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Design of automotive structural components using high strength sheet steels mechanical properties of materials

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DESIGN OF AUTOMOTIVE STRUCTURAL COMPONENTS USING HIGH STRENGTH SHEET STEELS

MECHANICAL PROPERTIES OF MATERIALS

by

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I. INTRODUCTION

It is well known that the material properties of steels and the strengths of cold-formed steel members are affected by strain rate. Therefore, the research project sponsored by the American Iron and Steel Institute (AISI) at the University of MIssouri-Rolla during the period from January 1988 through December 1991 was concentrated on a study of the effect of strain rate on mechanical properties of sheet steels and the structural behavior and strength of cold-formed steel members subjected to dynamic loads.

Because the previous UMR studies were limited only to the structural members such as stub columns and beams which were assembled with the same material in a given section, the objective of this investigation is to study the structural strength of hybrid automotive structural components using different sheet steels. In this report, two selected sheet steels (25AK and 50SK) were tested to study the effect of strain rate on mechanical properties. The mechanical properties of 25AK and 50SK sheet steels obtained from materials tests will be used later in the evaluation of test results of structural members. A total of 48 tensile coupons and 48 compressive coupons were tested in this phase of study and reported herein.

This study was primarily involved with the experimental determination of the dynamic properties of two different sheet steels with nominal static yield strengths of 25 and 50 ksi. The strain rates used in the tests ranged from 10^{-4} to 1.0 in./in./sec.. All tests were performed at Engineering Research Laboratory of University of Missouri-Rolla by using the MTS 880 test system. In Chapter II of this report, the experimental study of the mechanical properties of the selected sheet steels are presented in detail. The material test results are evaluated in Chapter III. Finally, conclusions are presented in Chapter IV.

II. EXPERIMENTAL INVESTIGATION

A. GENERAL

In order to study the effect of strain rate on the mechanical properties of high strength sheet steels, tension and compression coupon tests of two selected sheet steels (25AK and 50SK) were conducted under different strain rates ranging from 10^{-4} to 1.0 in./in./sec. The nominal yield strengths of these two sheet steels varied from 25 to 50 ksi. These two virgin materials were uniaxially tested in the longitudinal (parallel to the direction of rolling) and transverse (perpendicular to the direction of rolling) directions in tension and compression under four different strain rates. In this chapter, the experimental investigation of material properties of two selected sheet steels is discussed in detail.

B. TENSION TESTS

All tension tests followed the procedures outlined in the ASTM Specifications listed below :

E8-69	Tension Testing of Metalic Materials
E83-67	Standard Method of Verification and Classification of Extensometers
E111-82	Standard Test Method for Young's Modulus, Tangent Modulus and Chord Modulus

Two sheet steels (25AK and 50SK) were tested in both longitudinal and transverse directions to determine the effects of strain rate on mechanical properties. Four strain rates were selected for the tension tests. They were 10^{-4}, 10^{-2}, 10^{-1}, and 1.0 in./in./sec..

1. Specimens. As can be seen from Figure 2.1, the test specimens were cut longitudinally and transversely from the quarter points of the steel sheets. All tensile specimens were prepared in the machine shop of the Department of Civil Engineering at the University of Missouri-Rolla. Figure 2.2 shows the dimensions of tension coupons. In this phase of study, 24 coupons were cut from the 25AK sheet steel and 24 coupons from the 50SK sheet steel. A total of four different cases were conducted for the tension tests which are summarized in Table 2.1.

2. Instrumentation. All tests were performed by using a 110 kip MTS 880 Test System located at the UMR Engineering Research Laboratory. As shown in Figure 2.3, this test system consists of an MTS load frame, an MTS control console, and the CAMAC (Computer Automated Measurement and Control) Data Acquisition System. After the test data were acquired in the CAMAC Data Acquistion System, it was downloaded to the Data General MV-10000 Mini Computer for analysis purpose. Other equipment used to analyze the test data includes an IBM PS/2 Model 30 personal computer with an IBM color plotter and an NEC Pinwrite P5XL printer.

The loading apparatus was a servohydraulic closed-loop type. The moving position is driven by a double-action hydraulic cylinder, so that it can operate under tension and compression. The fluid pressure in the chamber is controlled by a servovalve, which responds to the difference between the measured signal and the desired signal. The signal is amplified to drive the valve so as to remove the error. The load was measured by an MTS System Model 380041-06 load cell and associated conditioning, which was calibrated prior to testing according to the procedure of the National Bureau of Standards.

The data acquisition used in this system conforms to the CAMAC standards. The main data acquisition module is a Kinetic Systems Model 4022 Transient Recorder. This unit has 64 simultaneous sampling input channels at a resolution of 12 bits. It is capable of acquiring the test data at the maximum rate of 25,000 sets of readings per second.

An MTS Model No. 732.25b-20 extensometer (Figure 2.4) with a 2-in. gage length was used to measure the strains from zero load to failure. The classification of this extensometer according to ASTM Designation E-83 was found to be dependent on the extensometer range used in the test. Table 2.2 contains the classification of the four extensometer ranges according to the MTS transducer calibration data.

There are three modes of operating the machine, commonly referred to as load, strain, and stroke (displacement). There are four different ranges of operation (100%, 50%, 20%, and 10%) for each mode. Table 2.3 summarizes the transducer ranges and the corresponding load, strain, and displacement values. Under the stroke mode, the movement of the piston is the controlling variable. Under the load mode, it is the load acting on the test specimen. Under the strain mode, it is the strain, as read from the extensometer. For each of these three modes, different time functions can be established by the function generator to match the application needed. Tensile tests under a constant strain rate can be made by setting a ramp function under the strain mode. The slope of this ramp is the desired strain rate.

3. Test Procedure. All tensile coupons were cut and machined to the desired shapes. Prior to testing, the dimensions were measured to the nearest 0.001 inch. The specimen was then cleaned with acetone, and the gage length was marked in ink. The grips of the load frame were aligned by operating the machine under stroke mode. Then, the specimen was placed in the grips such that the longitudinal axis of the specimen coincided with the center line of the grips.

For most tension tests, load range 4, strain range 1, and stroke range 1 were selected. The function generator was programmed to produce the desired ramp. Ramp time 1 (RT1) was chosen for the desired strain-rate value and ram time 2 (RT2) was chosen to give enough time to remove the extensometer and the specimen from the load unit as illustrated in Figure 2.5.

Before running the test, the load mode was selected to place the specimen in the grips. The extensometer was attached to the specimen such that the knife edges of extensometer lined up with the gage marks as shown in Figure 2.4. The load mode was then transfered to the strain mode before the test was started. After the test was completed, the test data was saved by the Data General Mini Computer for later plotting and determination of mechanical properties.

4. Test Results. A constant strain rate is very difficult to maintain with the conventional test machine especially at higher strain rate. For this series of tests, the strain rate was controlled

electronically by the MTS 880 Test System, which allowed the exact strain rate to be maintained without any difficulty. Figure 2.6 shows the strain-time curve for the specimen 25LT3A fabricated from 25AK sheet steel and tested under 0.1 in./in./sec. strain rate. The stress-strain curves and mechanical properties of two types of materials obtained from tension tests are discussed below :

a. Stress-Strain Relationships. To illustrate the effect of strain rate on the mechanical properties, Figures 2.7 and 2.8 show the typical stress-strain curves for 25AK and 50SK sheet steels tested in the longitudinal direction, respectively. Each figure includes four stress-strain curves representing the test data obtained from the same sheet steel using different strain rates (10^{-4}, 10^{-2}, 10^{-1}, and 1.0 in./in./sec.). Similar plots for 25AK and 50SK sheet steels tested in the transverse direction are shown in Figures 2.9 and 2.10.

The stress-strain relationships were plotted by using the Data General graphics software named "Trendview" with the stress and strain data recalled from the computer storage. Because the stresses were calculated by dividing the loads by the original, unreduced areas of the specimens, they should be regarded as the engineering stress-strain curves.

b. Mechanical Properties. The mechanical properties determined from tension tests are yield strength (F_y), ultimate tensile strength (F_u), and elongation in 2-in. gage length. The material properties derived from each individual test are presented in Tables 2.4 and 2.5 for 25AK and 50SK sheet steels, respectively. Tables 2.6 through 2.9 present the average values of the mechanical properties for each material tested in either longitudinal tension (LT) or transverse tension (TT) under different strain rates (10^{-4}, 10^{-2}, 10^{-1}, or 1.0 in./in./sec.). The procedures used for determining the mechanical properties of sheet steels are discussed in the following paragraphs.

* Yield Strength. The method commonly used to determine the yield strength of sheet steels depends on whether the stress-strain curve is the gradual-yielding or sharp-yielding type. For the types of sheet steels tested in this phase of study, the stress-strain curves of 50SK sheet steel are the sharp-yielding type, while the stress-strain curves of 25AK sheet steel are the gradual-yielding type.

The yield strength of sharp-yielding sheet steel was determined by the lower yield point, for which the stress-strain curve becomes horizontal. For the stress-strain curves of gradual-yielding type, the yield strength was determined by the intersection of the stress-strain curve and the straight line drawn parallel to the elastic portion of the stress-strain curve at an offset of 0.2 percent.

* Ultimate Tensile Strength. The ultimate tensile strength was determined from each of the tension tests as the maximum stress that the given tension coupon could withstand before fracture.

* Ductility. In this study, ductility was determined by the total elongation in a 2-in. gage length. For this method, the maximum strain recorded by the computer before fracture was taken as the ductility. The maximum elongation was also verified by placing the fractured ends of the specimen together and measuring the distance between the gage marks.

C. COMPRESSION TESTS

The materials used for the tension tests, were also unaxially tested in compression in the longitudinal and transverse directions under four different strain rates of 10^{-4}, 10^{-2}, 10^{-1}, and 1.0 in./in./sec.. All compression tests followed the procedures outlined in the ASTM Specifications listed below :

E9-70	Standard Method of Compression Testing of Matallic Materials at Room Temperature
E83-67	Standard Method of Verification and Classification of Extensometers
E111-82	Standard Test Method for Young's Modulus, Tangent Modulus and Chord Modulus

1. Specimens. All test specimens were cut from the steel sheet and prepared in the Machine Shop of the Department of Civil Engineering at the University of Missouri-Rolla. Figure 2.11 shows the shape and dimensions of the specimen used for the compression test. The specimen dimensions were selected to fit a Montgomery-Templin compression test fixture as shown in Figure 2.12. The notches along one edge were for the installation of the knife edges of the compressometer. Special care was taken to ensure that the ends of the specimens were parallel and thus the same length was used for both longitudinal sides of the specimen. Twenty-four (24) coupons cut from each of 25AK and 50SK sheet steels were tested in this phase of study. Four different cases were conducted for the compression tests which are summarized in Table 2.10.

2. Intrumentation. All compression tests were performed in the same MTS 880 machine as discussed for the tension tests. Two compression platens were installed for conducting the compression tests.

Figure 2.13 shows the assembly of the test specimen and the test fixture. The load was applied to the compression coupon by means of a specially made subpress as shown in Figure 2.12. The subpress base and ram are constructed of a hardened steel in order to minimize their deformation when applying the load. As can be seen from Figure 2.13, the compression specimen was placed in a Montgomery-Templin compression test fixture, which contains a series of rollers to prevent buckling.

An MTS compressometer (Figure 2.12) with a 1-in. gage length was used to measure compression strains from zero to 0.02 in./in.. A special fixture was designed to fit the MTS compressometer in the compression jig. According to ASTM Designation E83, the classification of this compressometer was found to be dependent on the compressometer range used in the tests. Table 2.11 contains the classification of four compressometer ranges according to the MTS transducer calibration data.

Similar to the tension tests, compression tests under a constant strain rate were made by setting a ramp function under the strain mode, which was used to operate the machine. The slope of this ramp is the desired strain rate. Figure 2.14 shows the strain-time curve of specimen 25LC1B tested under 10^{-4} in./in./sec..

3. Test Procedure. Prior to testing, the dimensions of the compression coupons were measured to the nearest 0.001 inch. The specimen was then placed in the compression test fixture and tightened firmly

against the both sides of the specimen by the lateral roller supports. Special care was taken to ensure that the specimen was aligned vertically in the compression jig. The compressometer was then attached to one side of the compression jig such that the knife edges of the compressometer inserted into the notches of the specimen correctly. Next, the compression jig with the specimen and compressometer was placed in the compression subpress. A small stub is provided on each side of the bottom surface of compression jig. These stubs fit into indentations on the base of the subpress in order to ensure proper alignment of the subpress ram with the longtidinal axis of specimen. Next step was to place the entire test unit between two compression platens in the loading frame such that the longitudinal axis of the subpress lined up with the center of the platens.

For all the compression tests, the strain mode was selected to maintain a constant strain rate. Range 4 was chosen for the load, strain, and stroke modes in the MTS control console. The function generator was programmed to produce the desired ramp. The test data was recorded in the Data General Mini Computer for later plotting and analysis.

4. Test Results. As pointed out in preceding section, a constant strain rate was conducted for each compression test by using the MTS 880 Test System without any difficulty. The stress-strain curves and mechanical properties of two types of sheet steel (25AK and 50SK) were obtained from compression tests as discussed below :

a. Stress-Strain Relationships. Figures 2.15 and 2.16 present the typical stress-strain curves for the two different sheet steels tested in the longitudinal direction. Each figure includes four stress-strain curves representing the test data obtained from the same sheet steel but using different strain rates (10^{-4}, 10^{-2}, 10^{-1}, and 1.0 in./in./sec.). The typical compressive stress-strain curves for 25AK and 50SK sheet steels tested in the transverse direction are shown in Figures 2.17 and 2.18, respectively.

b. Mechanical Properties. The mechanical properties determined from compression tests included proportional limit (F_{pr}), and yield strength (F_y). The material properties derived from each individual test are presented in Tables 2.12 and 2.13. Tables 2.14 through 2.17 present the average values of the mechanical properties for each material tested in either longitudinal compression (LC) or transverse compression (TC) under different strain rates. The procedures used for determining the mechanical properties of sheet steels are discussed in the subsequent paragraphs.

* Proportional Limit. The proportional limit is usually defined as the point above which the stress-strain curve becomes nonlinear. Because it is often difficult to determine the exact location of the true proportional limit in the stress-strain diagram, the proportional limit can be determined by the 0.01 percent offset method for sheet steel.

As illustrated in Figure 2.19, the proportional limit of 25AK sheet steel tested in the transverse compression under the strain rate of 10^{-4} in./in./sec. was obtained by using the 0.01 percent offset method. Because of the waving effect of the impact load on the stress-strain curves of the tests conducted at the strain rate of 1.0 in./in./sec., reliable values for the proportional limit were difficult to obtain.

* Yield Strength. The yield strength of sharp-yielding sheet steel was determined by the stress where the stress-strain curve becomes horizontal. Therefore, the lower yield point of stress-strain diagram was used to determine the yield strengths listed in the tables for 50SK sheet steel. For the gradual-yielding type stress-strain curves (25AK sheet steel), the yield strength was determined by the intersection of the stress-strain curve and the straight line drawn parallel to the elastic portion of the stress-strain curve at an offset of 0.2 percent.

III. EVALUATION OF EXPERIMENTAL DATA

A. GENERAL

The materials used in the experimental program were virgin steels (25AK and 50SK) tested for tensile and compression. The tension and compression coupons were tested in both longitudinal and transverse directions under different strain rates. The strain rates varied from 10^{-4} to 1.0 in./in./sec.. In this study, the work was emphasized on the effect of strain rate on the mechanical properties of sheet steels, the strain-rate sensitivity, and the development of empirical equations on the basis of the test results.

B. MECHANICAL PROPERTIES

The test results indicated that all mechanical properties are affected by the strain rate. It was found that most of the mechanical properties incresed with increasing strain rate for these two types of sheet steels. The effect of strain rate on proportional limit, yield strength, and ultimate tensile strength are dicussed in the subsequent sections.

1. Proportional Limit. From Tables 2.14 through 2.17, it can be seen that the proportional limit of sheet steels tested in compression increased with increasing strain rate. The proportional limit were difficult to obtain from tensile tests because of limited number of data points recorded by the MTS extensomter in the linear range of the stress-strain curves. The percentage increases in proportional limits

for the two sheet steels tested in longitudinal and transverse compression were found to be : 43% and 55% for 25AK sheet steel and 6% and 19% for 50SK sheet steel when the strain rate increased from 10^{-4} to 10^{-1} in./in./sec.. It seems that the percentage increases for both sheet steels tested in transverse direction are higher than these sheet steels tested in longitudinal direction.

2. Yield Strength. Similar to the effect of strain rate on proportional limit, the yield strength of sheet steels increased with increasing strain rate. Table 3.1 compares the dynamic tension yield stresses, $(F_y)_d$, determined at the strain rate of 1.0 in.in./sec. with the static tension yield stresses, $(F_y)_s$, determined at the strain rate of 10^{-4} in./in./sec.. Similarly, Table 3.2 shows the comparison between dynamic yield stresses and static yield stresses in compression. It can be seen from these tables that the values of $(F_y)_d/(F_y)_s$ ratio in longitudinal tension and compression are smaller than those in transverse tension and compression for 50SK sheet steel. For 25AK sheet steel tested in compression, the values of $(F_y)_d/(F_y)_s$ ratio in transverse direction is smaller than that in the longitudinal direction. It was noted that the percentage increases in proportional limit obtained from the compression tests are slightly larger than the percentage increases in yield stress when the strain rate was increased from 10^{-4} to 0.1 in./in./sec..

3. Ultimate Tensile Strength. Comparisons between dynamic ultimate tensile strength to static ultimate tensile strength are also shown in Table 3.1. Similar to the effect of strain rate on yield strength, the ultimate tensile strengths of sheet steels increased with increasing

strain rate. It was noted that the amount of increase in ultimate tensile strength due to the increase in strain rate is approximately the same for both longitudinal and transverse tension. The increases in ultimate tensile strengths for the two materials tested in longitudinal and transverse tension were found to be : 20% and 22% for 25AK sheet steel and 14% and 15% for 50SK sheet steel when the strain rate was increased from 10^{-4} to 1.0 in./in./sec.. The ultimate compressive strengths could not be obtained because the buckling of the unsupported lengths at each end of the compression coupon limited the obtainable range of the stress-strain relationships to approximately 2.0 percent.

