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MEMORANDUM REPORT NO. 2589 ✓

QUASI-STATIC COMPRESSION STRESS-STRAIN CURVES-II, RESULTS FOR 7039 ALUMINUM

E. Allen Murray, Jr.

February 1976

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I. INTRODUCTION

The quasi-static compression tests reported here were conducted in connection with the Core Materials Program of the Solid Mechanics Branch of the Terminal Ballistics Laboratory.

The purpose of the Core Materials Program is to characterize the mechanical behavior of armor and armor penetrator materials. This characterization should prove useful to the designers of armor vehicles and projectiles and will provide valuable input data for computer codes modeling penetration processes. It will be arrived at by the compilation of a series of quasi-static and dynamic laboratory experiments performed under carefully controlled conditions.

7039 aluminum armor is the second material tested in a series which includes six other aluminums and seven steels.¹ Specimens for these tests were grouped into four categories. Group one was cut from one half inch (1.27 cm) rod such that the axial direction of the specimen corresponded to the axial direction of the rod. Groups two and three were cut from three quarter inch (1.91 cm) aluminum armor plate such that the axial direction of the specimen was 1) parallel with the rolling direction of the plate for group two and 2) perpendicular to the rolling direction of the plate for group three.

Specimens in group four were cut from aluminum armor plate one and one half inches (3.81 cm) thick such that the axial direction of the specimen was through the plate, perpendicular to the rolling direction.

The test specimens were 9.5 mm diameter, 28.6 mm long, right circular cylinders, carefully machined with the last six cuts 0.001 inch (0.0254 mm) per cut.

The results reported here consist of the yield strength for each specimen orientation, the stress-strain curves, Poisson's ratio, Young's modulus, and hardnesses for each group.

II. APPARATUS

A. Instron

The testing machine used in the quasi-static compression tests is a 10,000 kilogram capacity Instron Universal Testing Instrument, floor model TT-DML. The machine has a testing speed range from 0.005 to 5.0 centimeters per minute with the speed of the moving crosshead held constant regardless of the applied load. The moving crosshead travels

¹BRL Memorandum Report No. 2399, "Quasi-Static Compression Stress-Strain Curves-I, Data Gathering and Reduction Procedures; Results for 1066 Steel", E. A. Murray Jr. & J. H. Suckling, July 1974. AD# 922704L.

on two vertical drive screws and is controlled by a positional servo-mechanism that incorporates an amplidyne power drive and synchro-control elements.

B. Subpress

Because of the great difficulty in aligning small specimens, a Tinius-Oison subpress was employed. The subpress, shown in Figure 1, consists of a frame, a hemispherical bottom plate, and a precision fitted right circular cylinder. The Instron presses on a flat disk that is connected to a one inch (2.54 cm) rod. At the other end of the rod is a ball. This rod-ball assembly fits into and presses at the bottom of a cavity in the right circular cylinder. This configuration allows the load to be applied close to the test specimen and below the surface where the cylinder contacts the subpress frame. Thus, non-axial loads are reduced and bending is kept to a minimum.

C. Load Cell

The load cell used in the quasi-static compression tests has a load range of 0-10,000 kilograms. Stress measurements are taken from strain gages which are factory mounted in the load cell. The spindle at the top of the load cell has a spherical surface, designed to support a load-table which is self-aligning over small angles. Compression cells require a compression overload carriage, which consists of a spring overloaded cell carrier and an automatic shut off switch.

The load cell is calibrated by placing 50 kilograms of precision weights on the testing machine and recording the output on a chart recorder.

D. Chart Recorder

A six channel Rikadenki chart recorder* is used to record the load and strain voltages (details of the strain measurements will be found in the test procedures section). The recorder has an attenuation range of 1 millivolt to 5 volts in ten steps and chart speeds from 15 millimeters per hour through 600 millimeters per minute.

E. Data Reader and Card Punch

The charts are read on a Data Reducer 099 manufactured by Telecomputing Corporation. With this device, the operator reads simultaneous values of load and strain voltages (as vertical chart coordinates in arbitrary data units: "counts"). The sensitivity of the system is 15.59 counts per millimeter. These counts are fed to a Telecordex and are punched on IBM cards by an IBM Gang Summary Punch 523.

* Rikadenki Model B641.

