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QUASI-STATIC STRESS-STRAIN CURVES, S-7 TOOL STEEL

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October 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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The results of quasi-static, uniaxial, compression, and tensile and sonic elastic moduli room temperature tests of S-7 tool steel are presented. The modulus of elasticity, shear modulus, Poisson's ratio, yield strength, and bulk modulus of various tempers of S-7 tool steel are reported as well as the stress-strain curves for both compression and tensile loading.

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I. INTRODUCTION

This report presents the results of quasi-static, uniaxial compression and tensile tests, and sonic elastic moduli tests of S-7 tool steel. Table I lists the nominal chemistry for this steel. Table II lists the specimens used in the quasi-static tests; Table III lists similar information for the sonic test specimens. The steel used in test series 4-9 was prepared via a vacuum induction melting, vacuum arc remelting (VIMVAR) process*.

TABLE I

S-7 TOOL STEEL

Element	Percent Composition by Weight	
	Nominal[1] %	Test Series 5 to 8** %
Carbon	0.5	0.51
Silicon	0.25	0.28
Manganese	0.76	0.73
Chromium	3.25	3.25
Molybdenum	1.40	1.41
Sulfur	----	0.006
Phosphorus	----	0.009
Iron	Remainder	Remainder

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*Carpenter Technology Corp., Reading, PA.

[1] "Bearcat Tool Steel", Engineering Alloys Digest, Inc., Upper Montclair, N.J.

**Carpenter Technology Corporation - CARP Order No. W93154.

TABLE II

STEEL SPECIMENS FOR QUASI-STATIC TESTS

Test Series	Number of Specimens	Source of Specimens	Hardness Rockwell "C" Scale	Specimen Dimensions Length mm	Specimen Dimensions Diameter mm	Type of Test
1	1	Off Shelf	58	19.05	6.35	Compression
2	3	Off Shelf	55	19.05	6.35	Compression
3	4	Off Shelf	55	57.2	6.35	Tensile
4	3	VIMVAR*	47	19.05	6.35	Compression
5	6	VIMVAR, S-7	47	25.40	8.11	Compression
6	3	VIMVAR, S-7	47	20.90	6.99	Compression
7	1	VIMVAR, S-7	47	19.05	6.35	Compression
8	1	ViMVAR, S-7	53-54	22.90	7.62	Compression
9	9	VIMVAR, S-7	varied**	19.05	6.35	Compression

*S-7 Steel except that it contained no Molybdenum.
**See Table IV for heat treatments.

TABLE III

STEEL SPECIMENS FOR SONIC TESTS

Test Series*	Number of Specimens	Specimen Dimensions Length mm	Specimen Dimensions Diameter mm
2	1	160.03	8.075
4	1	159.84	7.330
5	1	250.34	8.108
6	1	250.22	8.113

*See Table II for information about Test Series.

All the specimens were heat-treated prior to testing. The tempering temperatures of test series 9 specimens are listed in Table IV. The heat-treatments for series 9 specimens, with the exception of specimens 9-4B and 9-5C, involved rapidly heating the steel to tempering temperature and then maintaining this temperature for 90 minutes. The procedure differed for specimens 9-4B and 9-5C in that the specimens were kept at the tempering temperature for 120 minutes.

TABLE IV

TEMPERING TEMPERATURES USED FOR TEST SERIES 9 SPECIMENS

Specimen	Tempering Temperature* C°
9-1	315
9-2	425
9-3	540
9-4 (A,B)	565
9-5 (A,B,C)	595
9-6	620

*Temperature as sensed by a thermocouple present in tempering furnace, probable precision is no better then ± 10°C.

In addition to the S-7 steels, one VIMVAR processed steel (test series 4) with identical chemistry but without molybdenum was also tested. The hardnesses given in Table II were not measured on the specific test specimen but were obtained on similar specimens from the same heat of steel, heat-treated at the same time.