C. STRAIN RATE SENSITIVITY

The flow stress depends on strain (ε) and strain rate ($\dot{\varepsilon}$):

$$\sigma = \sigma(\varepsilon, \dot{\varepsilon}) \qquad (3.1)$$

Based on the research findings presented in Reference 1 and 2, it is recognized that the stress can be obtained by applying the material constant and strain-rate sensitivity to strain rate as follows :

$$\sigma = C\,\dot{\varepsilon}^{m} \qquad (3.2)$$

where σ = true stress

$\dot{\varepsilon}$ = true strain rate

m = strain rate sensitivity exponent

C = material constant

By applying Equaion 3.2 to two different strain rates and eliminating C, we have[3]

$$m = \frac{\ln(\sigma_2/\sigma_1)}{\ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)} \tag{3.3}$$

On the basis of Equation 3.3, the values of the strain-rate sensitivity for 25AK and 50SK sheet steels in tension and compression were computed and listed in Tables 3.3 and 3.4, respectively. In these two tables, the values of m_1 were calculated for the yield strengths corresponding to the strain rates of 10^{-4} and 10^{-2} in./in./sec.; the values of m_2 were calculated for the yield strengths corresponding to the strain rates of 10^{-2} and 0.1 in./in./sec.; and the values of m_3 were calculated for the yield strengths corresponding to the strain rates of 10^{-4} and 1.0 in./in./sec.. From these two tables, it can be seen that, in general, the strain-rate sensitivity "m" in tension and compression increases as the strain rate increases. The strain-rate sensitivity decreases progressively as the static yield strength level increases.

D. PREDICTION OF YIELD STRENGTH FOR HIGH STRAIN RATE

A second degree polynominal form (Equation 3.4) was developed for prediction of the yield strength and ultimate tensile strength by using the least square method. The range of strain rate used to calculate the polynominal was from 10^{-4} to 1.0 in./in./sec..

$$Y = A + BX + CX^2 \tag{3.4}$$

where Y = yield stress

X = $\log(\dot{\varepsilon})$

A, B, and C = constants

Figures 3.1 through 3.4 show the test data of tension yield stresses and the predictions calculated from these test data for two sheet steels (25AK and 50SK) in the virgin condition and tested in the longitudinal and transverse directions under different strain rates. Similar plots for the sheet steels tested in compression are shown from Figures 3.5 through 3.8. The data plotted in these figures are in terms of yield stress versus logarithmic strain rate. The polynominal used for drawing the curve in each plot are shown at the up-left corner of each figure. Figures 3.9 through 3.12 show the test data of tensile ultimate stresses and the polynominals for 25AK and 50SK sheet steels in the virgin condition and tested in the longitudinal and transverse directions.

IV. CONCLUSIONS

This study dealt primarily with the experimental determination of the dynamic properties of sheet steels. Two selected sheet steels (25AK and 50SK) were tested and studied in this report. These sheet steels were uniaxially tested in the longitudinal and transverse directions in tension and compression. A total of 96 coupons were tested under different strain rates. Based on the test results for 25AK and 50SK sheet steels, the following conclusion can be made :

1. The mechanical properties including proportional limit, yield strength, and ultimate strength, increase with increasing strain rate.
2. For most cases, the mechanical properties (proportional limit, yield strength, and ultimate strength) of both sheet steels tested in transverse direction are higher than those tested in longitudinal direction under the same strain rate.
3. Yield strength is more sensitive to strain rate than ultimate strength for both materials.
4. The strain rate sensitivity value (m) is not constant, it increases with increasing strain rate in most cases.
5. A second degree polynominal is well fitted to the experimental data for both tension and compression and can be used to predict the yield and ultimate strengths at high strain rates.

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REFERENCES

1. Hosford, W.F. and Caddel, R.W., Metal Forming-Mechanics and Metallurgy , Prentice Hall Inc., N.J., 1983, 80-84.

2. Chatfield, D.A., and Rote, R.R., "Strain Rate Effects on the Properties of High Strength, Low Alloy Steels", SAE Tech. Paper Ser. 740177, Feb. 25 - March 1, 1974.

3. Alder, J.F. and Chawla, K.K., Mechanical Metallurgy: Principles and Applications , Prentice Hall Inc., Englewood Cliffs, N.J., 1984.

4. Parks, M.B. and Yu, W.W., "Design of Automotive Structural Components Using High Strength Sheet Steels: Mechanical Properties of Materials", 2nd Progress Report, Civil Engineering Study 83-3, University of Missouri-Rolla, August 1983.

5. Kassar, M. and Yu, W.W., "Design of Automotive Structural Components Using High Strength Sheet Steels: Effect of Strain Rate on Material Properties of Sheet Steels and Structural Strengths of Cold-Formed Steel Members", Fourteenth Progress Report, Civil Engineering Study 90-2, University of Missouri-Rolla, May, 1990.

Table 2.1

Number of Performed Tensile Coupon Tests

Direction of testing	Type of Material	Number of Coupons Used
Longitudinal Tension (LT)	25LT	12
	50LT	12
Transverse Tension (TT)	25TT	12
	50TT	12

Table 2.2

Classification of the MTS Extensometer

Range	Maximum Strain in./in.	Maximum Error in./in.	ASTM Classification
100%	0.50	0.00065	Between Classes B-2 and C
50 %	0.25	0.00030	Between Classes B-2 and C
20 %	0.10	0.00011	Between Classes B-1 and B-2
10 %	0.05	0.00002	Between Classes A and B-1

Table 2.3

MTS Transducer Ranges and the Corresponding Load, Strain, or Displacement Values

Transducer	Range	Value
Load	100 % 50 % 20 % 10 %	100.0 kips 50.0 kips 20.0 kips 10.0 kips
Strain	100 % 50 % 20 % 10 %	0.50 in./in. 0.25 in./in. 0.10 in./in. 0.05 in./in.
Stroke	100 % 50 % 20 % 10 %	10.0 in. 5.00 in. 2.00 in. 1.00 in.

Table 2.4

Tested Mechanical Properties of 25AK Sheet Steel

Virgin Material in Tension

Test No.	Strain Rate in./in./sec.	F_y (ksi)	F_u (ksi)	Elongation in 2-in. Gage Length (percent)
25LT1A	0.0001	23.61	42.40	----
25LT1B	0.0001	24.87	43.13	----
25LT1C	0.0001	25.33	42.75	----
25LT2A	0.01	28.44	44.89	48.76
25LT2B	0.01	27.60	44.21	49.62
25LT2C	0.01	27.54	44.21	49.56
25LT3A	0.1	32.33	47.63	50.25
25LT3B	0.1	31.32	47.02	51.70
25LT3C	0.1	31.50	47.39	-----
25LT4A	1.0	35.12	51.29	59.15
25LT4B	1.0	35.57	51.28	56.70
25LT4C	1.0	34.71	51.17	58.70
25TT1A	0.0001	25.03	41.90	----
25TT1B	0.0001	26.21	42.88	----
25TT1C	0.0001	26.45	42.52	----
25TT2A	0.01	28.42	44.23	47.34
25TT2B	0.01	28.76	44.23	49.91
25TT2C	0.01	29.76	44.49	----
25TT3A	0.1	32.93	46.44	----
25TT3B	0.1	33.51	47.43	50.50
25TT3C	0.1	33.84	47.82	50.41
25TT4A	1.0	37.62	51.88	53.10
25TT4B	1.0	36.57	51.14	53.50
25TT4C	1.0	38.33	52.25	52.11

Table 2.5

Tested Mechanical Properties of 50SK Sheet Steel

Virgin Material in Tension

Test No.	Strain Rate in./in./sec.	F_y (ksi)	F_u (ksi)	Elongation in 2-in. Gage Length (percent)
50LT1A	0.0001	55.19	66.84	35.94
50LT1B	0.0001	55.27	67.12	36.55
50LT1C	0.0001	54.44	67.26	35.79
50LT2A	0.01	56.88	68.77	34.42
50LT2B	0.01	56.08	68.72	32.30
50LT2C	0.01	57.52	69.45	33.30
50LT3A	0.1	57.06	70.98	32.65
50LT3B	0.1	59.14	71.25	34.98
50LT3C	0.1	57.97	70.90	35.73
50LT4A	1.0	60.12	75.39	42.49
50LT4B	1.0	60.79	77.18	38.67
50LT4C	1.0	61.27	76.94	39.24
50TT1A	0.0001	58.64	69.20	35.80
50TT1B	0.0001	58.10	68.93	34.51
50TT1C	0.0001	58.42	68.92	34.31
50TT2A	0.01	59.98	70.39	32.26
50TT2B	0.01	59.74	71.32	31.84
50TT2C	0.01	60.67	71.03	31.24
50TT3A	0.1	62.15	74.37	31.40
50TT3B	0.1	61.92	75.56	31.03
50TT3C	0.1	63.45	75.39	33.21
50TT4A	1.0	66.91	79.94	34.42
50TT4B	1.0	68.31	80.47	32.93
50TT4C	1.0	66.98	78.56	35.81

Table 2.6

Average Tested Mechanical Properties of 25AK Sheet Steel

Longitudinal Tension

Strain Rate in./in./sec.	F_y (ksi)	F_u (ksi)	Elongation (percent)
0.0001	24.60	42.76	-----
0.01	27.86	44.44	49.31
0.1	31.72	47.35	50.98*
1.0	35.13	51.25	58.18*

Table 2.7

Average Tested Mechanical Properties of 25AK Sheet Steel

Transverse Tension

Strain Rate in./in./sec.	F_y (ksi)	F_u (ksi)	Elongation (percent)
0.0001	25.90	42.43	-----
0.01	28.98	44.32	48.63
0.1	33.43	47.23	50.46*
1.0	37.51	51.76	52.90*

* : Because the maximum range for extensometer is 1.0 inch, these values were measured from the distance between the gage marks of tension coupons.

Table 2.8

Average Tested Mechanical Properties of 50SK Sheet Steel

Longitudinal Tension

Strain Rate in./in./sec.	F_y (ksi)	F_u (ksi)	Elongation (percent)
0.0001	54.97	67.07	36.09
0.01	56.83	68.98	33.34
0.1	58.06	71.04	34.45
1.0	60.73	76.50	40.13

Table 2.9

Average Tested Mechanical Properties of 50SK Sheet Steel

Transverse Tension

Strain Rate in./in./sec.	F_y (ksi)	F_u (ksi)	Elongation (percent)
0.0001	58.39	69.02	34.87
0.01	60.13	70.91	31.78
0.1	62.51	75.11	31.88
1.0	67.41	79.66	34.39

Table 2.10

Number of Performed Compressive Coupon Tests

Direction of Testing	Type of Material	Number of Coupons Used
Longitudinal Compression	25LC	12
(LC)	50LC	12
Transverse Compression	25TC	12
(TC)	50TC	12

Table 2.11

Classification of the MTS Compressometer

Range	Maximum Strain in./in.	Maximum Error in./in.	ASTM Classification
100%	0.20	0.000100	Class B-1
50 %	0.10	0.000050	Between Classes A and B-1
20 %	0.04	0.000012	Between Classes A and B-1
10 %	0.02	0.000008	Class A

Table 2.12

Tested Mechanical Properties of 25AK Sheet Steel
Virgin Material

Test No.	Strain Rate in./in./sec.	F_{pr} (ksi)	F_y (ksi)	F_{pr}/F_y
25LC1A	0.0001	15.42	21.85	0.71
25LC1B	0.0001	15.35	21.01	0.73
25LC1C	0.0001	17.03	22.11	0.77
25LC2A	0.01	19.07	23.92	0.80
25LC2B	0.01	19.37	24.80	0.78
25LC2C	0.01	20.21	25.58	0.79
25LC3A	0.1	22.43	29.08	0.77
25LC3B	0.1	24.75	30.97	0.80
25LC3C	0.1	21.24	29.35	0.72
25LC4A	1.0	-----	37.07	----
25LC4B	1.0	-----	39.36	----
25LC4C	1.0	-----	38.00	----
25TC1A	0.0001	19.21	24.75	0.78
25TC1B	0.0001	18.49	23.42	0.79
25TC1C	0.0001	18.43	23.31	0.79
25TC2A	0.01	24.87	27.58	0.90
25TC2B	0.01	25.34	28.12	0.90
25TC2C	0.01	23.92	26.20	0.91
25TC3A	0.1	29.00	31.27	0.93
25TC3B	0.1	29.54	33.65	0.88
25TC3C	0.1	28.60	31.41	0.91
25TC4A	1.0	-----	38.26	----
25TC4B	1.0	-----	40.29	----
25TC4C	1.0	-----	38.96	----

Table 2.13

Tested Mechanical Properties of 50SK Sheet Steel
Virgin Material

Test No.	Strain Rate in./in./sec.	F_{pr} (ksi)	F_y (ksi)	F_{pr}/F_y
50LC1A	0.0001	41.63	53.89	0.77
50LC1B	0.0001	42.87	54.08	0.79
50LC1C	0.0001	41.43	52.09	0.80
50LC2A	0.01	42.16	55.62	0.76
50LC2B	0.01	42.72	56.52	0.76
50LC2C	0.01	42.50	55.60	0.76
50LC3A	0.1	44.50	57.03	0.78
50LC3B	0.1	45.51	57.09	0.80
50LC3C	0.1	43.06	56.75	0.76
50LC4A	1.0	-----	60.26	----
50LC4B	1.0	-----	59.58	----
50LC4C	1.0	-----	58.39	----
50TC1A	0.0001	45.98	52.65	0.87
50TC1B	0.0001	45.24	53.94	0.84
50TC1C	0.0001	47.15	54.21	0.87
50TC2A	0.01	50.76	58.43	0.87
50TC2B	0.01	49.82	56.83	0.88
50TC2C	0.01	50.78	58.92	0.86
50TC3A	0.1	54.17	59.22	0.91
50TC3B	0.1	55.21	61.25	0.90
50TC3C	0.1	54.60	61.68	0.86
50TC4A	1.0	-----	67.95	----
50TC4B	1.0	-----	66.94	----
50TC4C	1.0	-----	65.22	----

Table 2.14

Average Tested Mechanical Properties of 25AK Sheet Steel

Longitudinal Compression

Strain Rate in./in./sec.	F_{pr} (ksi)	F_y (ksi)	F_{pr}/F_y
0.0001	15.93	21.66	0.74
0.01	19.55	24.77	0.79
0.1	22.81	29.80	0.76
1.0	-----	38.14	----

Table 2.15

Average Tested Mechanical Properties of 25AK Sheet Steel

Transverse Compression

Strain Rate in./in./sec.	F_{pr} (ksi)	F_y (ksi)	F_{pr}/F_y
0.0001	18.71	23.83	0.79
0.01	24.71	27.30	0.90
0.1	29.05	32.11	0.91
1.0	-----	39.17	----

Table 2.16

Average Tested Mechanical Properties of 50SK Sheet Steel

Longitudinal Compression

Strain Rate in./in./sec.	F_{pr} (ksi)	F_y (ksi)	F_{pr}/F_y
0.0001	41.98	53.35	0.79
0.01	42.46	55.91	0.76
0.1	44.36	56.96	0.78
1.0	-----	59.41	----

Table 2.17

Average Tested Mechanical Properties of 50SK Sheet Steel

Transverse Compression

Strain Rate in./in./sec.	F_{pr} (ksi)	F_y (ksi)	F_{pr}/F_y
0.0001	46.12	53.60	0.86
0.01	50.45	58.06	0.87
0.1	54.66	60.72	0.89
1.0	-----	66.70	----

Table 3.1

Ratios of Dynamic to Static Mechanical Properties for Two Sheet Steels (Tension)

Type of Sheet Steel	$(F_y)_d/(F_y)_s$	$(F_u)_d/(F_u)_s$
25AK-LT	1.43	1.20
25AK-TT	1.45	1.22
50SK-LT	1.10	1.14
50SK-TT	1.15	1.15

Table 3.2

Ratios of Dynamic to Static Compressive Yield Stresses for Two Sheet Steels (Compression)

Type of Sheet Steel	$(F_y)_d/(F_y)_s$
25AK-LC	1.76
25AK-TC	1.64
50SK-LC	1.11
50SK-TC	1.24

Notes :

$(F_y)_d$ = dynamic yield stress for the strain rate of 1.0 in./in./sec.

$(F_y)_s$ = static yield stress for the strain rate of 10^{-4} in./in./sec.

$(F_u)_d$ = dynamic ultimate stress for the strain rate of 1.0 in./in./sec.

$(F_u)_s$ = static ultimate stress for the strain rate of 10^{-4} in./in./sec.

Table 3.3

Values of Strain Rate Sensitivities m for Two Sheet Steels Based on the Changes of the Yield Stresses at Different Strain Rates (Tension)

Type of Sheet Steel	m_1	m_2	m_3
25AK-LT	0.027	0.037	0.039
25AK-TT	0.024	0.037	0.040
50SK-LT	0.007	0.008	0.011
50SK-TT	0.006	0.010	0.015

Table 3.4

Values of Strain Rate Sensitivities m for Two Sheet Steels Based on the Changes of the Yield Stresses at Different Strain Rates (Compression)

Type of Sheet Steel	m_1	m_2	m_3
25AK-LC	0.029	0.046	0.061
25AK-TC	0.030	0.043	0.054
50SK-LC	0.010	0.009	0.012
50SK-TC	0.017	0.018	0.024

Notes:

m_1 = strain rate sensitivity based on the changes of yield stress between strain rates of 0.0001 and 0.01 in./in./sec.

m_2 = strain rate sensitivity based on the changes of yield stress between strain rates of 0.0001 and 0.1 in./in./sec.

m_3 = strain rate sensitivity based on the changes of yield stress between strain rates of 0.0001 and 1.0 in./in./sec.