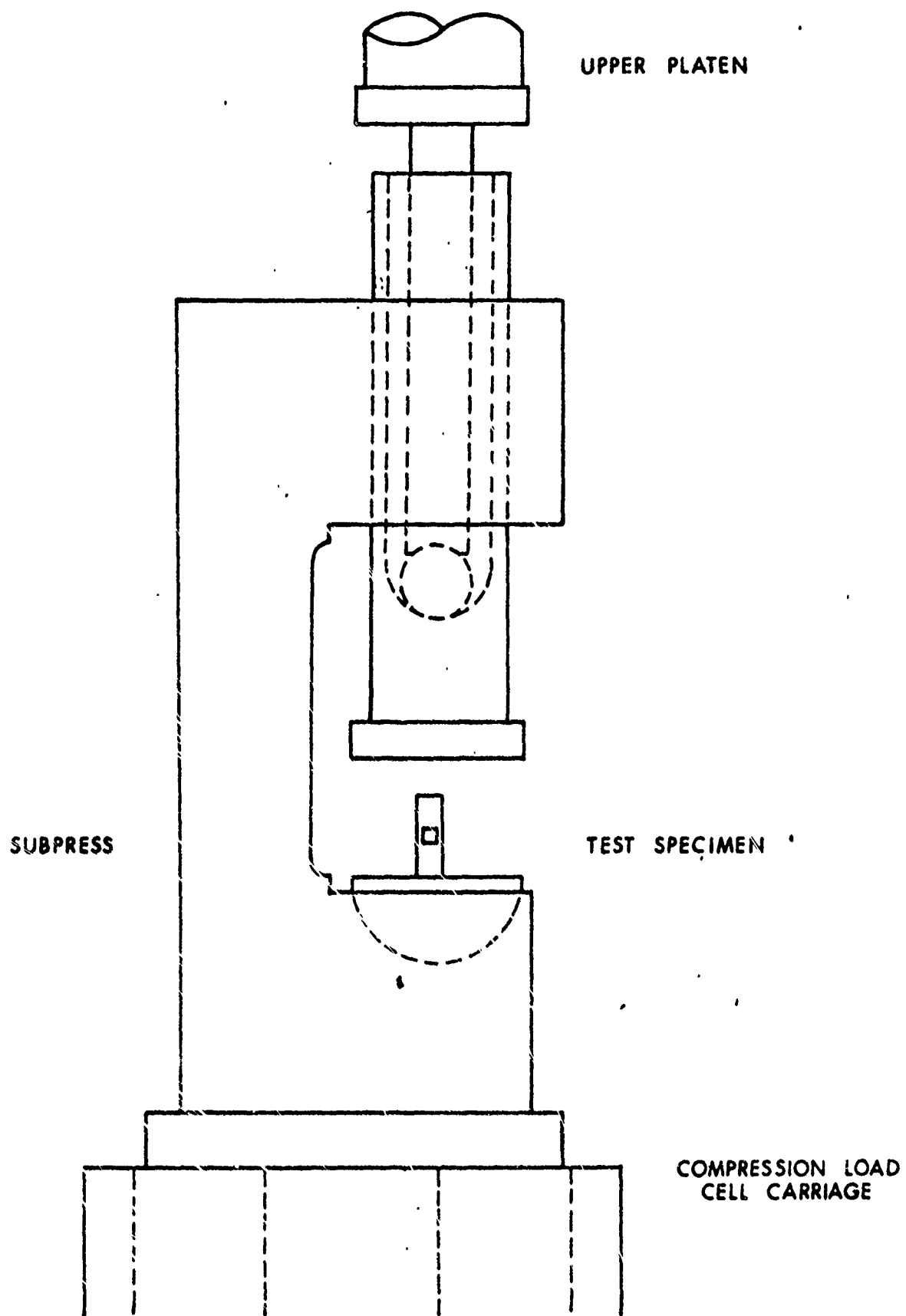


Figure 1. Schematic of Specimen and Subpress Installed in Static Testing Machine

F. Data Processor - BRLESC and Cal Comp Plotter

The data are processed on one of the Computer Support Division's primary digital computers, BRLESC II. Auxiliary equipment used with the BRLESC II includes the memory disc, on line printer, and plotter tape. The plotter tape in turn is used to produce data plots on a Cal Comp Plotter.*

III. TEST PROCEDURES

A. Preparations

The specimens are three-eighth inch (9.5 mm) in diameter by one and one-eighth inches (28.6 mm) long right circular cylinders. Each specimen is carefully machined by following a schedule designed to minimize work hardening of the material. Disks, one quarter inch (6.35 mm) thick are machined from material between each pair of specimens and used to monitor material hardness and chemical properties. The surface of the specimen is next prepared for strain gages. Throughout the process, great care is taken to promote cleanliness. The surface is precleaned with solvent, then wet lapped with grit paper and metal conditioner. After the surface has been marked for gage layout, it is flushed with neutralizer and wiped dry. The surface is now ready for gage application.

Similar precautions are taken with the strain gages. The gages are cleaned and wetted with a neutralizer. Just before application of the gage, a catalyst is applied and allowed to dry. The gage is cemented with Eastman 910. Although manufacturing specifications indicate that the Eastman 910 cement sets instantaneously, we wait at least an hour before testing.