II. TEST PROCEDURES

A. Quasi-Static Tests.

The test machine used for these tests is a 10,000 kilogram capacity, Instron Universal Testing Instrument, Floor Model TT-DML. Compression tests used a Tinius Olson 10,000 kg capacity sub-press to minimize bending in the small samples. The specimens for the compression tests were right circular cylinders with a length to diameter ratio of approximately three. The tensile specimens were prepared in accordance with ASTM Standard E-8, Figure 8.[2] The overall length of the tensile specimens was 57.2mm, the gage section diameter was 6.35mm, and the gage length 25mm. The specimens were placed in the testing machine in series with a universal unit to insure good alignment. For all the tests, both tensile and compressive, the cross head motion was 0.005 cm min^{-1}. The average room temperature was 23.5 ± 1°C with relative humidity 52 ± 8 percent.

[2] *ASTM E8-69 "Standard Methods of Tension Testing of Metallic Materials", Figure 8, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.*

The strains were determined by measuring the resistance of foil strain gages bonded to the surface at the specimen midpoints. The gages were placed symmetrically around the midpoint and were attached via M-Bond 200 adhesive*. Test series 1 through 5 used two 90-degree rosette gages, i.e. two axial and two circumferentially mounted gages, 180° apart, on each specimen. Series 6 through 9 used three 90-degree rosette gages. applied 120° apart. In addition to the foil strain gages, a clip-on extensometer was used for the tensile tests to insure the continuation of axial strain measurements should the gage fail during the test. Two types of foil strain gages were used, BLH-SR4** and M M-EP*. The gages are similar and contain two 1/16-inch long grids, set perpendicular to each other.

For test series 1-6, the gage resistance was determined by making the gage one leg of a Wheatstone Bridge circuit and recording the bridge output on a calibrated chart recorder. The output from an unbalanced Wheatstone Bridge is inherently non-linear and appropriate corrections were made to the data. Corrections were also made for transverse strains in accordance with the gage manufacturer's specifications. For test series 7, 8, and 9 the data collection procedures were improved by the use of an automatic data-logging system***. This system uses a digital multimeter to measure the gage resistance directly and record it on tape.

In the Appendix it is shown that the nominal or engineering strain, ε, is related to the gage resistance, R, by the expression

$$\varepsilon = -1 + \sqrt{R/R_o} \qquad (1)$$

where R_o is the initial resistance of the gage. Equation (1) was used to calculate all the strains reported herein.

B. Sonic Measurements.

The apparatus and experimental procedures for these tests have been reported previously.[3] The specimens were right cylindrical rods machined from the same batch of steel used to make the compression and tensile specimens. The modulus of elasticity, shear modulus and Poisson's ratio of the steels were determined at 22°C.

Micro-Measurements, Romulus, Michigan.

***BLH Electronics, Inc., Waltham, Mass.*

****Hewlett-Packard 3455A Digital Voltmeter in conjunction with a 3495A scanner and a 9815A desk calculator.*

[3]*R. Benck and G. L. Filbey, Jr., BRL Memorandum Report #2649, "Elastic Constants of Aluminum Alloys, 2024-T3510, 5083-H131 and 7039-T64 as Measured by a Sonic Technique", Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1976.* (AD#B012953L)

III. RESULTS

Table V presents the results of the quasi-static and sonic measurements for the individual specimens of test series 9. The average values of all the specimens tested in test series 1 through 8 are presented in Table VI.

Young's modulus and Poisson's ratio for the quasi-static tests were determined using least square fits of stress versus axial strain and axial versus circumferential strain data respectively, below the proportional limit. The bulk modulus was determined as the least squares fit of the pressure, P, versus the volumetric strain.

TABLE V

MATERIAL PROPERTIES OF S-7 STEEL
(TEST SERIES 9)

Specimen	Modulus of Elasticity GPa	Poisson's Ratio	Yield Strength GPa	Bulk Modulus GPa
9-1	215	0.293	1.85	174
9-2	216	0.295	1.79	176
9-3	211	0.300	1.70	175
9-4A	216	0.297	1.42	178
9-4B	216	0.296	1.40	177
9-5A	217	0.301	1.52	182
9-5B	215	0.292	1.53	173
9-5C	218	0.294	1.15	176
9-6	217	0.296	1.25	178

The volumetric strain was calculated by using Equation 2:

$$\frac{\Delta V}{V_o} = (1+\varepsilon_A)\,(1+\varepsilon_C)^2 - 1 \qquad (2)$$

where $\frac{\Delta V}{V_o}$ = volumetric strain

ε_A = axial engineering strain

ε_C = circumferential engineering strain.