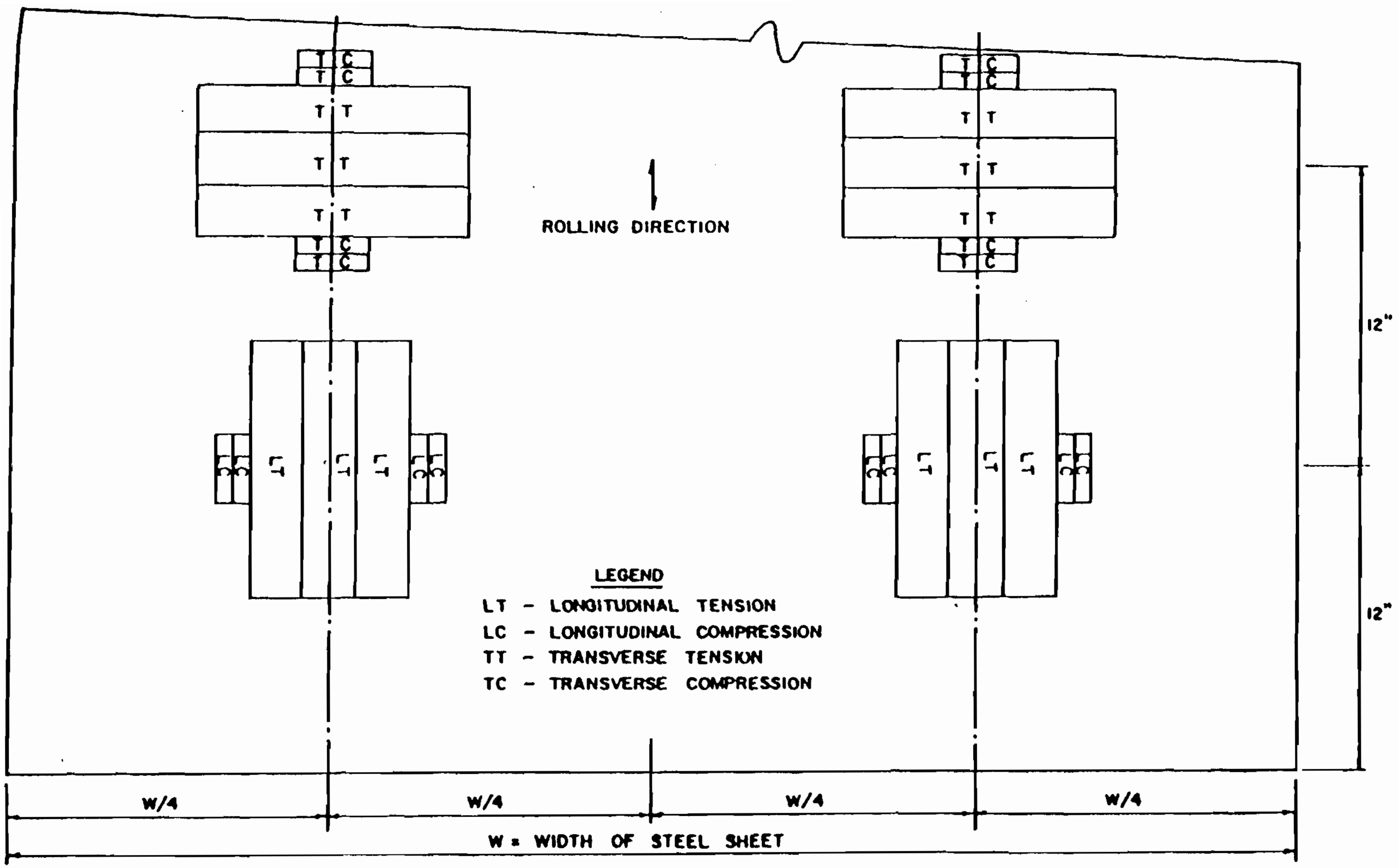

Figure 2.1 Location of Tension and Compression Coupons [4,5]

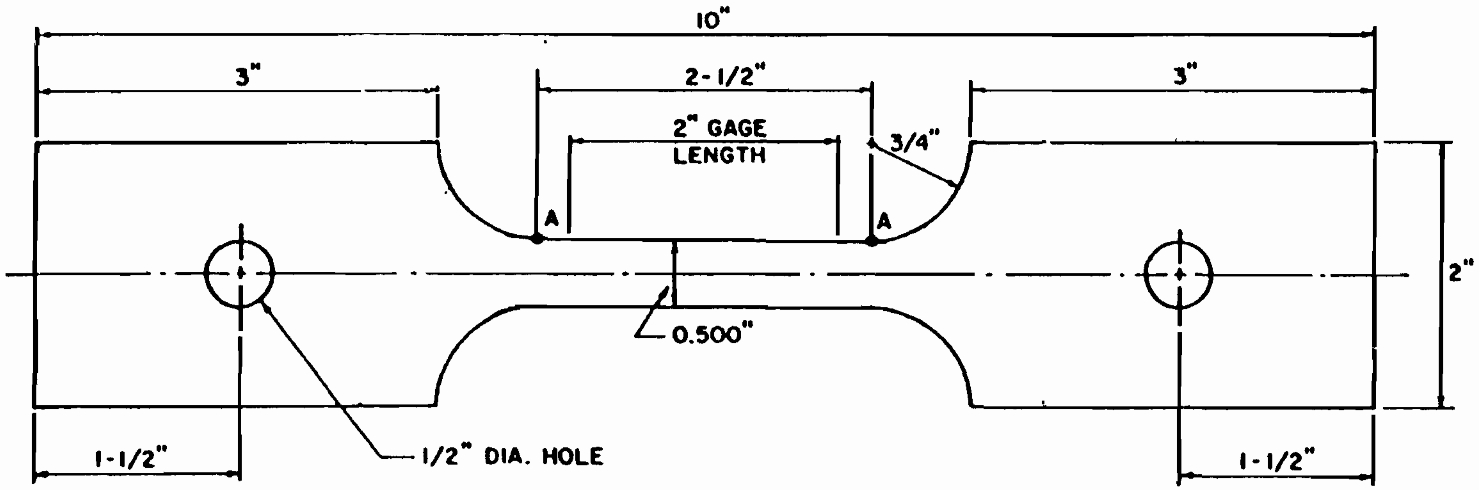

Figure 2.2 Nominal Dimensions of Tension Coupons Used for 25AK 50SK Sheet Steels[4,5]

Figure 2.3 Material Test System (MTS) 880 Used for Tension Tests

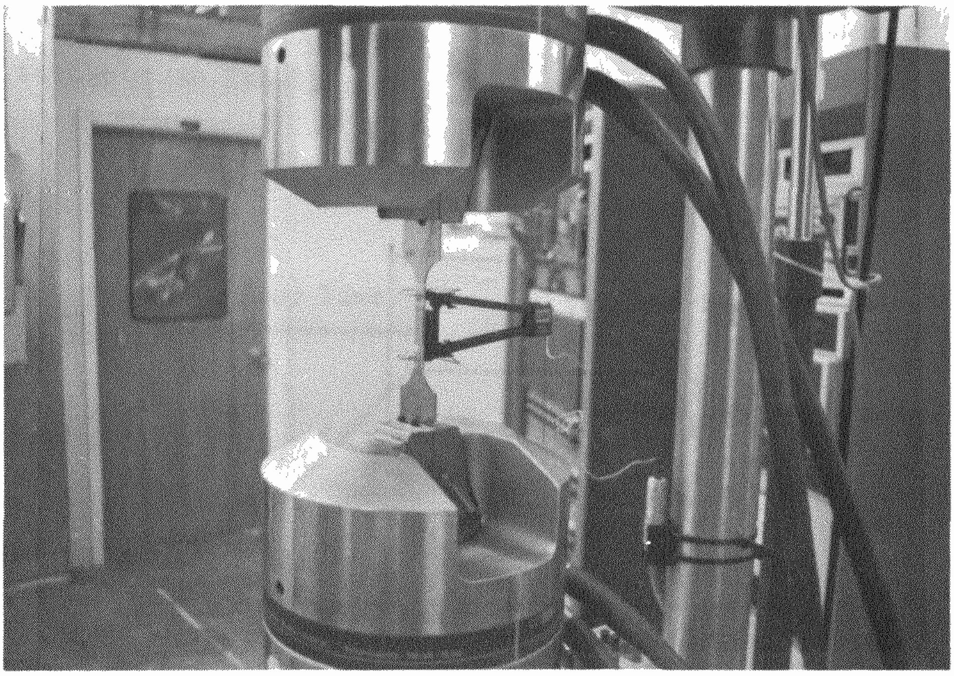

Figure 2.4 Test Setup Showing the Attachment of Extensometer

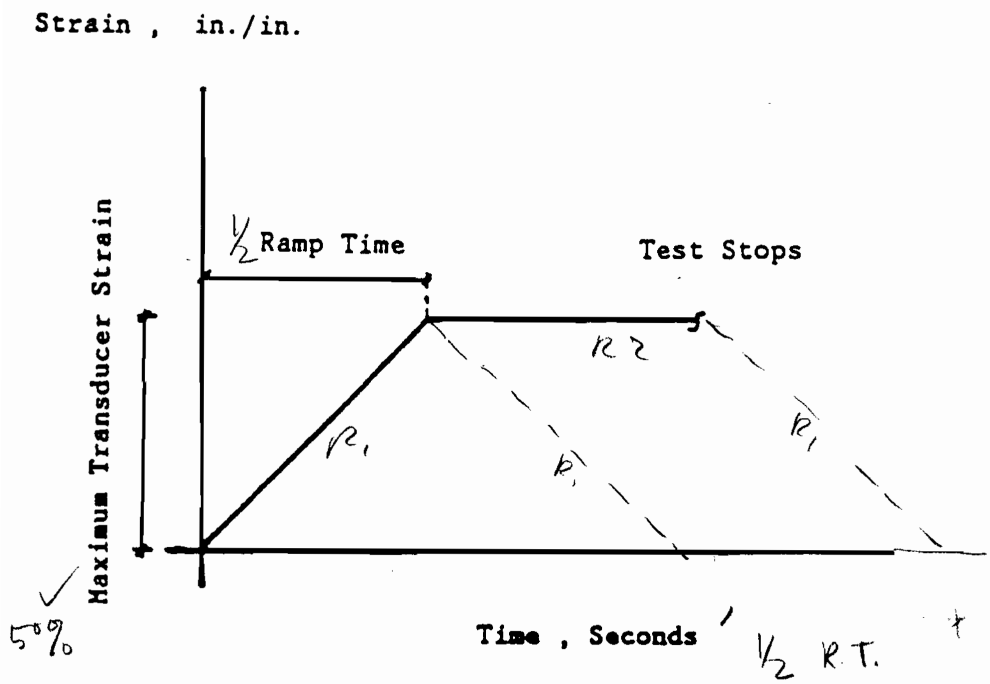

Figure 2.5 Typical Function Generator Ramp Waveform [5]