Two dual element BLH type FAET-06D-12 PEL gages are mounted on the central circumference of each specimen 180° apart such that one element of each gage is aligned axially and the other element is aligned perpendicular to the axis.** The two axially aligned gages are monitored separately to record the strain in the longitudinal direction. This also makes for an easy check of alignment of the specimen in the Instron. If one gage shows a significantly higher strain than the other while the specimen is still in the elastic region, the test can be stopped, the load released, the specimen realigned and the test begun again. If, after careful alignment, one gage shows a higher strain than the other gage, this denotes bending of the specimen.

'California Computer Products, Inc.'

**See section V where the use of other gages is discussed.*

The elements of the two gages aligned perpendicular to the loading axis are connected in series and monitored as one. These gages measure the circumferential strain. The combination of circumferential strain and longitudinal axial strain allows us to compute Poisson's ratio; Young's modulus is calculated from the slope of the elastic portion of the stress-strain curve.

The next step in the test procedure is to calibrate the Instron load cell. Ten 5 kilogram calibration weights are placed on the load cell plate and the output is recorded on the chart recorder. After calibration, the weights are removed and the subpress placed in the Instron and aligned. Next, the specimen is placed in the subpress and aligned. To prevent specimen barreling, 4 mil (0.1 mm) disks of teflon are placed between the specimen and the subpress. The strain gage leads are connected to the six channel paper chart recorder through Wheatstone bridge circuits. The bridges are balanced and the recording pens zeroed. Each gage is calibrated with a precision resistor and the calibration is recorded on the chart. The last step before the test is begun is to record the time, temperature, and humidity.

B. Testing

The Rikadenki chart recorder is started at a speed of 60 millimeters per minute and a setting of 1 millivolt full scale. As each pen on the recorder reaches full scale, that individual channel is attenuated. The cross head speed of the Instron is held constant at 0.005 centimeters per minute.

The test is continued until the strain gage output becomes non-linear, the adhesive fails, or the limit of the testing apparatus is reached. The strain gages are high elongation gages and become non-linear around ten percent strain. The Eastman 910 cement is usually good for seven to ten percent strain. At the conclusion of the test the time, temperature, and humidity are recorded, and the specimen is labeled and stored.

IV. DATA REDUCTION

A. Generation of Data on IBM Cards from Chart Records

The raw data from each test consist of a paper chart containing four curves. These curves are voltage v vs time representations of the load, the circumferential strain, and the longitudinal strain at two points. The curves are read on a system that transfers the data to IBM cards. To make the data transfer, the chart is placed in the reader such that the horizontal cross hair is parallel with the horizontal lines on the chart. In all readings, only the position of the horizontal cross hair is recorded; i.e., we record load and strains at common values of time.

The first four sets of readings are the calibrations. To make a calibrated load reading, the horizontal cross hair is placed on the deflected calibration curve and the deflection is recorded. The cross hair is then returned to the no load portion of the curve and that location recorded. The difference between these two readings is the stress calibration for the test. Similarly, the circumferential strain and the two axial strain calibrations are read and recorded. All calibration readings are recorded on a single IBM card.

The recording pens have an inherent offset in the horizontal direction that makes it necessary to use a special jig when reading four curves at one time. To make a set of readings, the jig is positioned over the four curves. The horizontal cross hair is placed at the intersection of curve one and the corresponding vertical line on the jig. The location is recorded. Curves two, three and four are aligned and punched in order. This completes one set of data points at a single point in time. The jig is moved to the next location and another set is punched.*

The format for the data card is similar to that of the calibration card, with the first forty columns used to record data and columns 60 through 80 reserved for identification.

B. Computer Program

The IBM data cards from one test are included in the data section of the computer program deck¹ and processed on the BRLESC digital computer. The computer reads and prints out the calibration card. This section makes the calculations that determine the calibration constants including the factors that account for changes in sensitivity of the chart recorder.

The computer next goes through a loop where it reads and prints out each data card. In this loop it counts the number of data points and checks for a flag card which has been placed after the last data card. When this flag card is found, the computer moves out of the loop to the next section of the program.

The program calculates the stress at a data point then checks to see if there has been a scale change. In order for the computer to know there has been a scale change, two conditions must be met. The point count** must be less than three quarters of the previous point count and the previous point count must have been over 3000. When these two conditions are met, the computer moves to the next step in the appropriate array and makes the necessary multiplications as previously arranged in the calibration section.

* Density of readings varies with the complexity of the curve.

** Full scale point count on the Data Reducer 099 is 4000 counts.

The program continues at the same data point by calculating the longitudinal strains and the circumferential strain. Again the computer checks for scale changes and makes necessary adjustments. Poisson's ratio is calculated from the ratio of the circumferential strain to the average of the two longitudinal strains. The program cycles in a loop until all the data points have been processed.

In the next section the computer prints out the data point number, the stress, both longitudinal strains, the circumferential strain, the averaged longitudinal strain and Poisson's ratio for each data point.