P was taken as one third the true stress calculated from the load and the cross-sectional area change using the expression:

TABLE VI

MATERIAL PROPERTIES OF S-7 STEEL
(TEST SERIES 1-8)

Test Series	Modulus of Elasticity Quasi-Static	Modulus of Elasticity Sonic	Poisson's Ratio Quasi-Static	Poisson's Ratio Sonic	Yield Strength	Maximum Stress Before Buckling*	Bulk Modulus	Shear Modulus
	GPa	GPa			GPa	GPa	GPa	GPa
1	212	---	.285	---	1.80	2.45	163	---
2	219	217	.294	.273	1.51	1.98	176	84.5
3**	194	---	.286	---	1.40	***	153	---
4	197	208	.286	.274	1.82	1.70	152	80.9
5	212	211	.292	.286	1.45	1.82	169	82.0
6	214	210	.300	.284	1.60	1.98	177	81.6
7	217	---	.296	---	1.43	1.75	177	---
8	214	---	.291	---	1.85	2.20	170	---

*Onset of buckling defined as that point when the axial strain gages differ between themselves by more than 0.25 percent strain.

**Tensile Test Results are based on a clip-on extensometer.

***Ultimate stress was 1.75 GPa at 5.3 percent strain, sample fractured at 6.22 percent strain.

$$P = \sigma/3 = \frac{L}{3A_o(1+\varepsilon_C)^2} \tag{3}$$

where σ = true stress

L = load

A_o = initial cross-sectional area.

The yield strength is that engineering stress at which the engineering strain deviated 0.2 percent from the proportional limit.

The data presented in Table V (Test Series 9) were obtained from specimens that were loaded in compression and unloaded when the difference between the readings of the highest and lowest axial strain gages reached 0.05 percent.

Figure 1 presents engineering stress versus engineering strain for test series 1 through 8 compression tests. The reproducibility of the stress-strain curves of each similar set of specimens was such that in Figure 1, each test series is represented by the results from a single test. The unloading curves of four of the specimens are included. All the specimens shown in Figure 1 were compressed until the axial strain gages indicated buckling was becoming a problem. The largest difference allowed was 0.25 percent between the two or three axial gages. Test series 7 and 8 were recorded with the data logger system and the corresponding curves in Figure 1 are based on approximately 170 individual stress-strain datum points gathered at approximately 20 second intervals. The remaining curves in Figure 1 are based on 50 to 80 points taken from the strip chart records.

Figure 2 shows true stress versus true (logarithmic) strain for the same specimens included in Figure 1. The true stress is calculated using the load and the circumferential strain as discussed earlier. The true (logarithmic) strain, ε_L, is defined as

$$\varepsilon_L = \ln (1+\varepsilon)$$

where ε is the engineering strain.

Figure 3 is a comparison between the engineering stress-strain curves of a tensile and compression test of specimens from the same lot and heat-treatment.

Figure 4 depicts the same tests as shown in Figure 3, but this time as true stress-true (logarithmic) strain curves.

Figure 5 presents the engineering stress versus engineering strain curves for test series 9 specimens. These curves are based on the automatic data logging system and each curve represents approximately 180 datum points. Figure 6 is the true stress versus true strain curves for the series 9 specimens. Based on the apparently similar heat-treatments given to specimens 9-5A, B and C the discrepancy in yield strength, as indicated in Figures 5 and 6 and Table V is not understood. The thrust of the present research was not directed toward heat-treatments and, therefore, the solving of the apparently anomalous heat-treatment results will have to be deferred.

Table VI includes results from sonic (Elastomat) tests of four specimens. There is excellent agreement between the results of the sonic and quasi-static tests with the possible exception of the modulus of elasticity of test series 4. For series 4, the modulus based on the quasi-static tests may be suspect as the agreement between the three individual tests is not as good as for the other series. The individual moduli for series 4 are 192.7, 194.7 and 203.5 GPa. The reason for this inconsistency is not apparent.