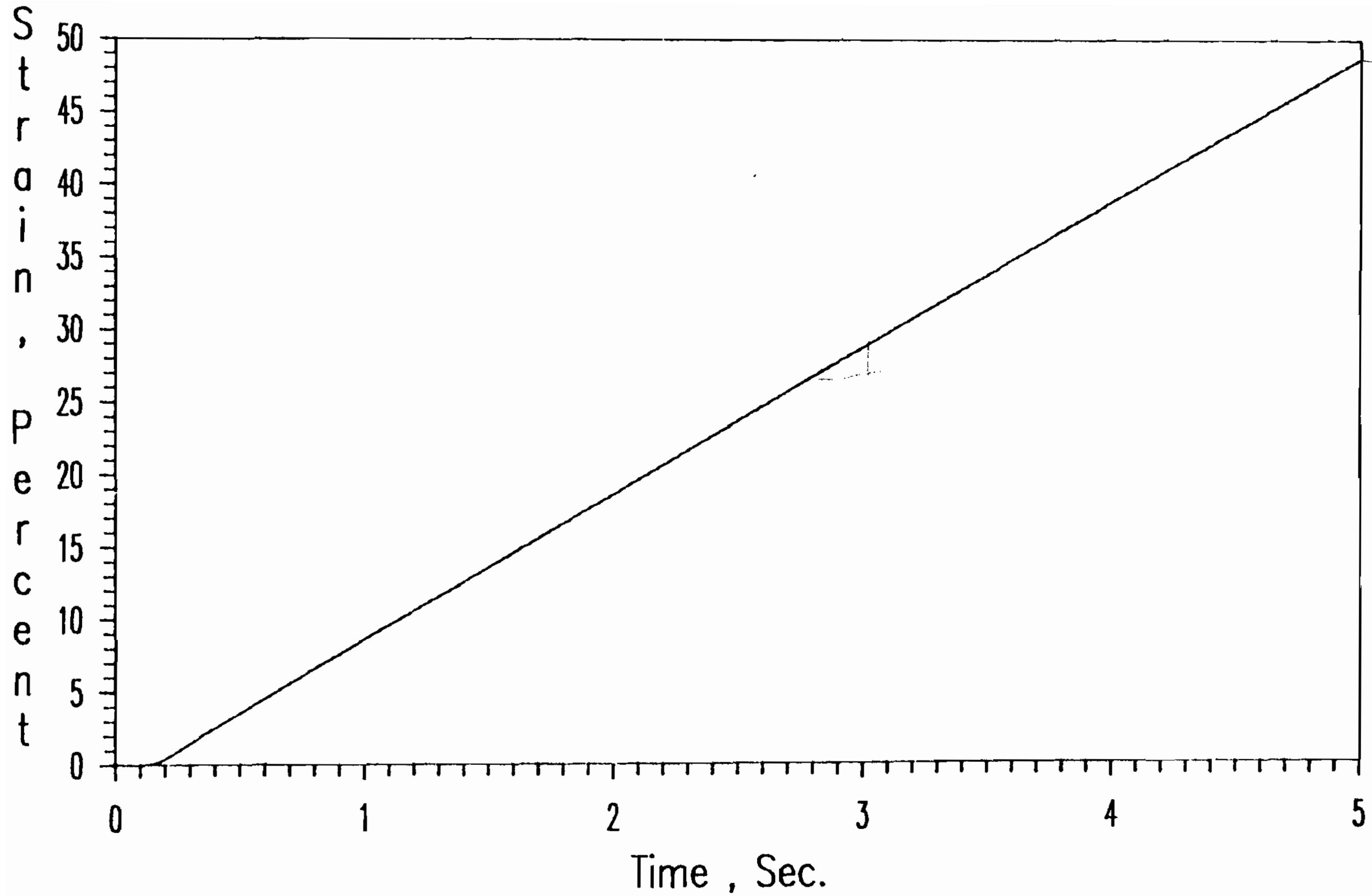

Figure 2.6 Strain-Time Curve for Specimen 25LT3A

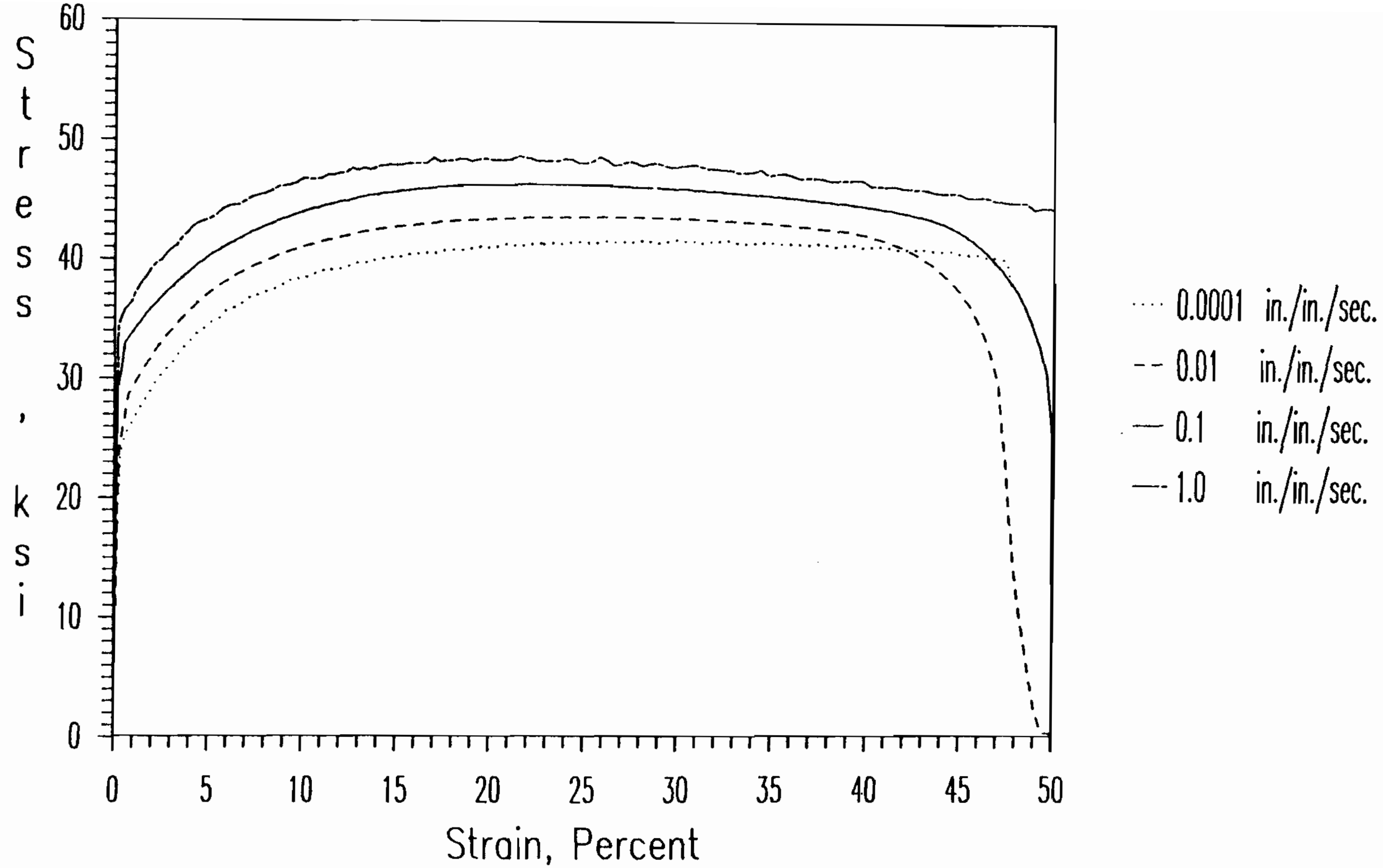

Figure 2.7 Stress-Strain Curves for 25LT Steel under Different Strain Rates

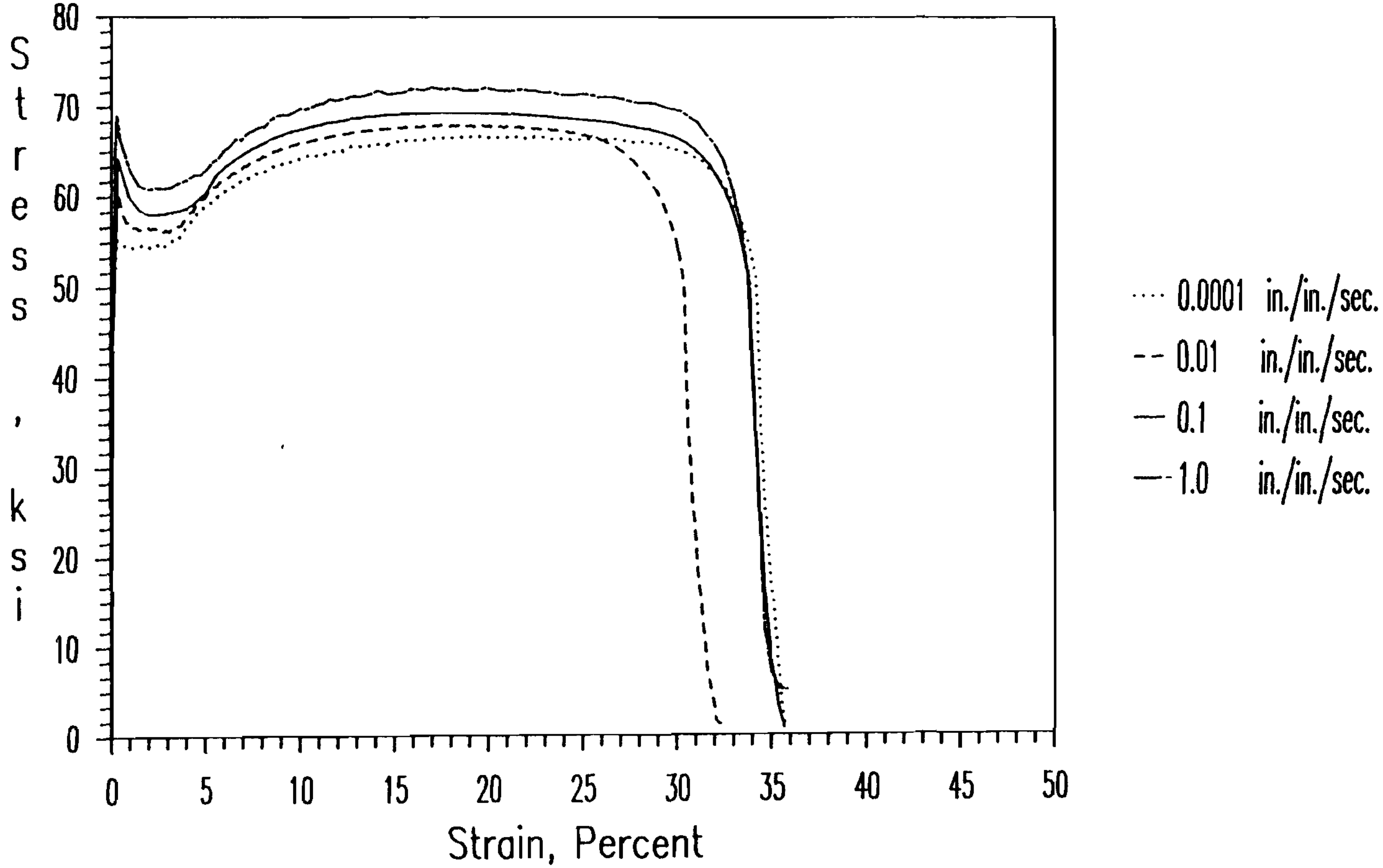

Figure 2.8 Stress-Strain Curves for 50LT Steel under Different Strain Rates

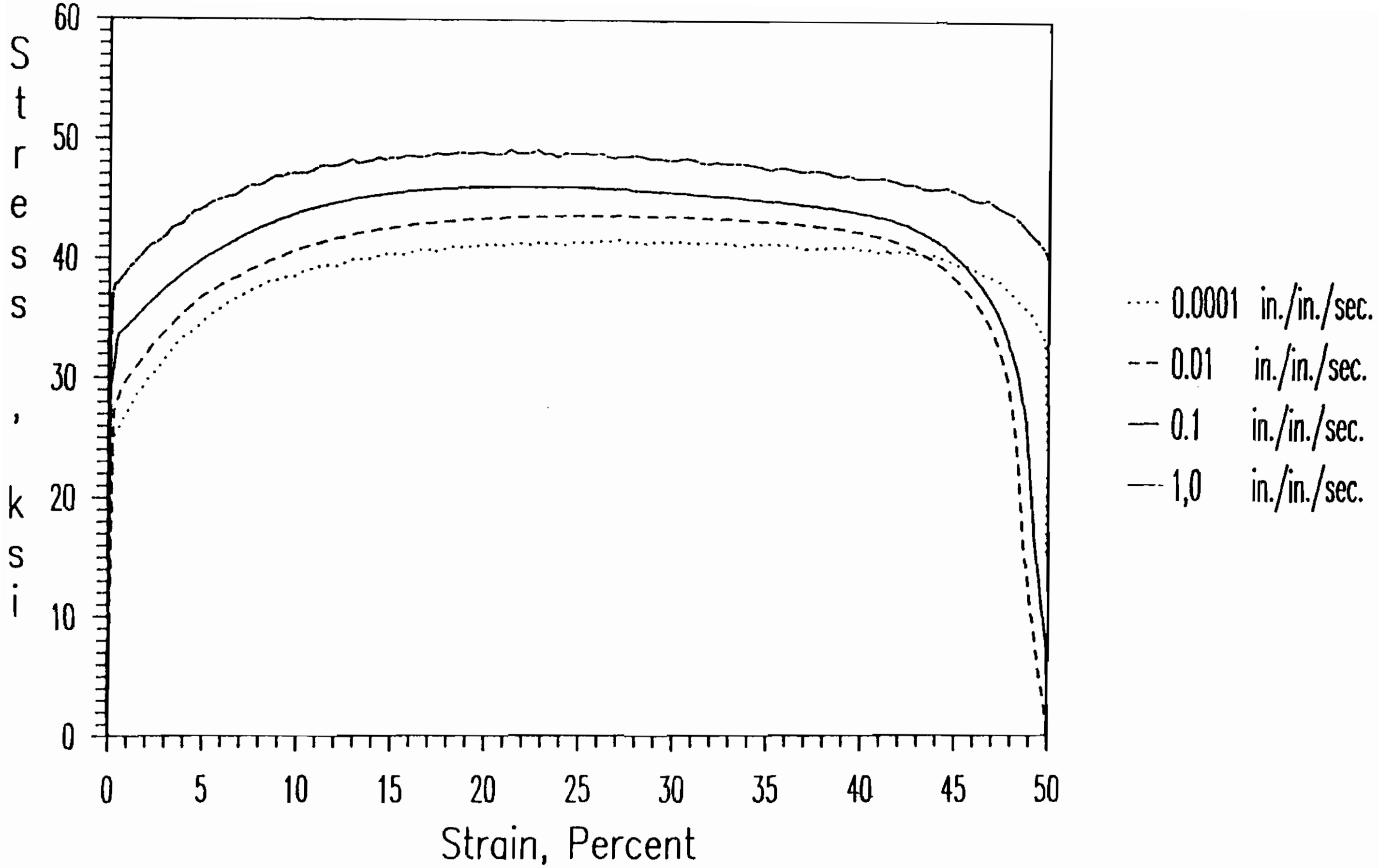

Figure 2.9 Stress-Strain Curves for 25TT Steel under Different Strain Rates

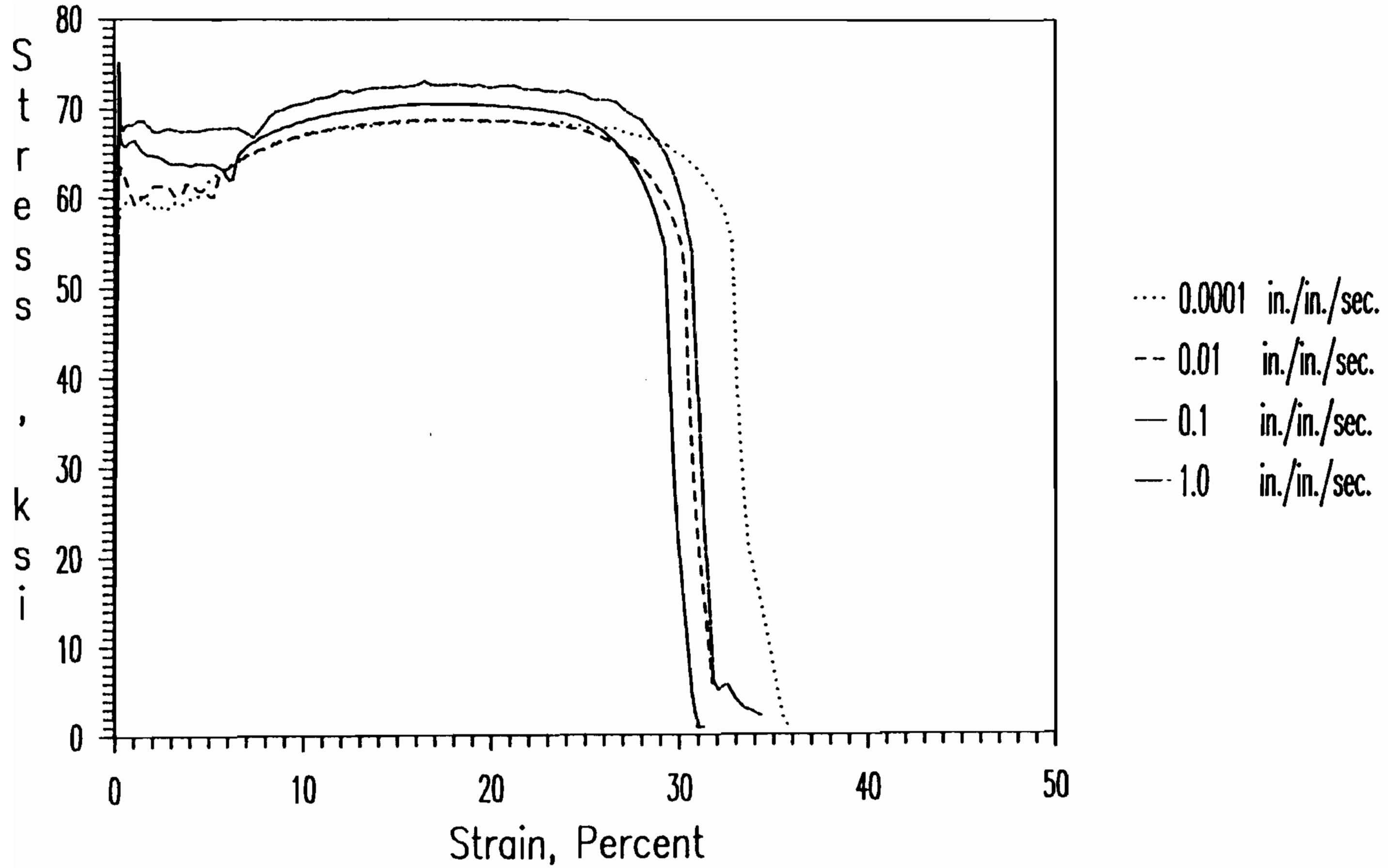

Figure 2.10 Stress-Strain Curves for 50TT Steel under Different Strain Rates

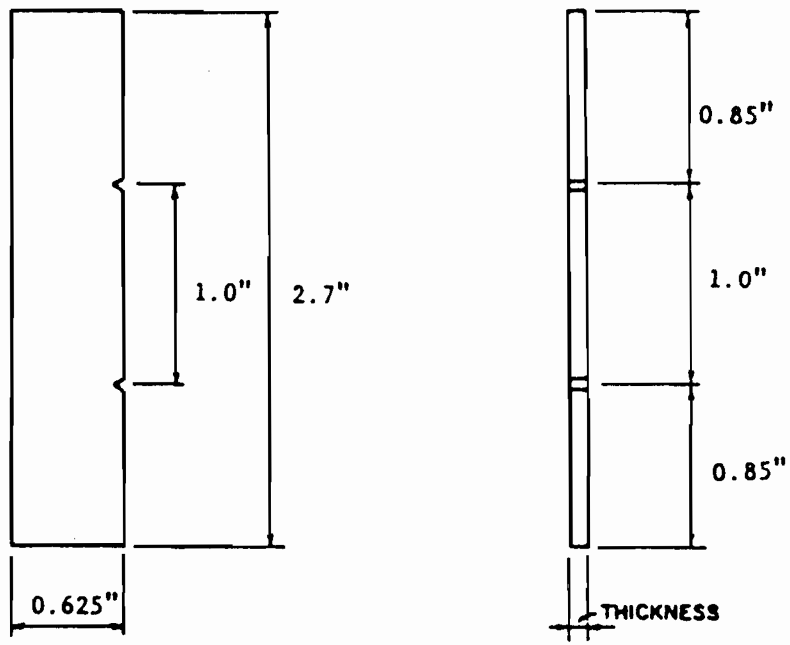

Figure 2.11 Nominal Dimensions of Compression Coupons Used for 25AK and 50SK Sheet Steels [5]

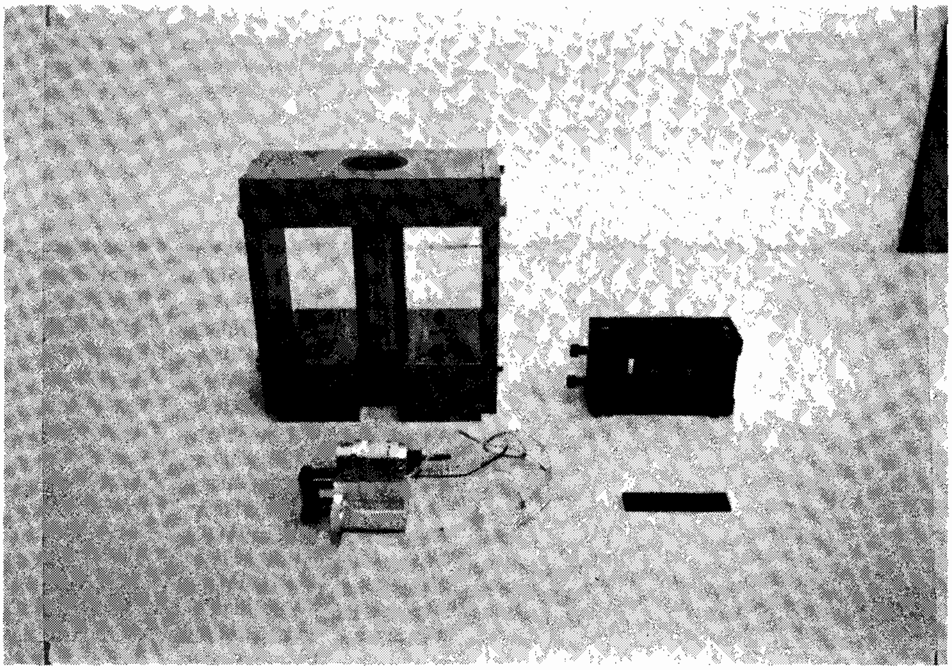

Figure 2.12 Compression Subpress, Jig, Compressometer, and Test Specimen Used for Compression Tests