The last section controls the Cal Comp Plotter. The plots for a single test consist of a large size stress-strain curve from zero to 1 percent strain, a smaller stress-strain curve from zero to 10 percent strain, and a Poisson's ratio curve from zero to 1 percent strain. The large stress-strain curve is plotted for maximum readability and can be used for comparison of slight differences between tests. The smaller stress-strain curve gives an overall look at the test.

C. Equations for Calculations of Stress, Strain, and Poisson's Ratio

$$\text{Stress, } \sigma = \frac{K/d_1}{A} D_1$$

where: K = calibration weight (kilograms)

d_1 = deflection on chart as a result of calibration weight (counts)

A = cross sectional area of test specimen (millimeters squared)

D_1 = deflection on chart of load curve adjusted for zero offset and scale changes (counts)

$$\text{Strain, } \epsilon = d_2 D_2$$

d_2 = calibrated deflection as a result of a known resistance change (strain per count)

D_2 = deflection on chart of strain gage output adjusted for zero offset and scale changes (counts)

$$\text{Poisson's ratio, } \nu = \frac{\epsilon_c}{\epsilon_1}$$

where: ϵ_c = circumferential strain

ϵ_1 = longitudinal strain

D. Average of Tests - Standard Deviations

After a series of specimens have been tested and analyzed, the data from all the tests are analyzed as a group. The computer program that does this is similar to the first computer program with some additions. The program will handle any number of sets of data.*

For the first test each calculated value of stress and strain is stored in two arrays which are labeled such that for each value of strain in the first array there is a corresponding value of stress in the second array. This procedure is repeated for the subsequent tests in the series by introducing the values of strain and stress into their respective arrays in subsequent sets of locations.

To calculate the average stress-strain curve a maximum strain value (EMAX) is established and divided into a number of increments, say 100 (any number can be chosen by the user). This division gives a set of finite strains to be used as an independent variable in the calculations. The computer then scans the strain array to find values such that one point is above and the previous point is below the first strain value (0.1 EMAX). The computer then does a linear interpolation to find the stress at that intermediate point. When the array has been scanned, and all the values found and interpolated, these stress values are summed and averaged. The procedure is repeated for subsequent, incremented values of strain.

The computer plots a single stress-strain curve with error bars of plus and minus one standard deviation.**

V. RESULTS & DISCUSSION

The quasi-static compression tests were run on 7039 aluminum armor plate and 7039 aluminum rod. In all, a total of 23 tests were run, with 5 discarded for various reasons such as early gage failure or excessive specimen bending. The specimens from the armor plate were cut with three orientations with respect to the plate rolling direction. See Figure 2.

The data reported here are based on four tests with the axis of the specimen parallel to the direction of rolling, three tests with the axis perpendicular to the direction of rolling, five tests with the axis through the plate, perpendicular to the direction of rolling, and six tests from bar stock purchased specifically for the Core Materials Program.

*Subject to the memory limitation of the computer.

**Bessel's correction for small samples was applied to the calculation of the standard deviation (see: M. J. Moroney, Facts From Figures 226, 1964 edition, Pelican Books Inc.).