IV. CONCLUSIONS

Uniaxial, quasi-static, compression and tension tests, and sonic measurements of resonant frequencies have been performed on S-7 tool steel of various tempers, some manufactured with a VIMVAR process. The proportional limit (see Figures 1, 2, 5, and 6) was approximately the same for all the tests. The 0.2 percent yield varied in approximate order with the hardness, the VIMVAR processed steel showing higher values.

Figures 3 and 4 clearly illustrate that S-7 exhibits a strength differential effect which is usually encountered in this type of steel.[4]

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[4] *G. C. Rauch and W. C. Leslie, "The Extent and Nature of the Strength-Differential Effect in Steels", Met. Trans.* *__3__, 373-385, Feb 1972.*

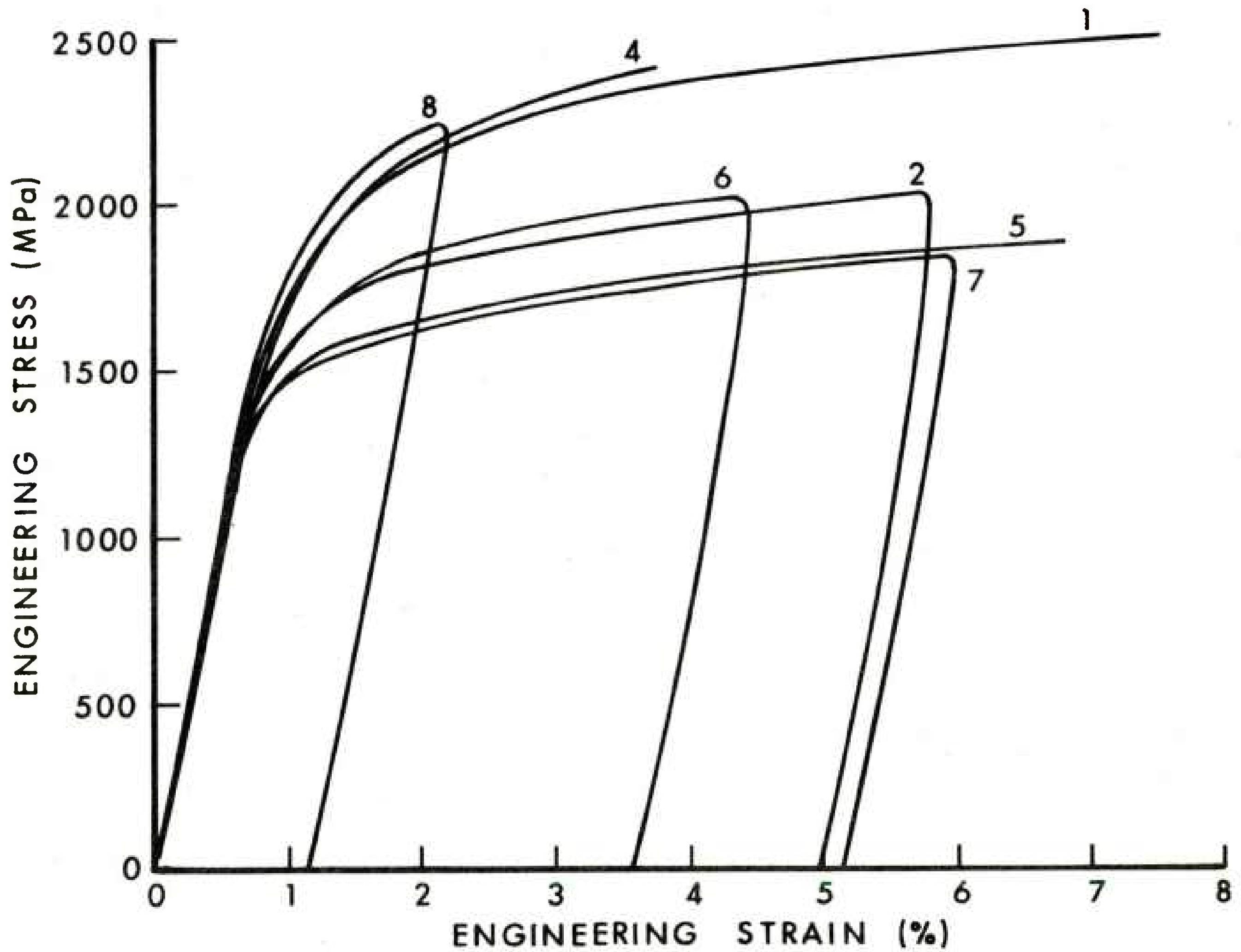

Figure 1: Engineering Stress vs. Engineering Strain for Compression Tests of Seven, S-7 Steel Specimens. (Numerals refer to test series)