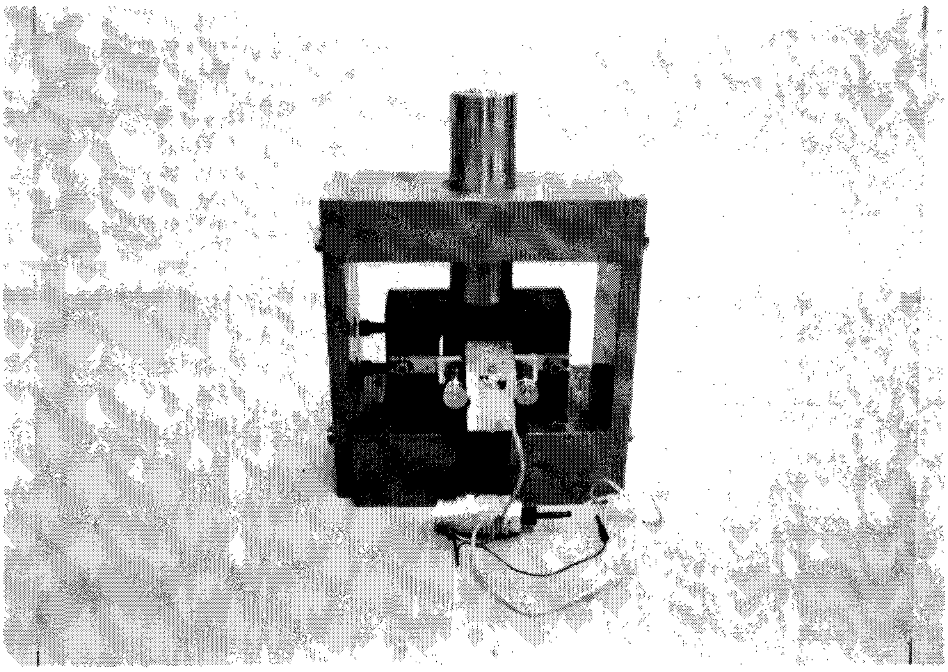

Figure 2.13 Assembly of Compression Subpress, Jig, and Compressometer

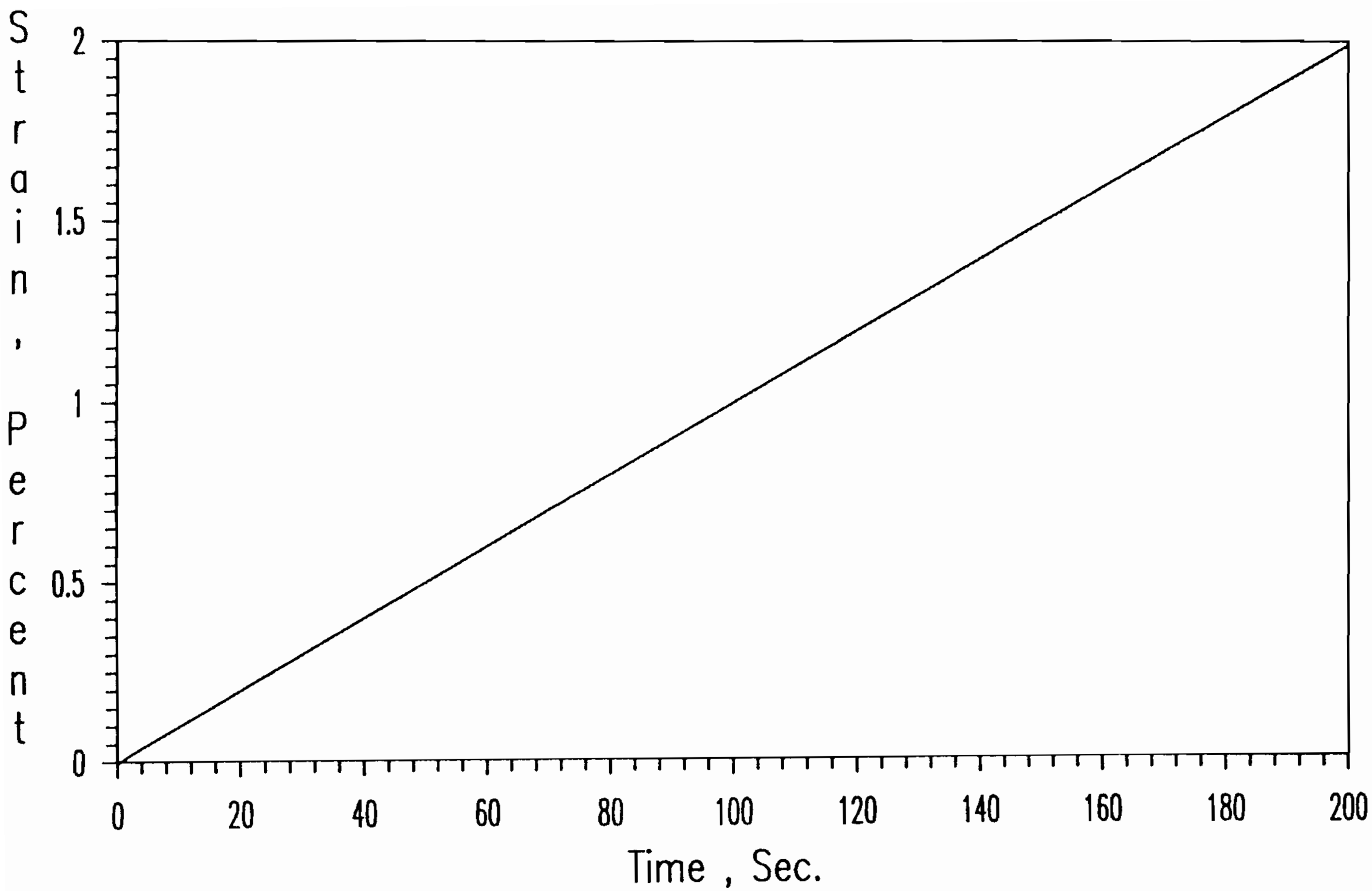

Figure 2.14 Strain-Time Curve for Specimen 25LC1B

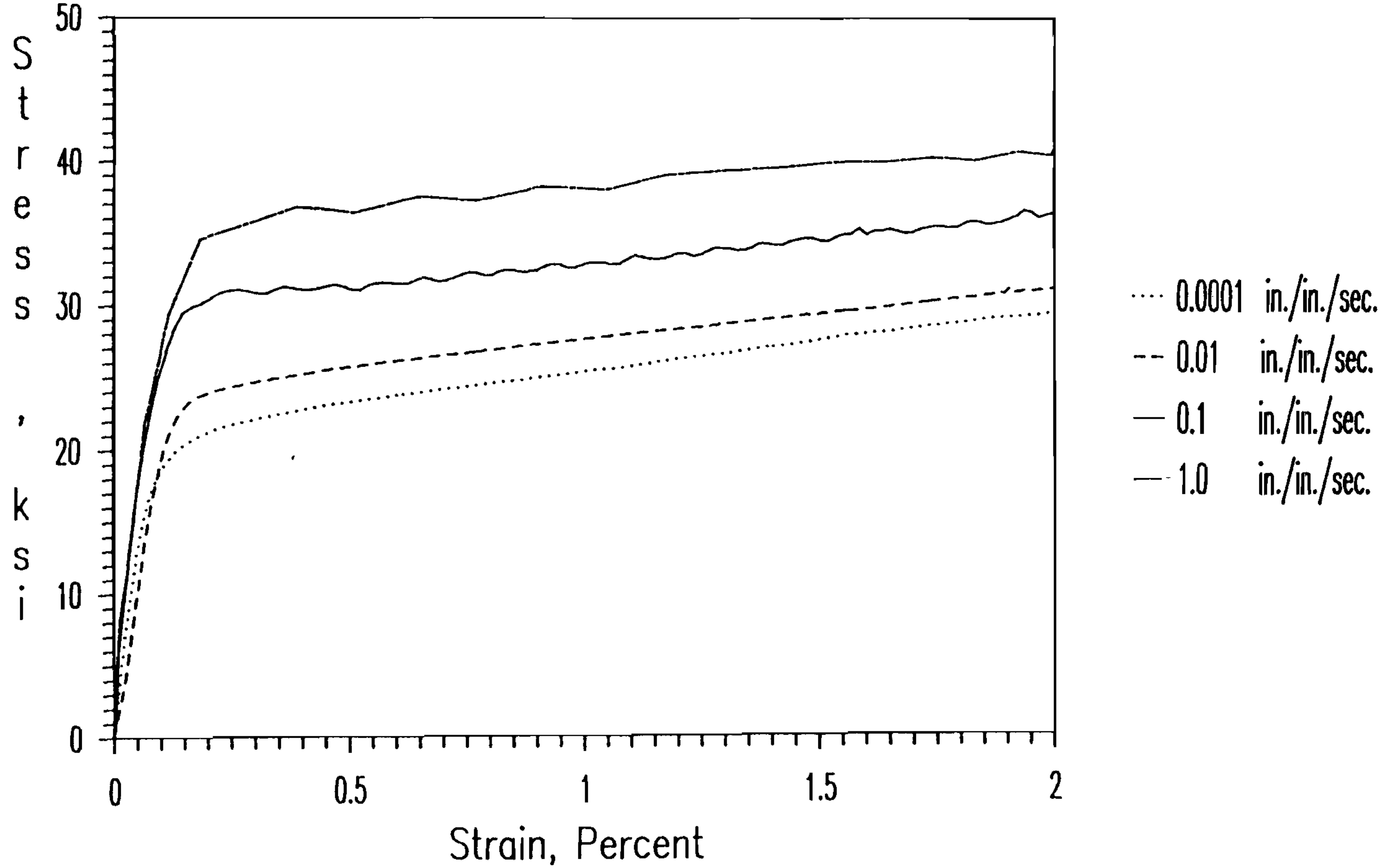

Figure 2.15 Stress-Strain Curves for 25LC Steel under Different Strain Rates

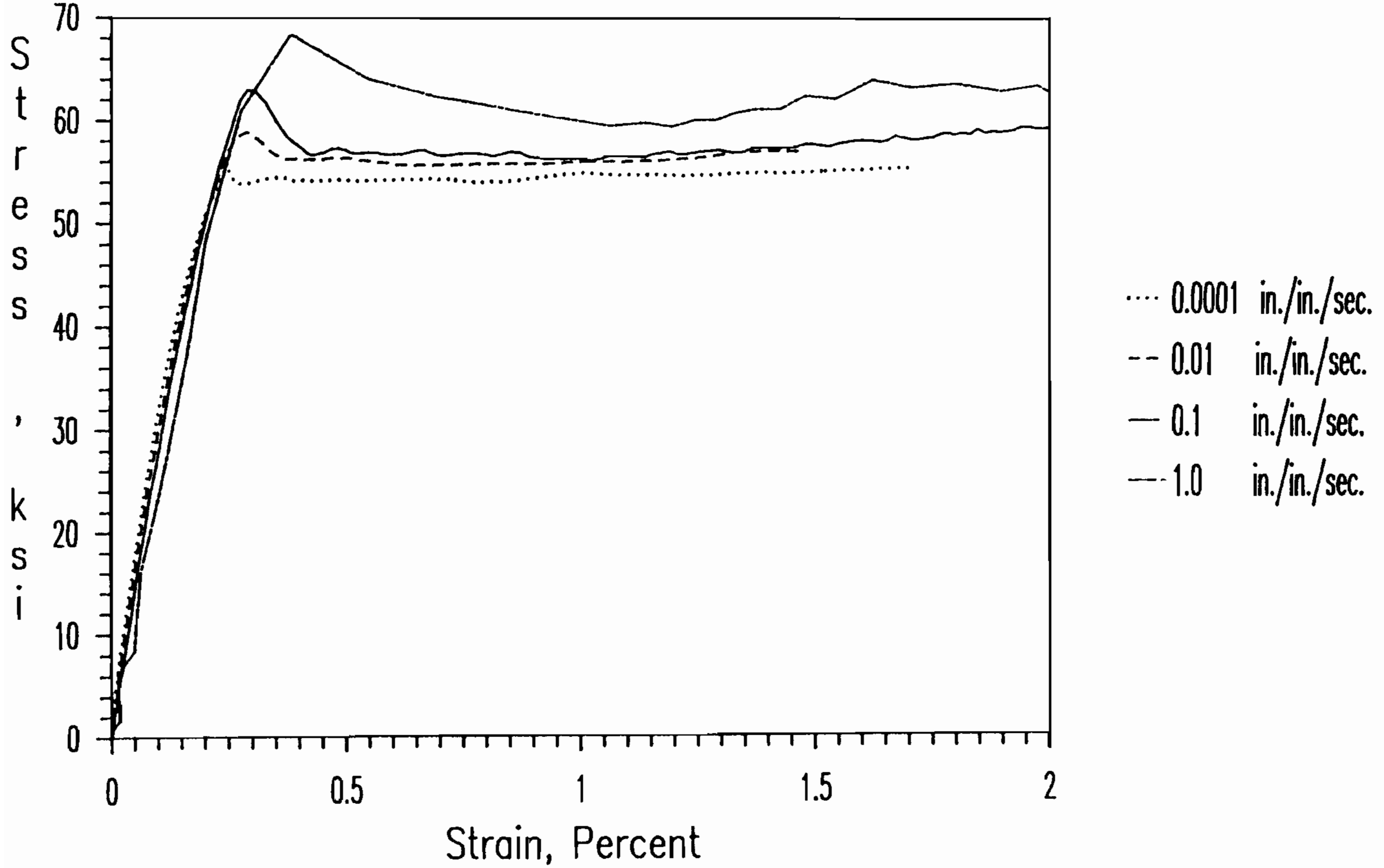

Figure 2.16 Stress-Strain Curves for 50LC Steel under Different Strain Rates

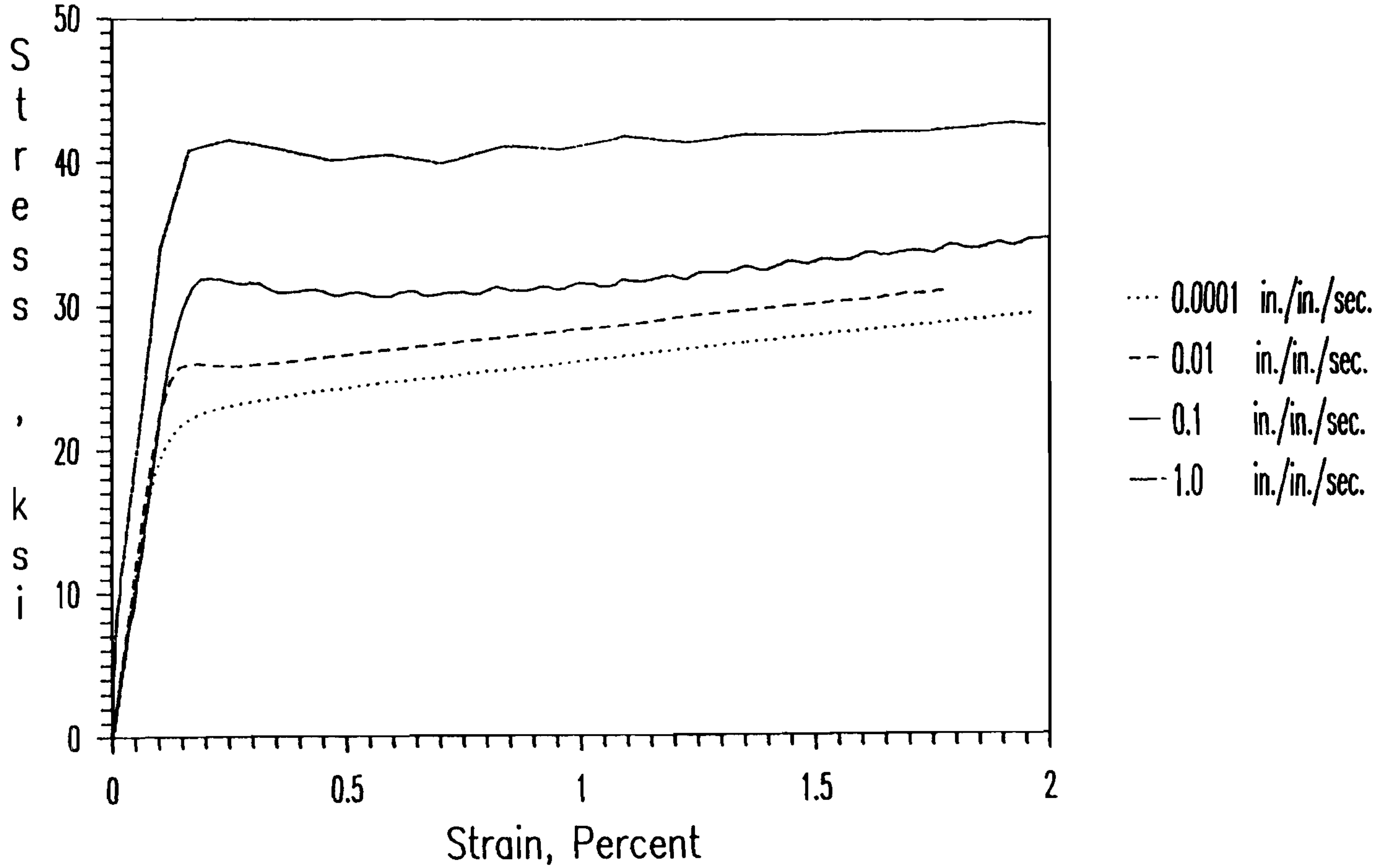

Figure 2.17 Stress-Strain Curves for 25TC Steel under Different Strain Rates

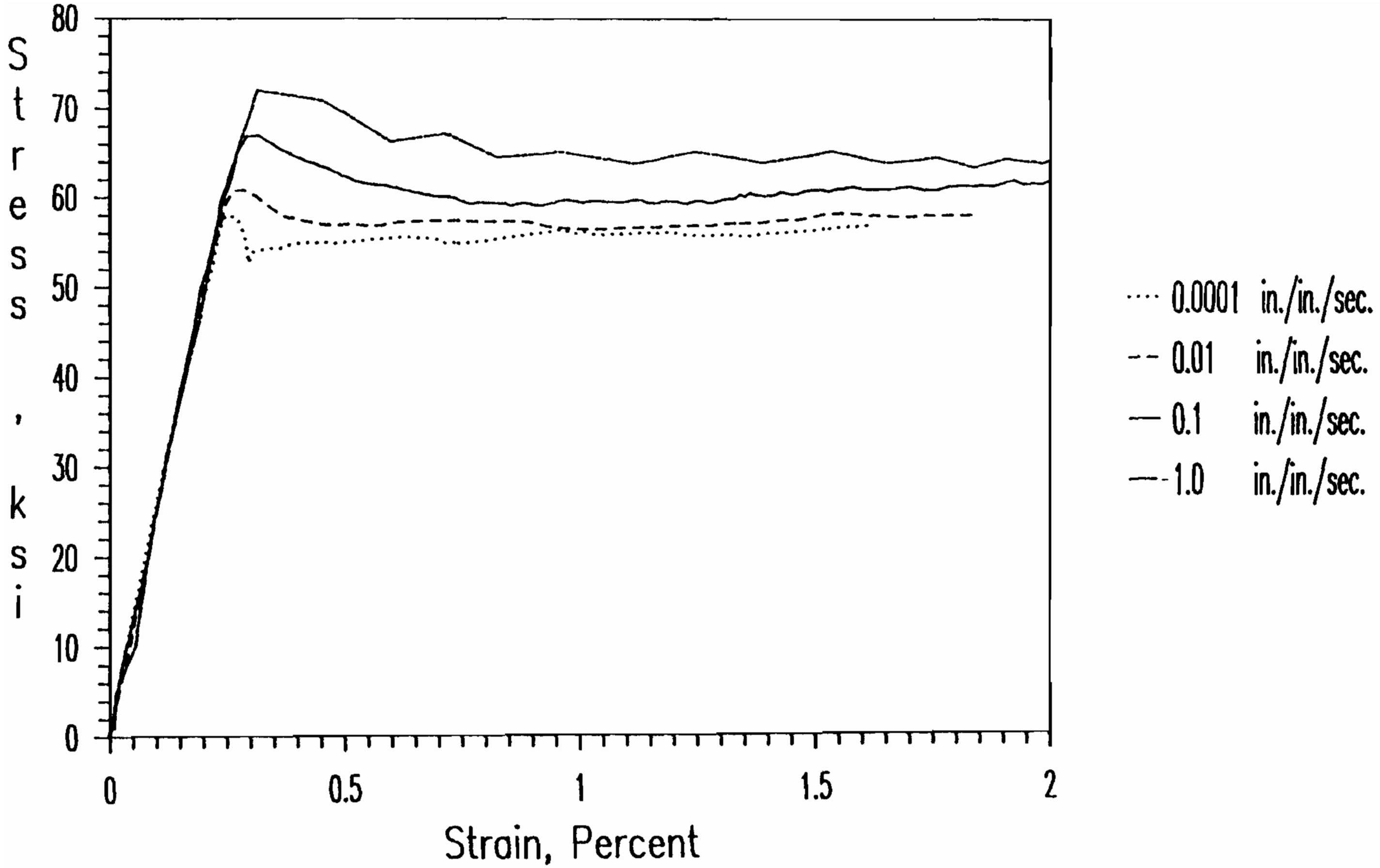