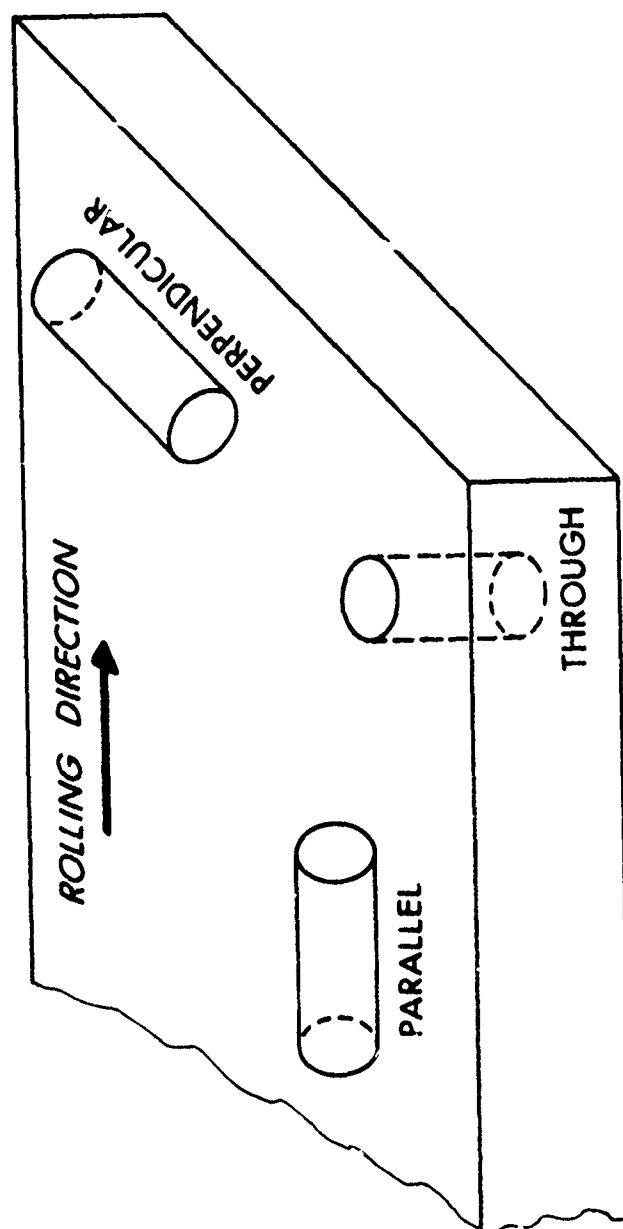


Figure 2. Schematic of specimens cut from armor plate showing three orientations with respect to the plate rolling direction.

The results of the quasi-static compression tests are reported in Table I.

The yield strength was taken to be the point where the strain deviates 0.2 percent from the proportionality of stress to strain.* Standard deviations given are calculated for the curves at the yield point.

Young's modulus was taken to be the slope of the elastic portion of the stress-strain curve. Standard deviations were calculated from an average of all the tests in a particular group of specimens.

Poisson's ratio is 0.31 (with a standard deviation of 0.01) in the elastic region and approaches 0.5 as the material becomes plastic. The Poisson's ratio and standard deviation calculation included all 18 tests.

The average stress-strain curves, with plus or minus one standard deviation, for each group of specimen orientations appear as Figures 3, 4, 5 and 6.

VI. CONCLUSION

This report has fulfilled its purpose by presenting certain mechanical behavior properties of 7039 aluminum armor. The data was generated from a series of quasi-static compression tests on samples of 7039 aluminum armor plate and 7039 aluminum rod.

ACKNOWLEDGEMENTS

The author would like to thank Mr. Ralph F. Benck for his assistance with the "rod" specimens and Mr. Dominick DiBerarado for instrumenting the samples and performing the compression tests.

* See: *ASM Metals Handbook*, 1948 edition, page 16.

Table I. Measured Material Properties of 7039 Aluminum

Property	Plate (Parallel) ¹	Plate (Perpendicular) ²	Plate (Through) ³	Rod
Average Yield Strength				
Megapascals (Standard deviation)	385 (2.85)	387 (3.90)	452 (5.22)	359 (2.40)
KSI (Standard deviation)	55.9 (0.41)	56.2 (0.57)	68.6 (0.76)	52.0 (0.35)
Young's Modulus				
Megapascals (Standard deviation)	75.4 (7.05) X 10 ³	74.4 (5.18) X 10 ³	72.0 (.16) X 10 ³	71.9 (.72) X 10 ³
KSI (Standard deviation)	10.9 (1.02) X 10 ³	10.8 (0.75) X 10 ³	10.4 (0.023) X 10 ³	10.4 (0.10) X 10 ³
Hardness (Brinell)	132	132	155	112

Poisson's ratio is 0.31 (with a standard deviation of 0.01 in the elastic region) and approaches 0.5 in the plastic region.

¹Parallel - Axis of specimen cut parallel to rolling direction of plate.

²Perpendicular - Axis of specimen cut perpendicular to rolling direction of plate.

³Through - Axis of specimen cut through the plate thickness.