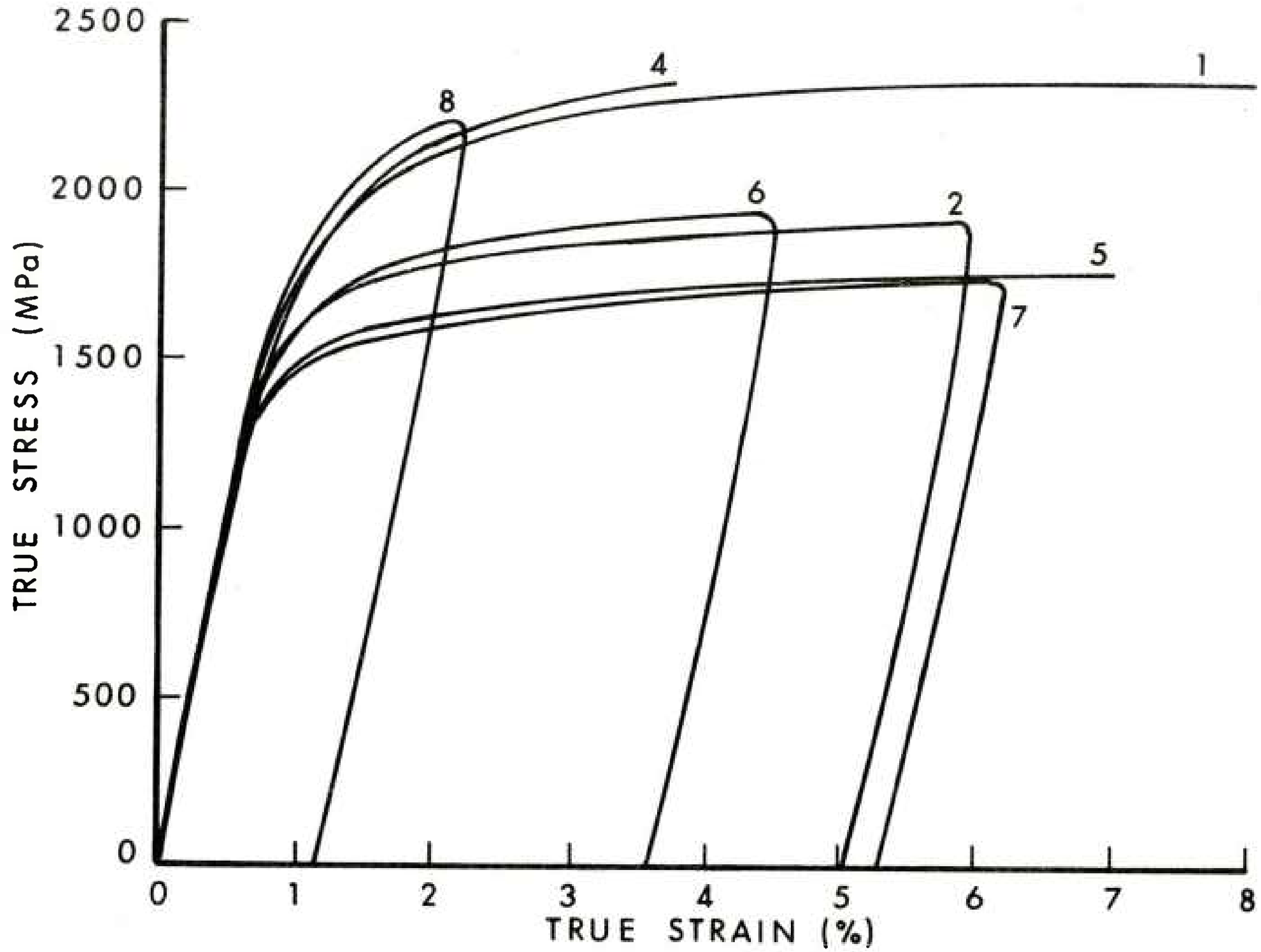

Figure 2: True Stress vs. True Strain for Compression Tests of Seven S-7 Steel Specimens. (Numerals refer to test series)