Figure 2.18 Stress-Strain Curves for 50TC Steel under Different Strain Rates

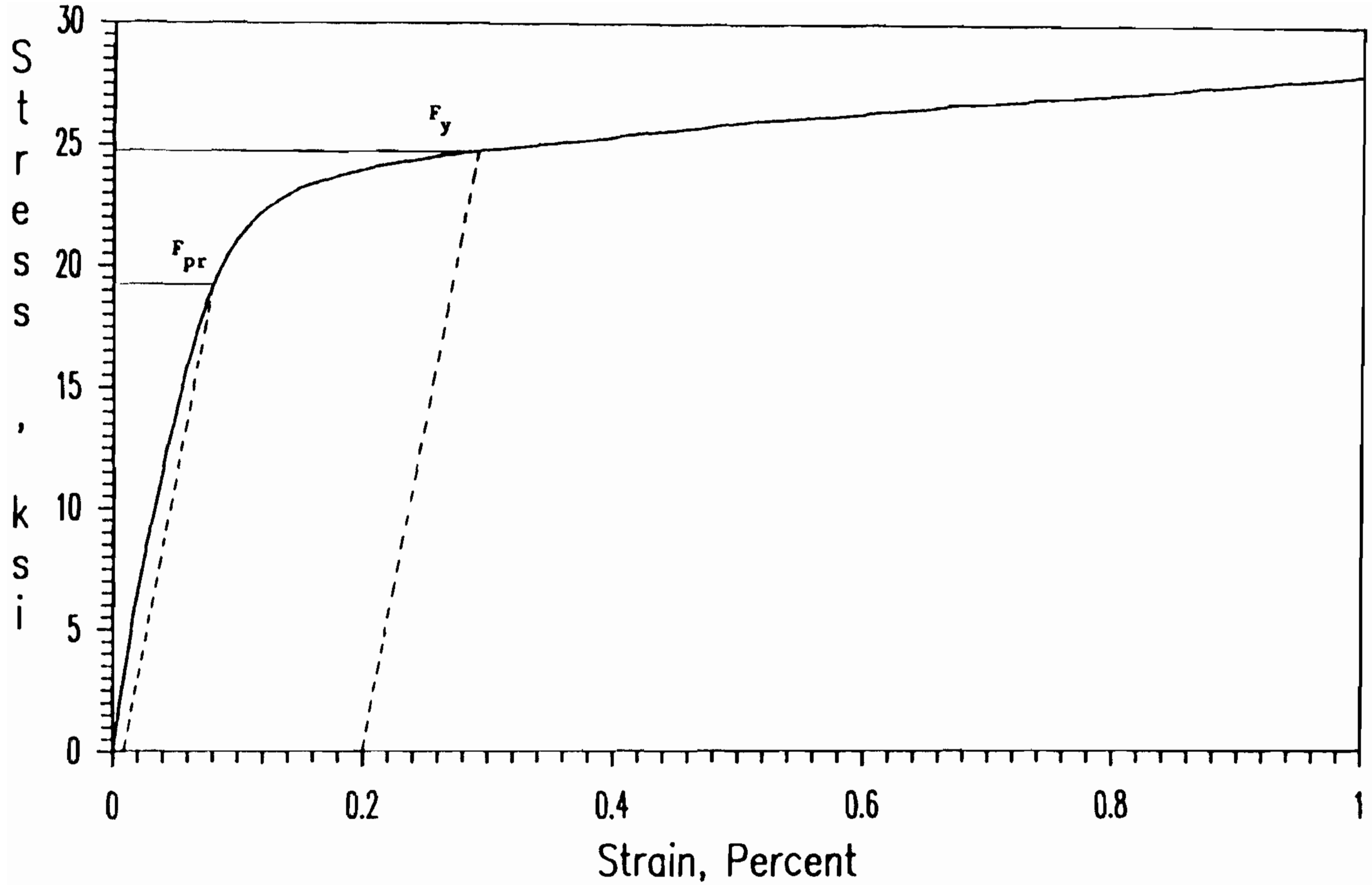

Figure 2.19 Stress-Strain Curves for Determination of Mechanical Properties of 25LC1A

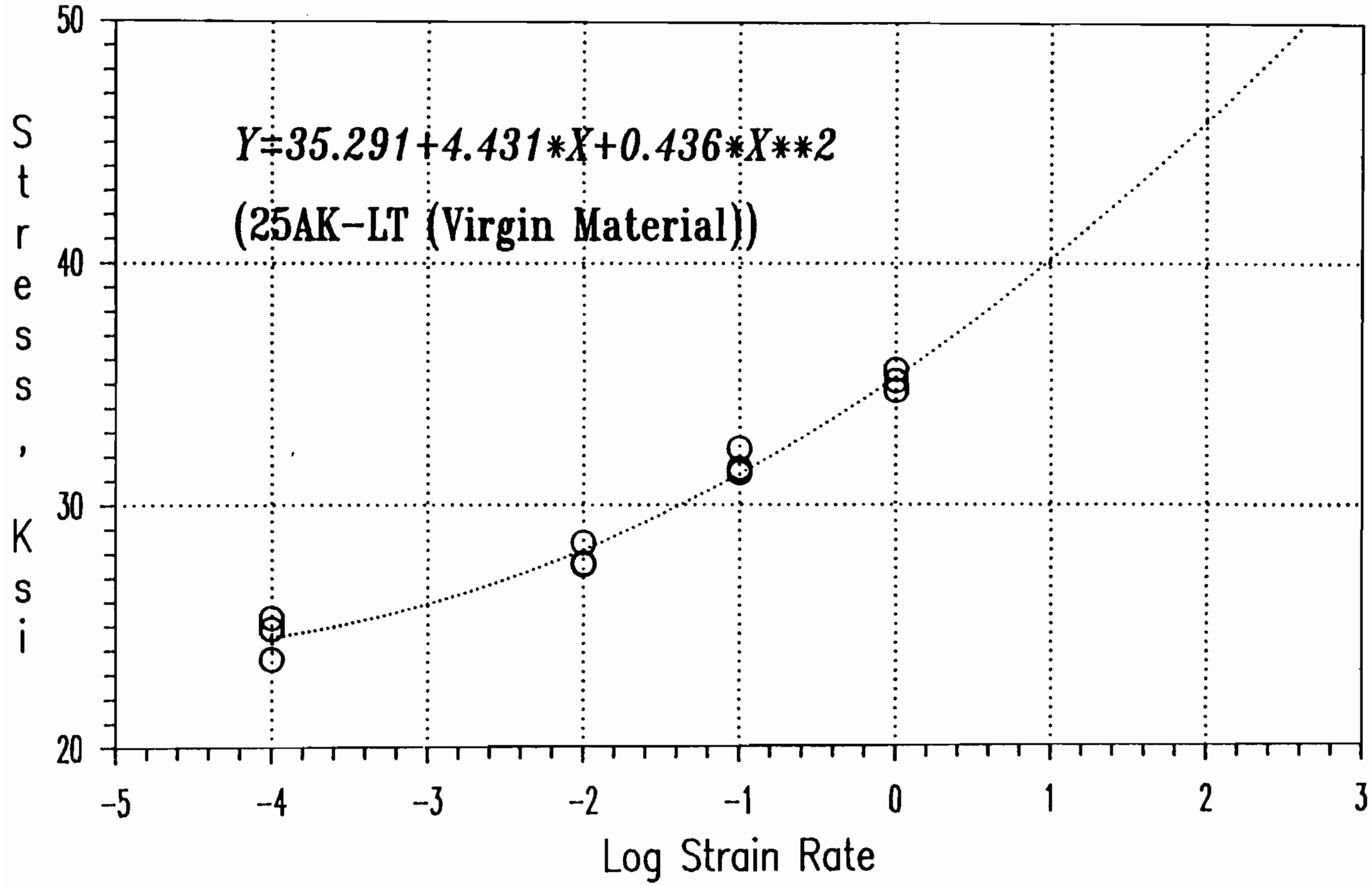

Figure 3.1 Tensile Yield Stress vs. Logarithmic Strain Rate Curve for 25AK Sheet Steel (Longitudinal Tension)

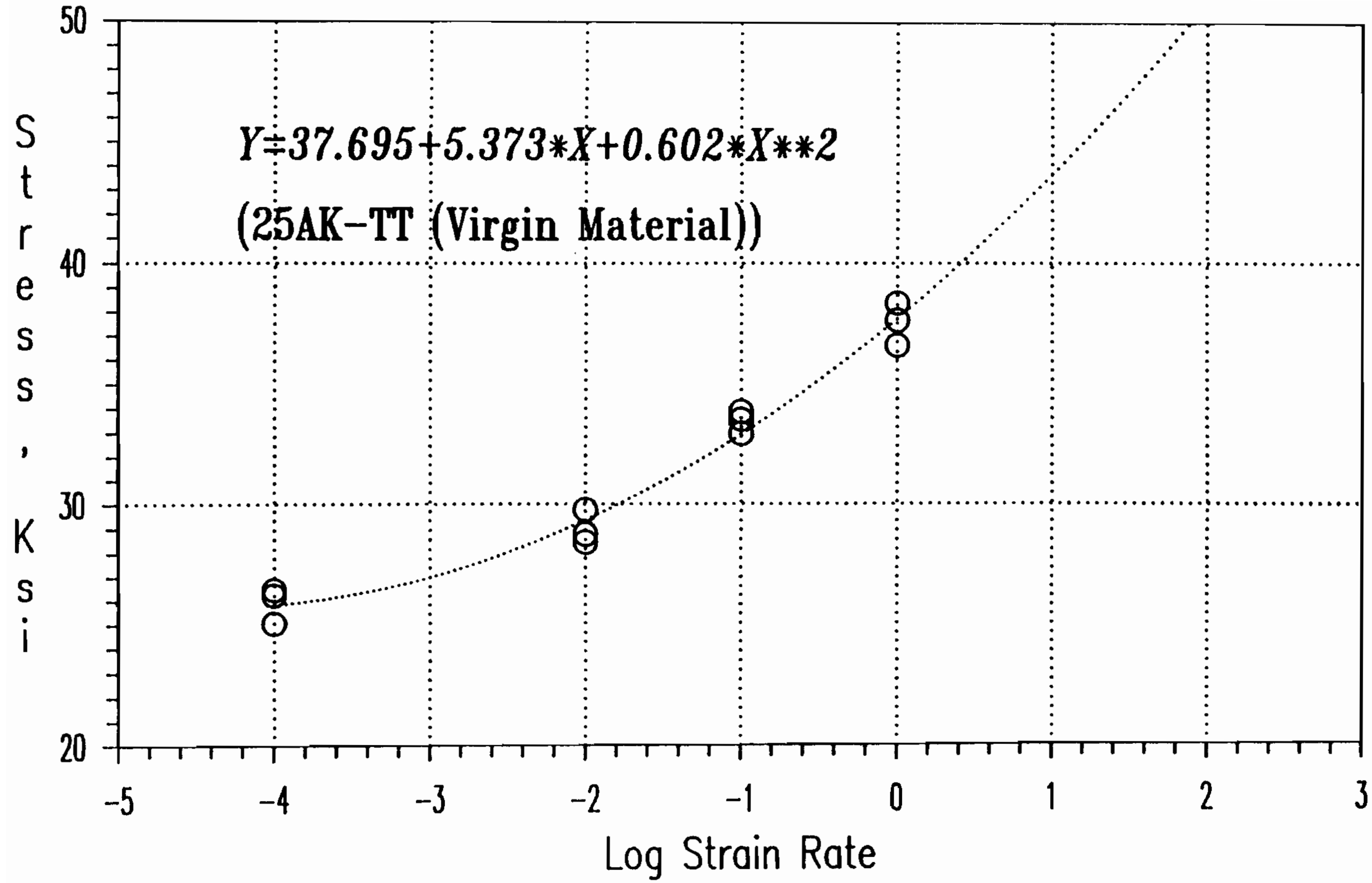

Figure 3.2 Tensile Yield Stress vs. Logarithmic Strain Rate Curve for 25AK Sheet Steel (Transverse Tension)

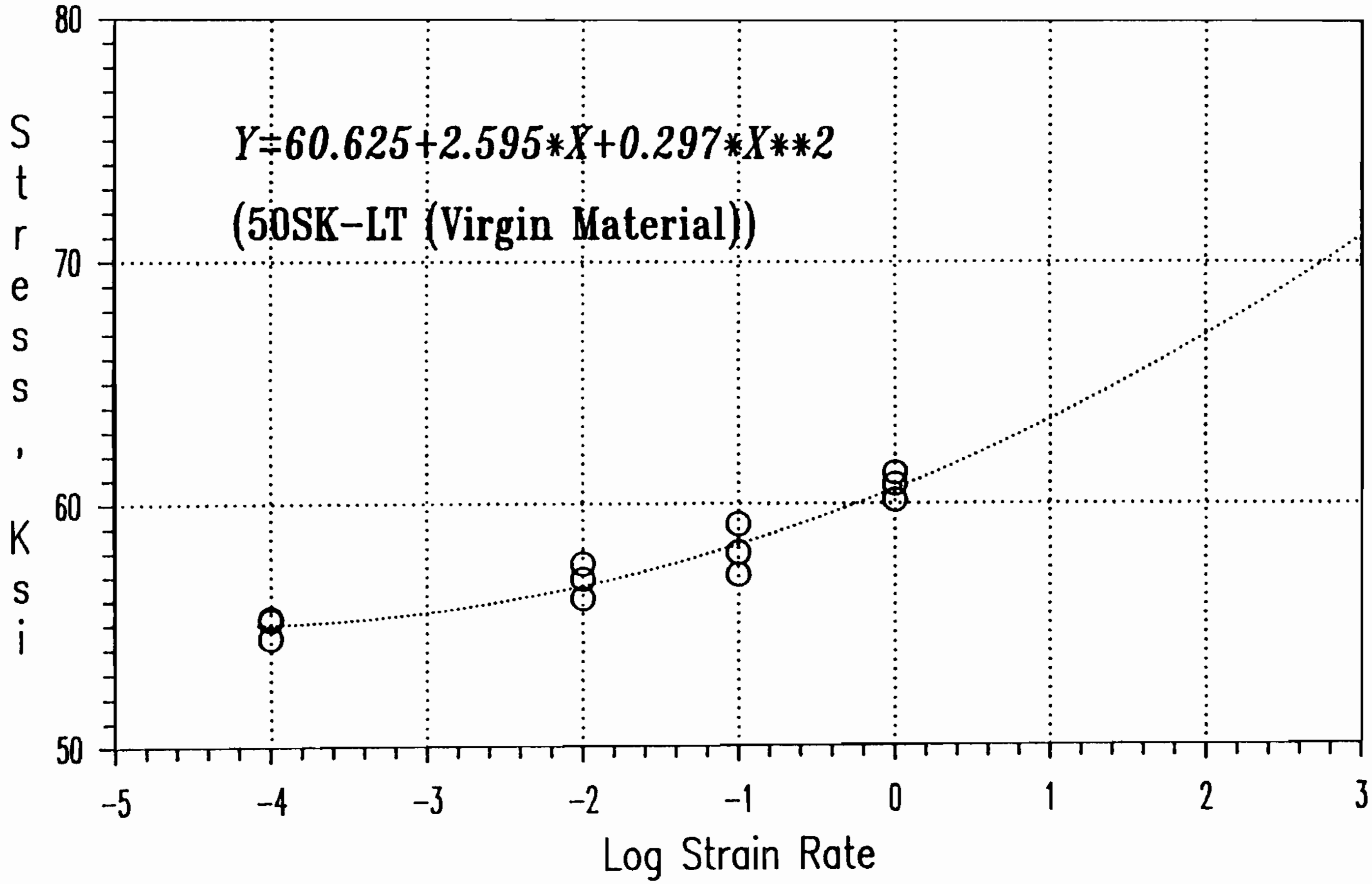

Figure 3.3 Tensile Yield Stress vs. Logarithmic Strain Rate Curve for 50SK Sheet Steel (Longitudinal Tension)