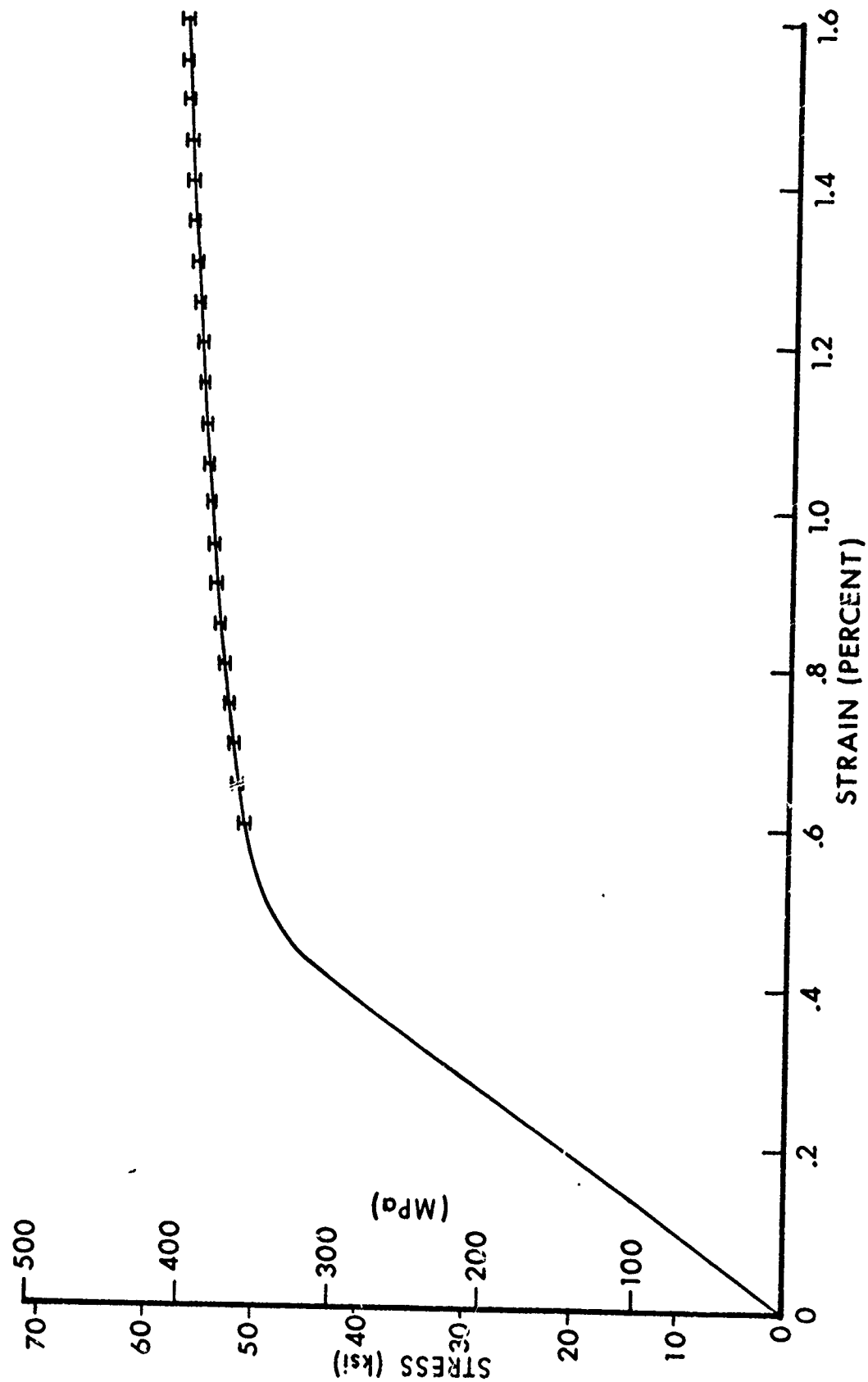


Figure 3. Stress-strain curve of a series of 7039 aluminum compression specimens cut from a one half inch aluminum rod.