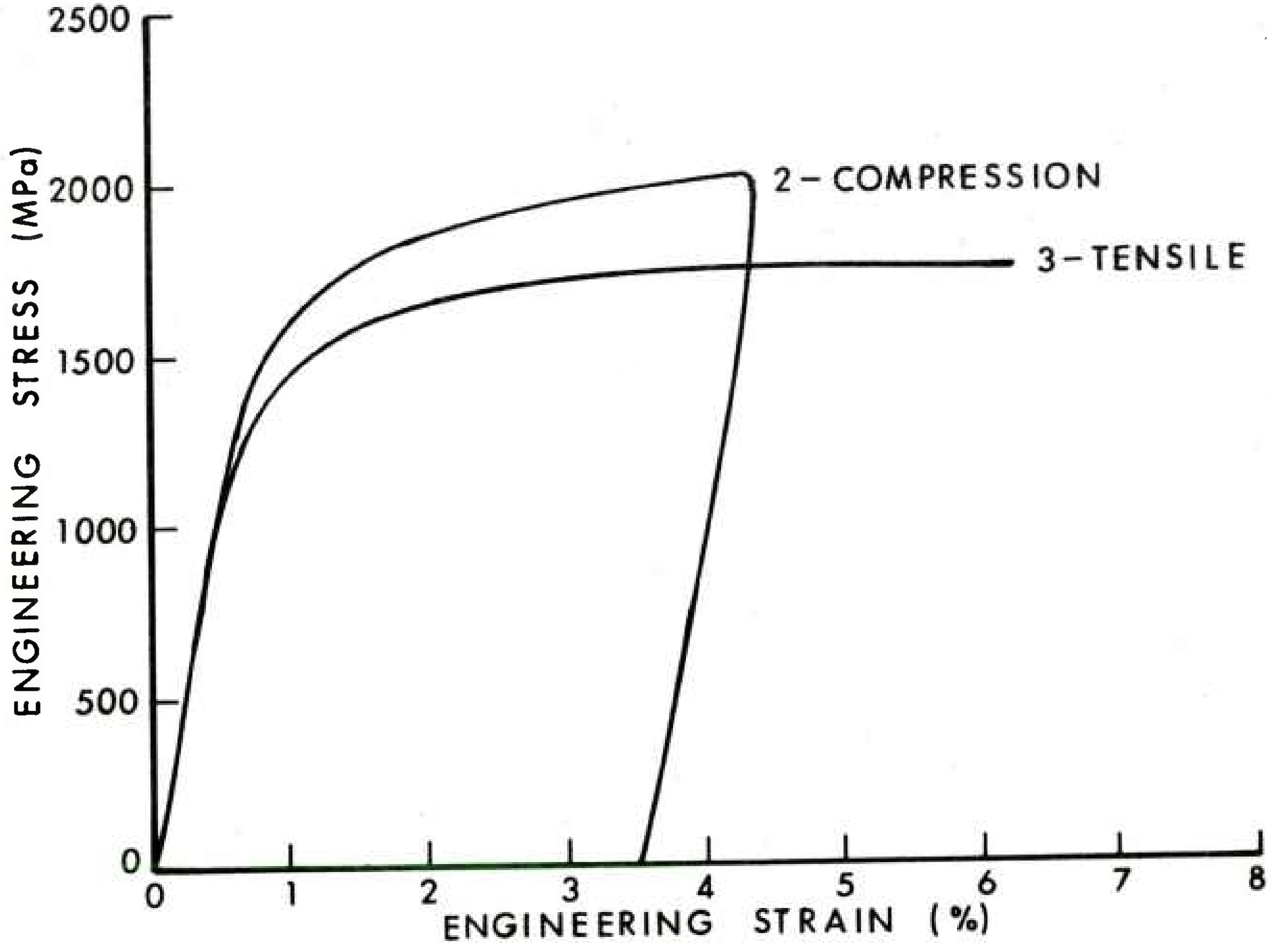

Figure 3: Engineering Stress vs. Engineering Strain for a Compression (2) and a Tensile (3) Test of S-7 Steel.