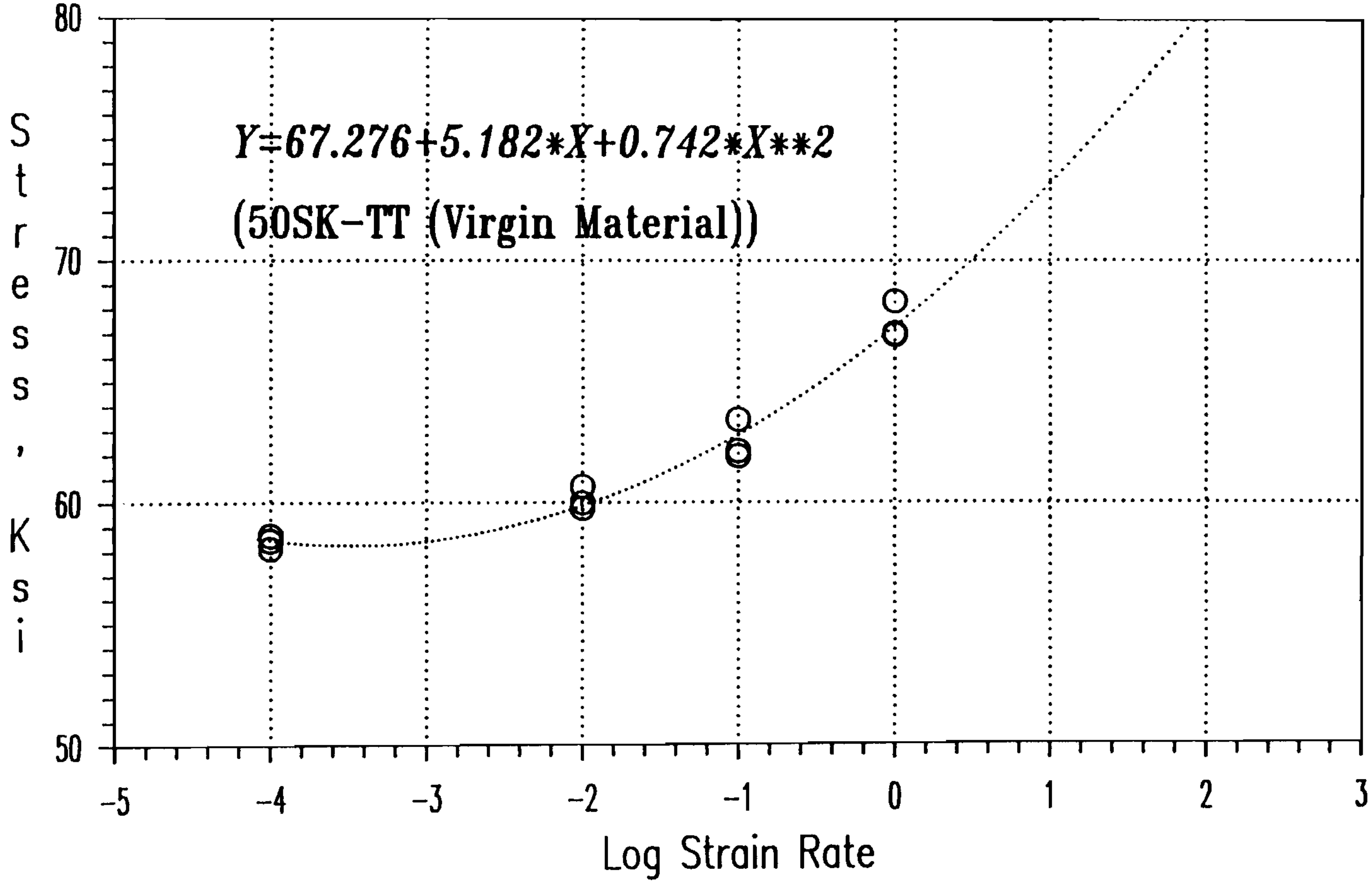

Figure 3.4 Tensile Yield Stress vs. Logarithmic Strain Rate Curve for 50SK Sheet Steel (Transverse Tension)

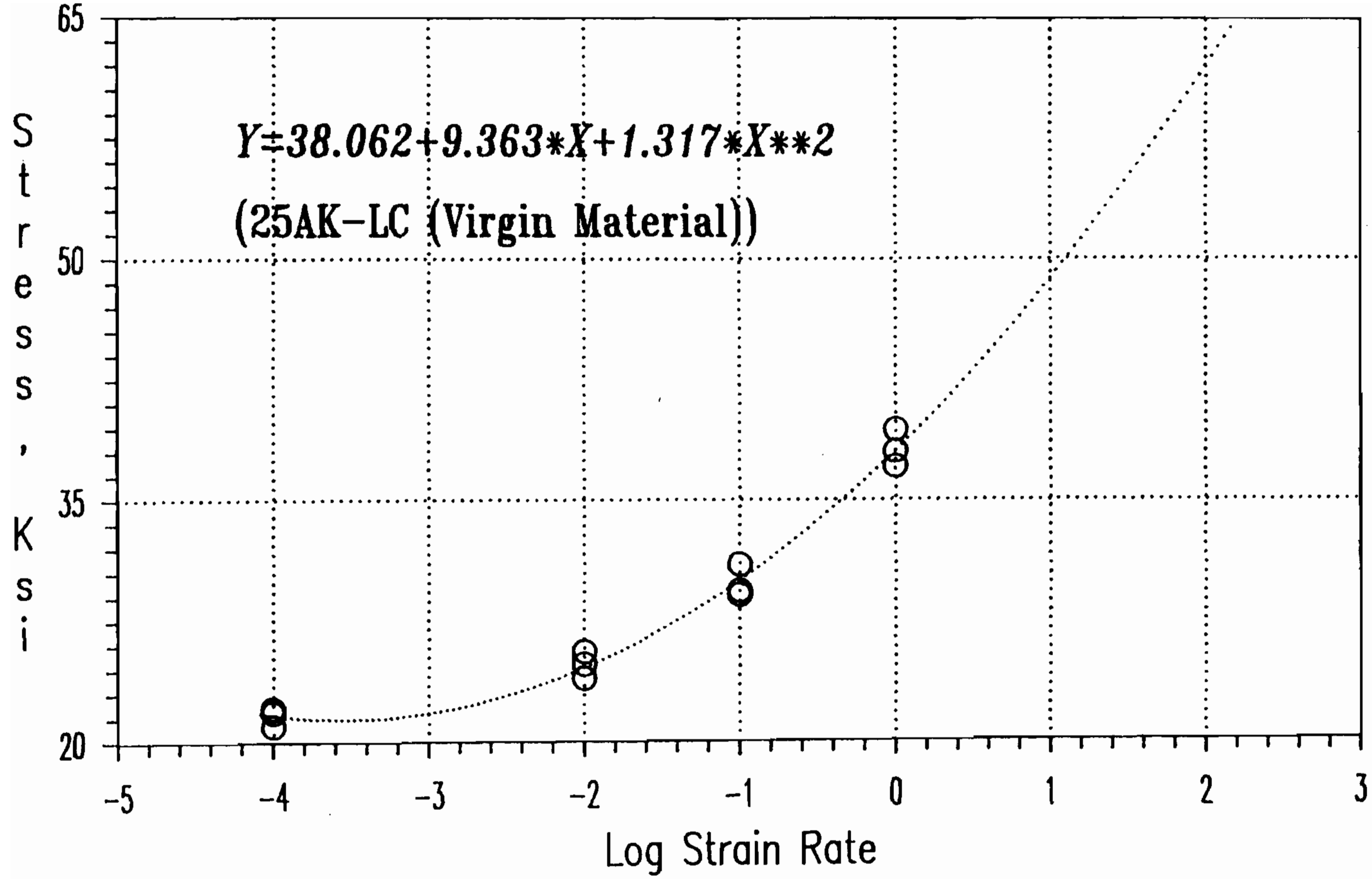

Figure 3.5 Compression Yield Stress vs. Logarithmic Strain Rate Curve for 25AK Sheet Steel (Longitudinal Compression)

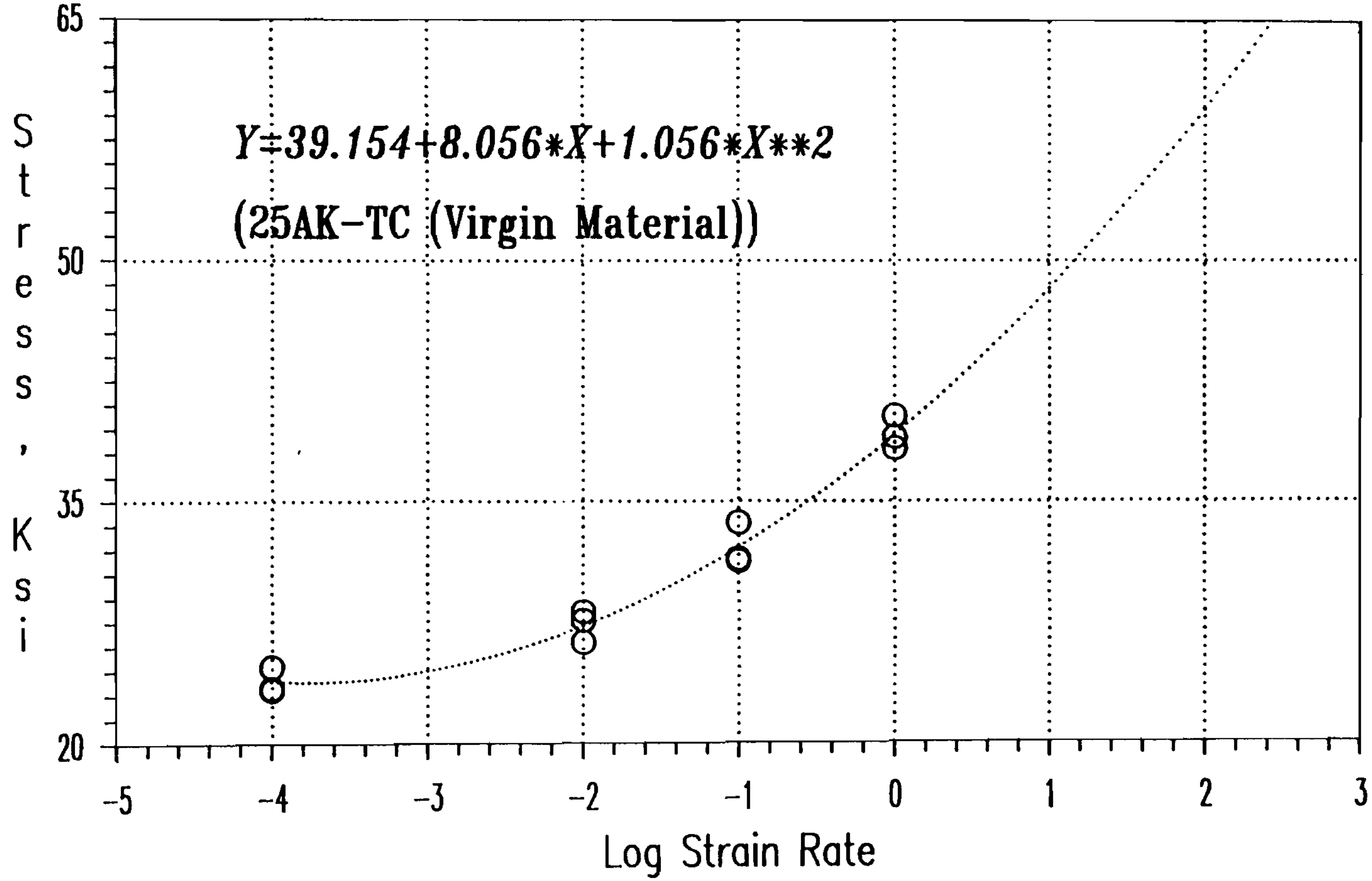

Figure 3.6 Compression Yield Stress vs. Logarithmic Strain Rate Curve for 25AK Sheet Steel (Transverse Compression)

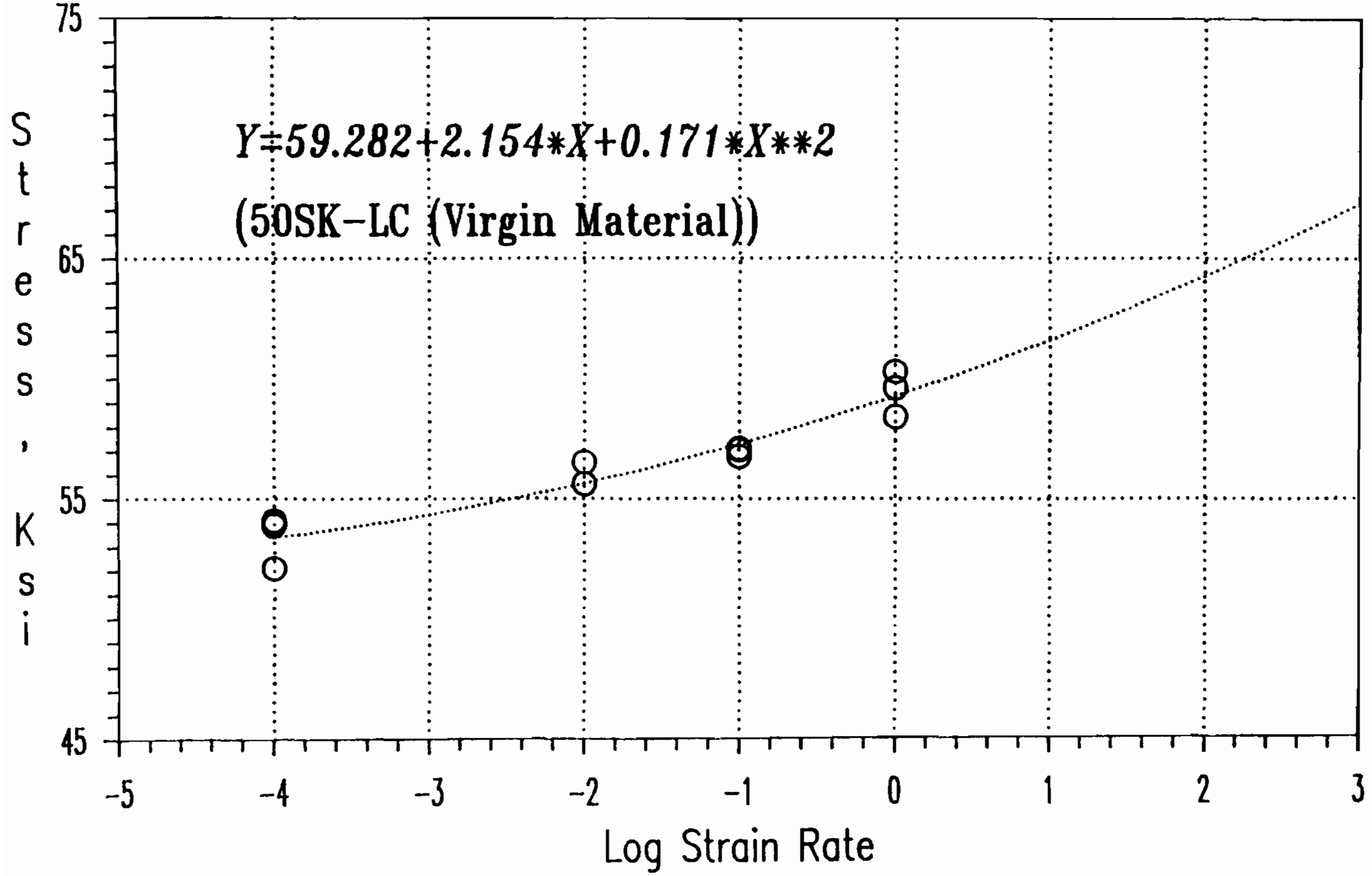

Figure 3.7 Compression Yield Stress vs. Logarithmic Strain Rate Curve for 50SK Sheet Steel (Longitudinal Compression)