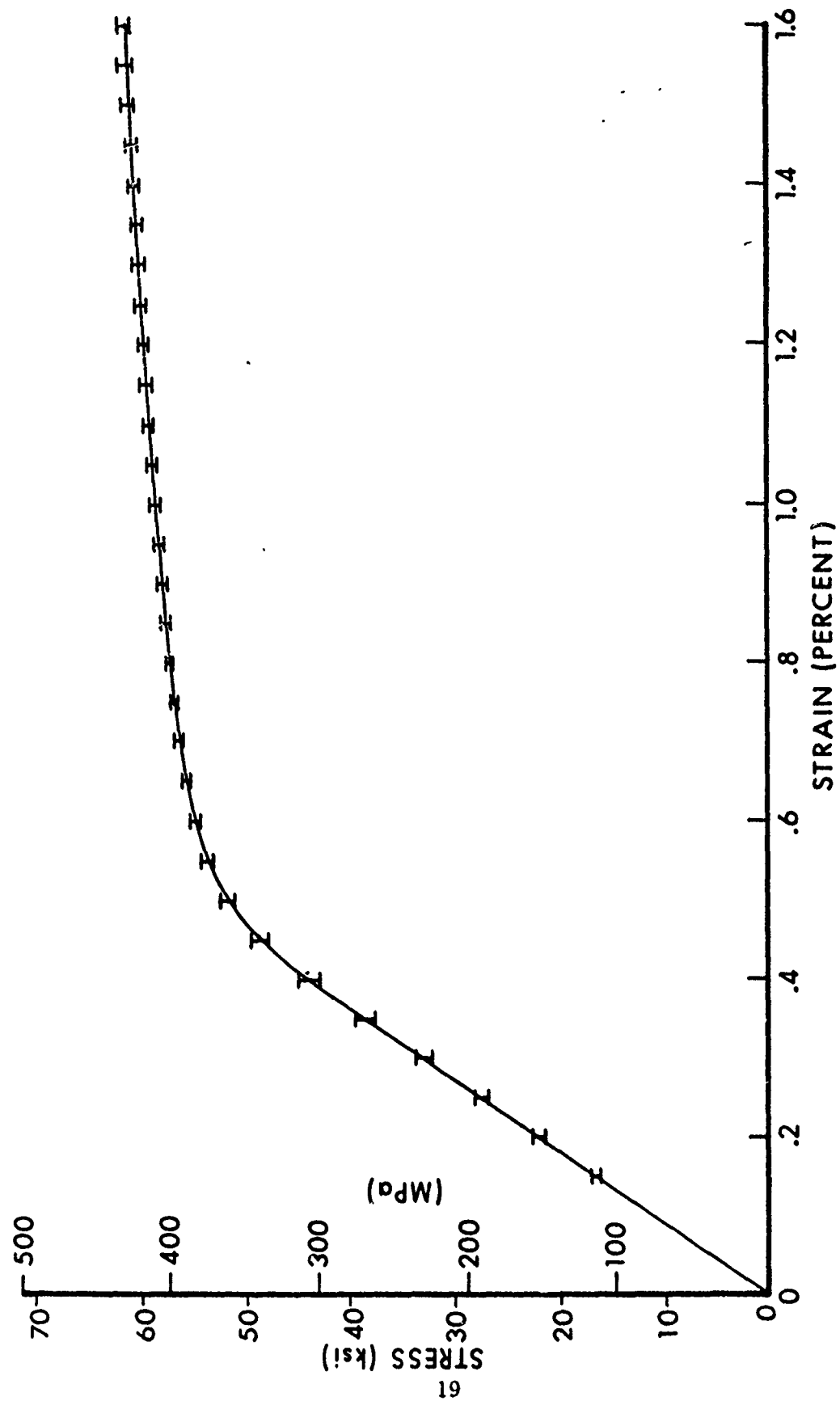


Figure 4. Stress-strain curve of a series of 7039 aluminum compression specimens cut from a three quarter inch armor plate, parallel to the rolling direction of the plate.

