FGND2,BGND2 :LOCATE 23,28
PRINT CHR$(15):LOCATE 23,28
A$ = INKEY$:IF A$ = "" THEN 9600
IF A$ = "N" OR A$ = "n" THEN 9640
IF A$ <> "Y" AND A$ <> "y" THEN 9600
GOTO 9310
RETURN
COLOR FGND3,BGND3:CLS
LOCATE 23,68:COLOR FGND1,BGND1:PRINT "Fl_Main Menu"
:LOCATE 8,37
PRINT " MENU LOCATE 23,1:PRINT " Please select your
choice : "
COLOR FGND3,BGND3 :LOCATE 23,32 :PRINT CHR$(15)
LOCATE 12,32 :PRINT "1. Print Data"
LOCATE 14,32 :PRINT "2. Save Actual Data"
LOCATE 16,32 :PRINT "3. Save Fitted Data"
LOCATE 23,32:A$ = INKEY$:IF A$ = "" THEN 9720
IF RIGHT$(A$,1) = CHR$(59) THEN 9780
IF ASC(A$) < 49 OR ASC(A$) > 51 THEN 9720
PRINT A$
on ASC(A$)-48 GOSUB 10010,9790,9890
GOTO 9650
RETURN
CLS:LOCATE 23,1:COLOR FGND1,BGND1:PRINT " Data file's
name : "
COLOR FGND3,BGND3 :LOCATE 23,24 :PRINT CHR$(15)
LOCATE 23,24 :INPUT "",NDAT$
IF NDAT$ = "" THEN 9880
OPEN NDAT$ FOR OUTPUT AS #1
FOR I = DBGN TO DEND
WRITE #1,X(I),Y(I)
NEXT I
CLOSE #1
RETURN
CLS:LOCATE 23,1:COLOR FGND1,BGND1:PRINT " Curve fit
file : "
COLOR FGND3,BGND3 :LOCATE 23,24 :PRINT CHR$(15)
LOCATE 23,24 :INPUT "",DOUT$
IF DOUT$ = "" THEN 10000
OPEN "curvefit" FOR INPUT AS #1
OPEN DOUT$ FOR OUTPUT AS #2
IF EOF(1) THEN 9990
INPUT #1,XI,P
WRITE #2,XI,P
GOTO 9950
CLOSE
RETURN
CLS :COLOR FGND1,BGND1 :LOCATE 23,1
PRINT " X - Label : ";CHR$(26)
COLOR FGND2,BGND2 :LOCATE 23,24 :PRINT CHR$(15)
LOCATE 23,24 :INPUT "",XLBS$
CLS :COLOR FGND1,BGND1 :LOCATE 23,1
10015 PRINT " Y - Label : ";CHR$(26)
10016 COLOR FGND2,BGND2 :LOCATE 23,24 :PRINT CHR$(15)
10017 LOCATE 23,24 :INPUT ",YLB$
10018 LOCATE 13,37 :COLOR FGND1+16,BGND1 :PRINT " WAIT "
:COLOR FGND2,BGND2
10019 J=DBGN
10020 K=1:FOR I = 1 TO 7:PRINT :NEXT I
10030 LPRINT TAB(20) "NO." TAB(30) XLB$ TAB(50) YLB$
:LPRINT
10040 LPRINT TAB(19) J-DBGN+1 TRB(30) X(J) TAB(50) Y(J)
10050 K = K+1 :J=J+1
10060 IF J >= DEND THEN 10100
10070 IF K < 46 THEN 10040
10080 LPRINT CHR$(12);
10090 GOTO 10020
10100 LPRINT CHR$(12);
10110 RETURN
IV. DISPLAY SCREEN PROGRAM

10 CLS :LOCATE 25,1 :PRINT "< COLOR=1, B/W=2, MONO & COLOR (OR B/W)=3 >"
20 LOCATE 23,1 :COLOR 0,7 :PRINT " Please select type of monitor : "
30 COLOR 7,0 :LOCATE 23,35 :PRINT CHR$(15);" ":LOCATE 23,35
40 A$ = INKEY$ :IF A$ = "" THEN 40
50 PRINT A$
60 IF ASC(A$) < 49 OR ASC(A$) > 51 THEN 30
70 IF ASC(A$) = 49 THEN B$=CHR$(4) + CHR$(1) + CHR$(1) + CHR$(2) + CHR$(14) + CHR$(15) + CHR$(5)
80 IF ASC(A$) = 50 THEN B$=CHR$(1) + CHR$(8) + CHR$(1) + CHR$(8) + CHR$(3) + CHR$(8)
90 IF ASC(A$) = 51 THEN B$=CHR$(1) + CHR$(8) + CHR$(2) + CHR$(8) + CHR$(3) + CHR$(8) + CHR$(8)
100 OPEN "display" FOR OUTPUT AS #1
110 PRINT #1,B$
120 CLOSE #1
130 END
VITA

Pithuk Keattipun was born in Bangkok, Thailand on April 25, 1951. He received his early education in Bangkok and pursued his college career in the same city at the Chulachomklao Royal Military Academy where he obtained his Bachelor of Science degree in 1974. After graduation, he was employed to be an instructor by the same college.

In 1979, he was awarded a scholarship by the Royal Thai Army to continue his education at Florida Institute of Technology where he obtained a Master of Science with a major in Mechanical Engineering.

In 1981, he entered the Louisiana State University in the Mechanical Engineering Department where he obtained a degree of Doctor of Philosophy in August, 1987.
DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Pithuk Keattipun

Major Field: Mechanical Engineering

Title of Dissertation: The Effect of Microstructure on Constitutive Equations for Metals

Approved:

[Signature]
Major Professor and Chairman

[Signature]
Dean of the Graduate School

EXAMINING COMMITTEE:

[Signature]

[Signature]

[Signature]

Date of Examination:

June 29, 1987