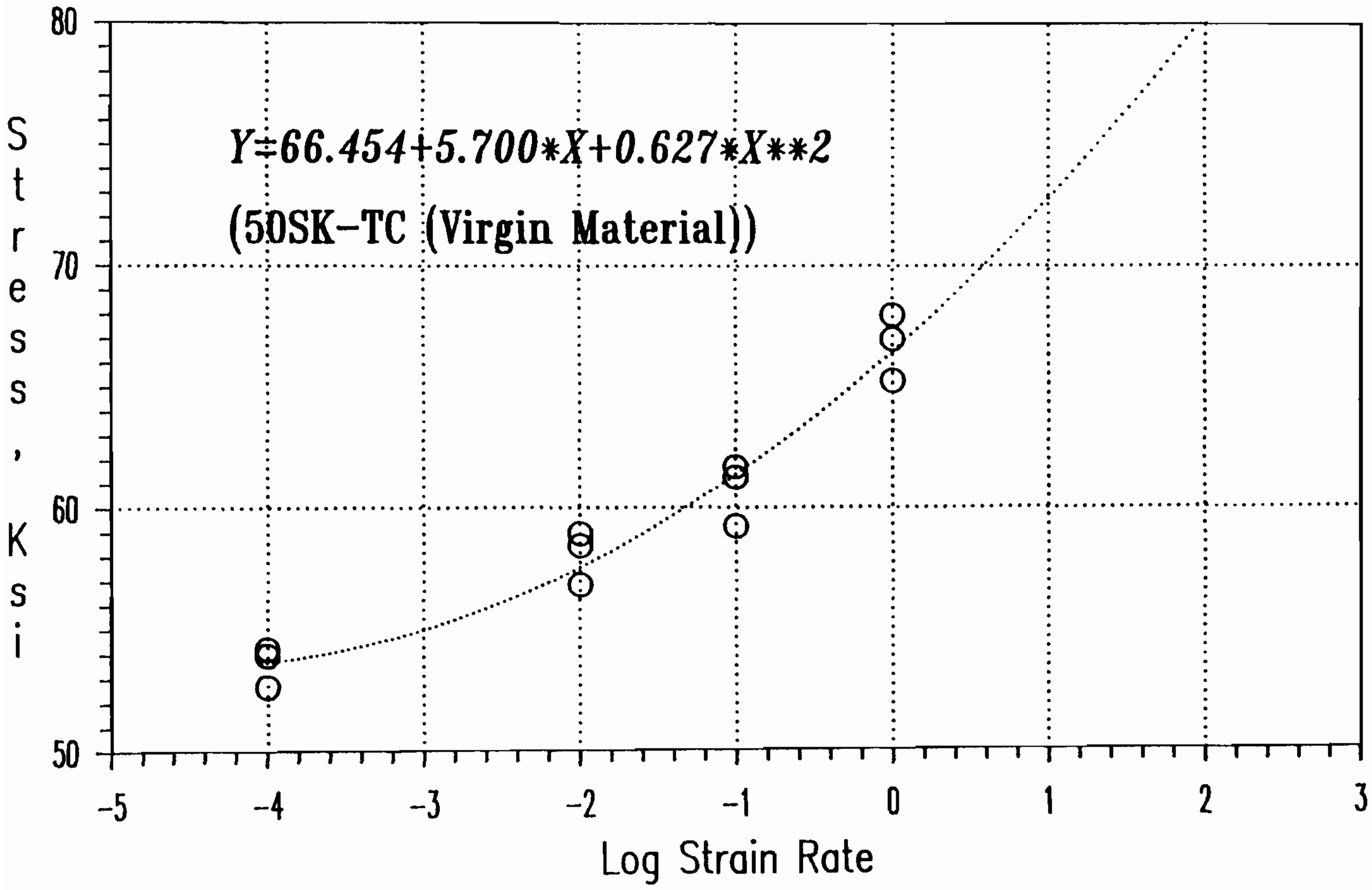

Figure 3.8 Compression Yield Stress vs. Logarithmic Strain Rate Curve for 50SK Sheet Steel (Transverse Compression)

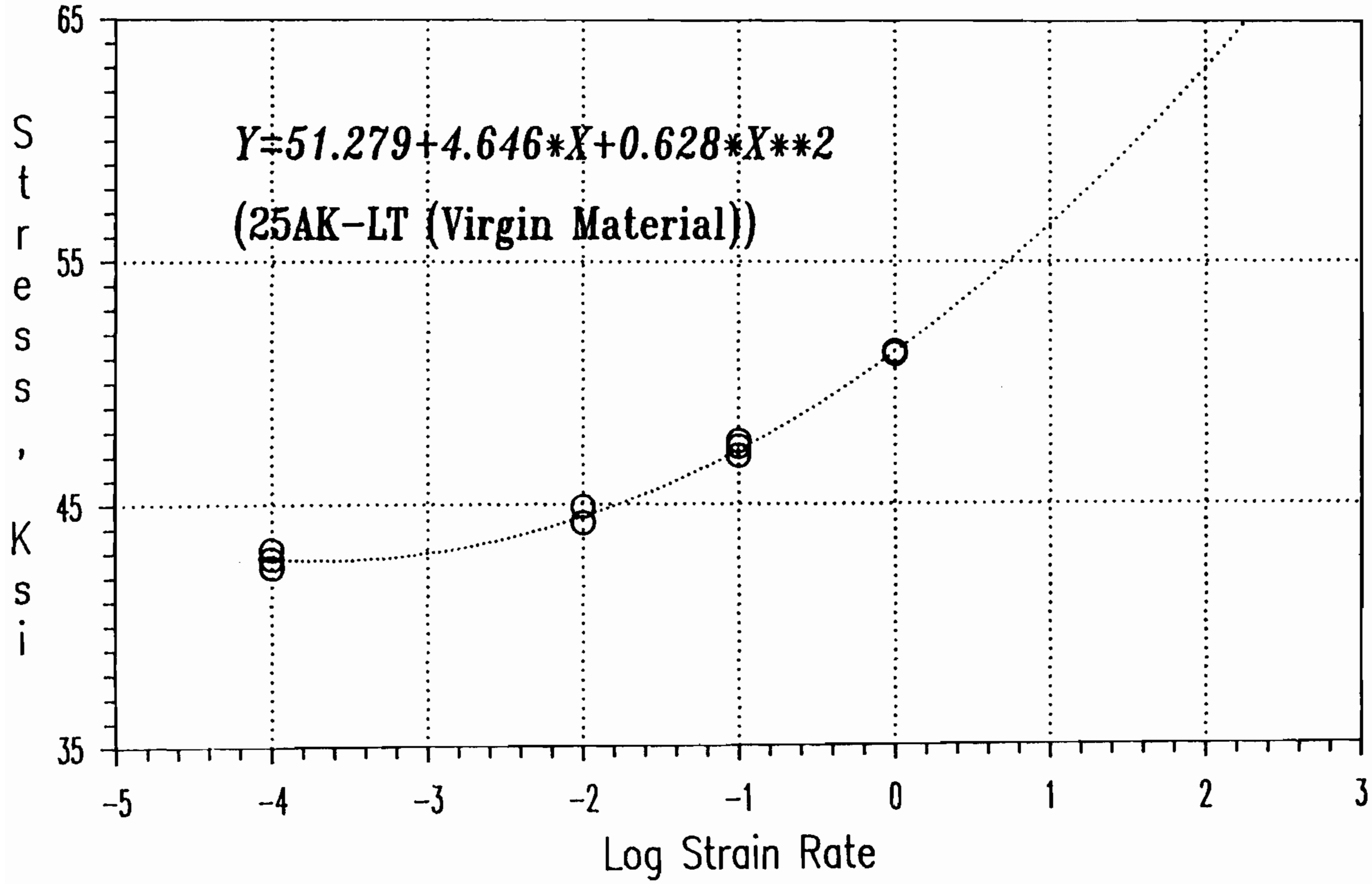

Figure 3.9 Tensile Ultimate Stress vs. Logarithmic Strain Rate Curve for 25AK Sheet Steel (Longitudinal Tension)

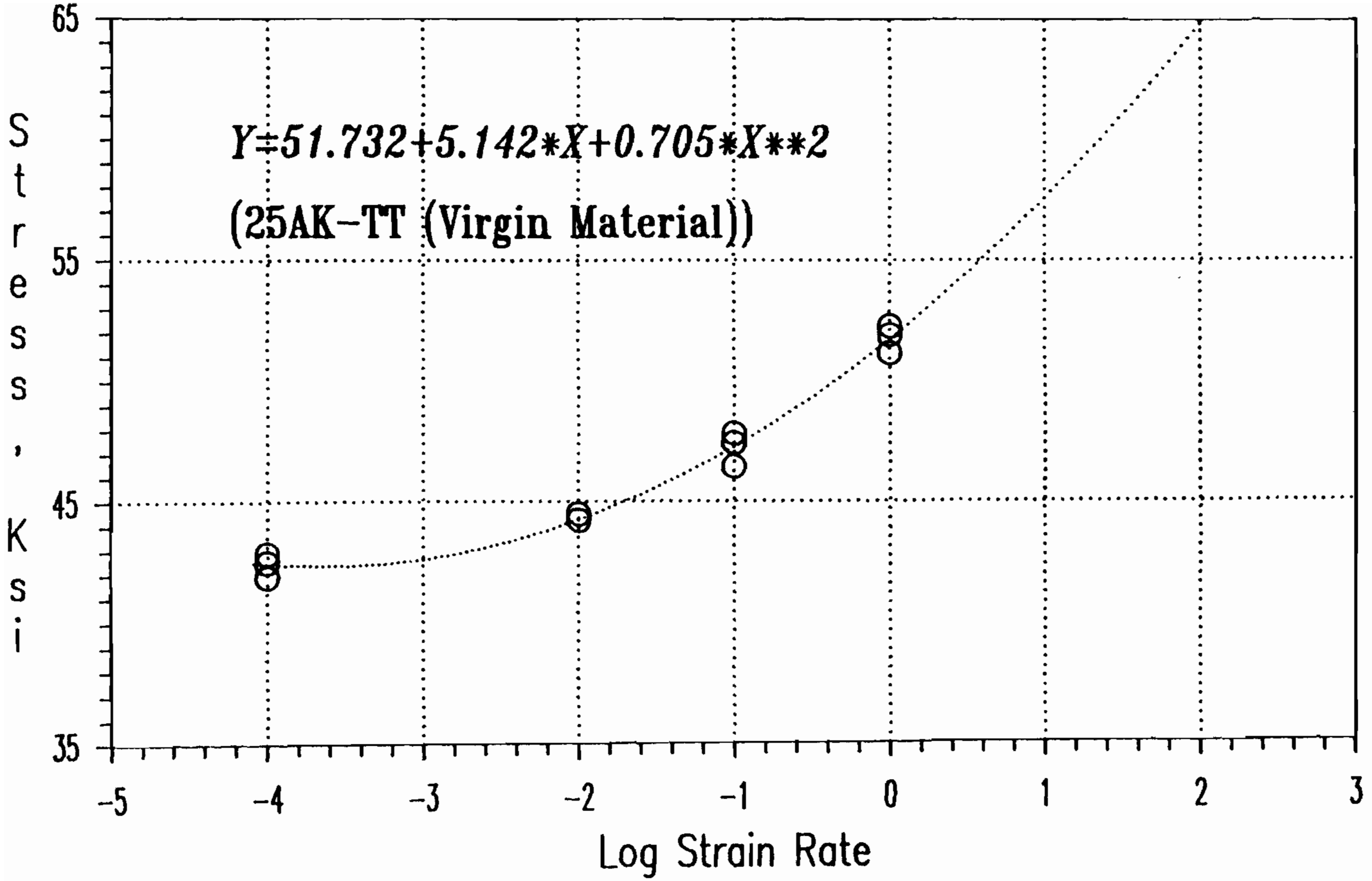

Figure 3.10 Tensile Ultimate Stress vs. Logarithmic Strain Rate Curve for 25AK Sheet Steel (Transverse Tension)

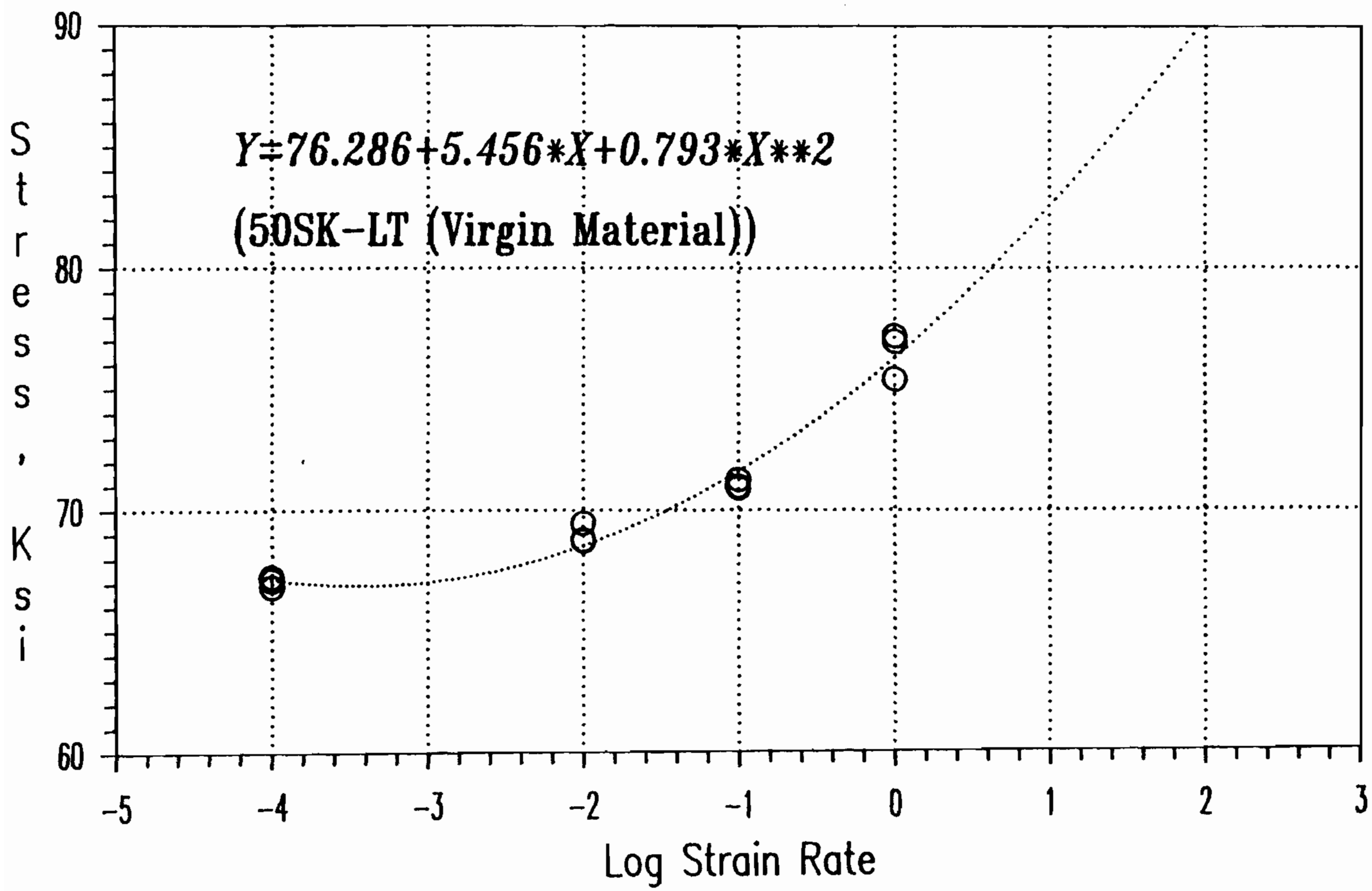

Figure 3.11 Tensile Ultimate Stress vs. Logarithmic Strain Rate Curve for 50SK Sheet Steel (Longitudinal Tension)

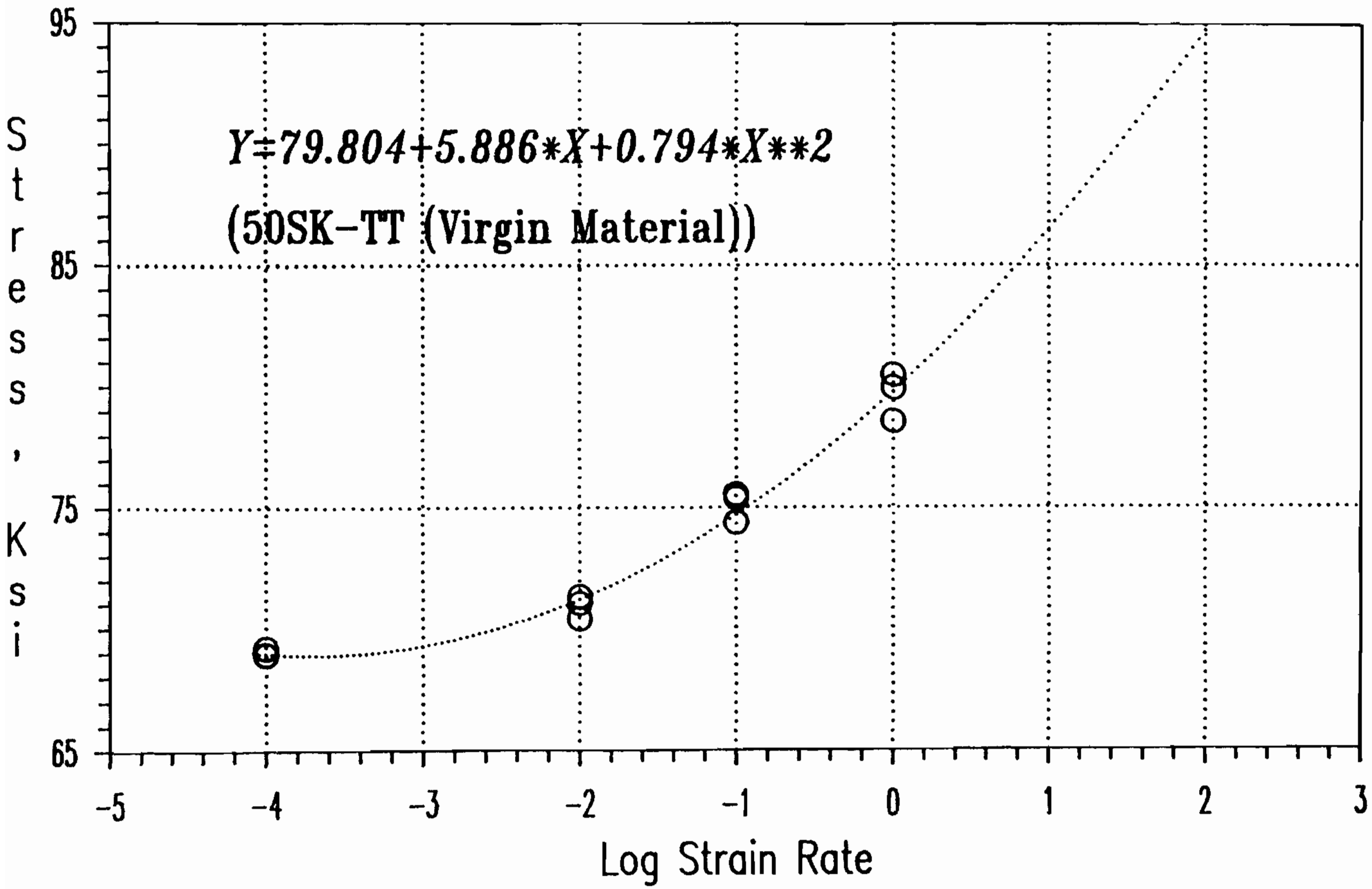

Figure 3.12 Tensile Ultimate Stress vs. Logarithmic Strain Rate Curve for 50SK Sheet Steel (Transverse Tension)