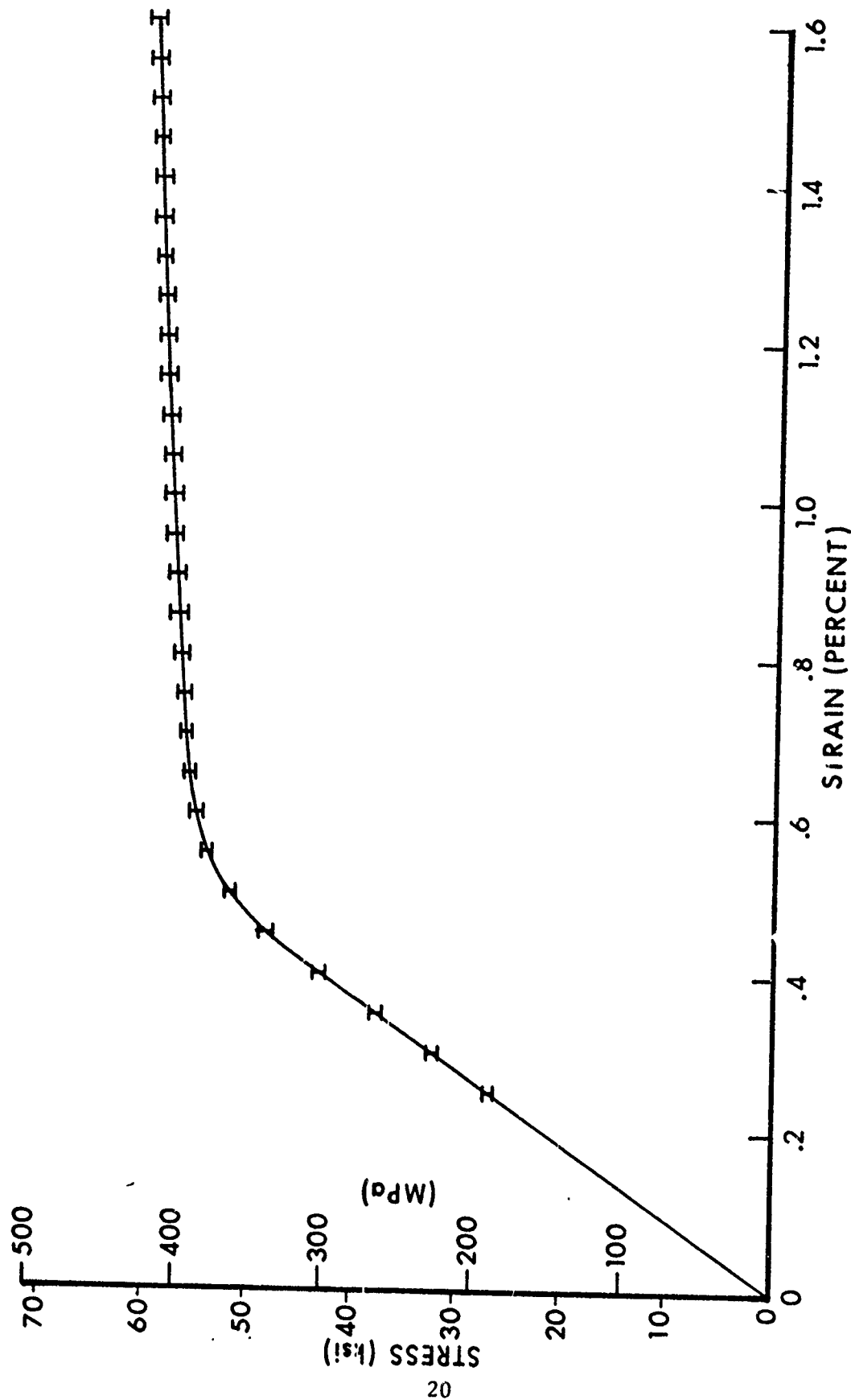


Figure 5. Stress-strain curve of a series of 7039 aluminum compression specimens cut from a three quarter inch armor plate, perpendicular to the rolling direction of the plate.

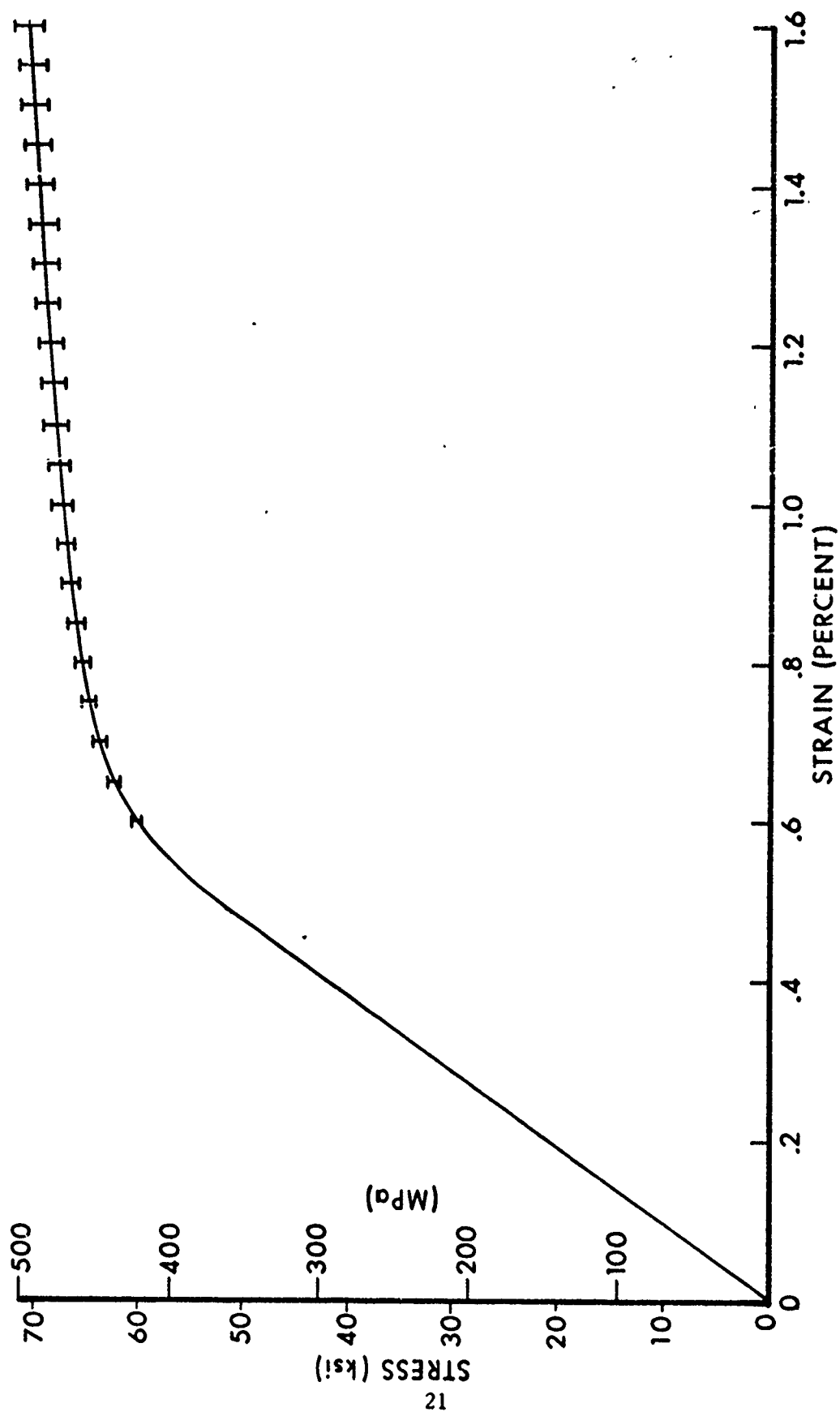


Figure 6. Stress-strain curve of a series of 7039 aluminum compression specimens cut from a one and one half inch armor plate, through the plate, perpendicular to the rolling direction of the plate.

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