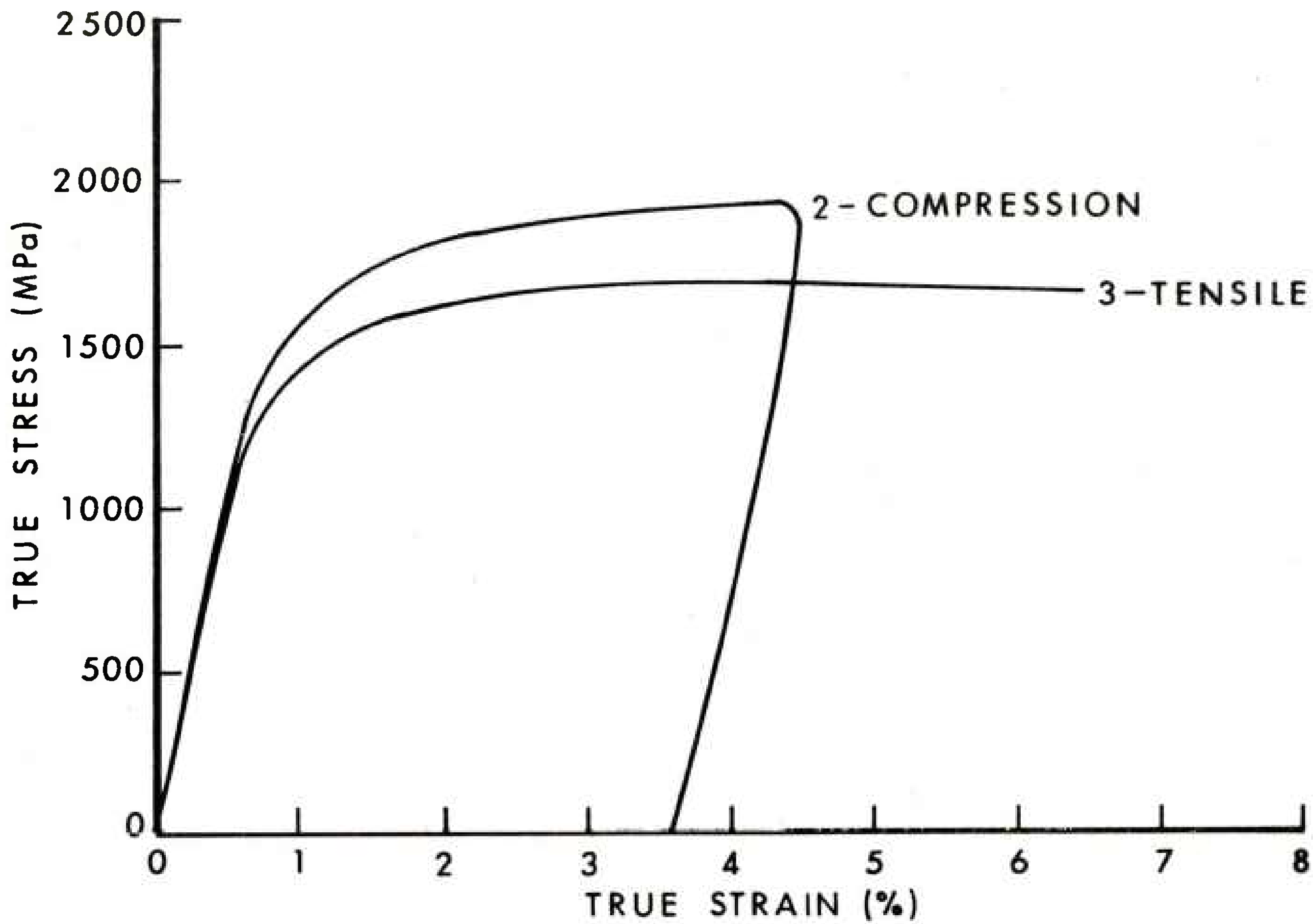

Figure 4: True Stress vs. True Strain for a Compression (2) and a Tensile (3) Test of S-7 Steel.

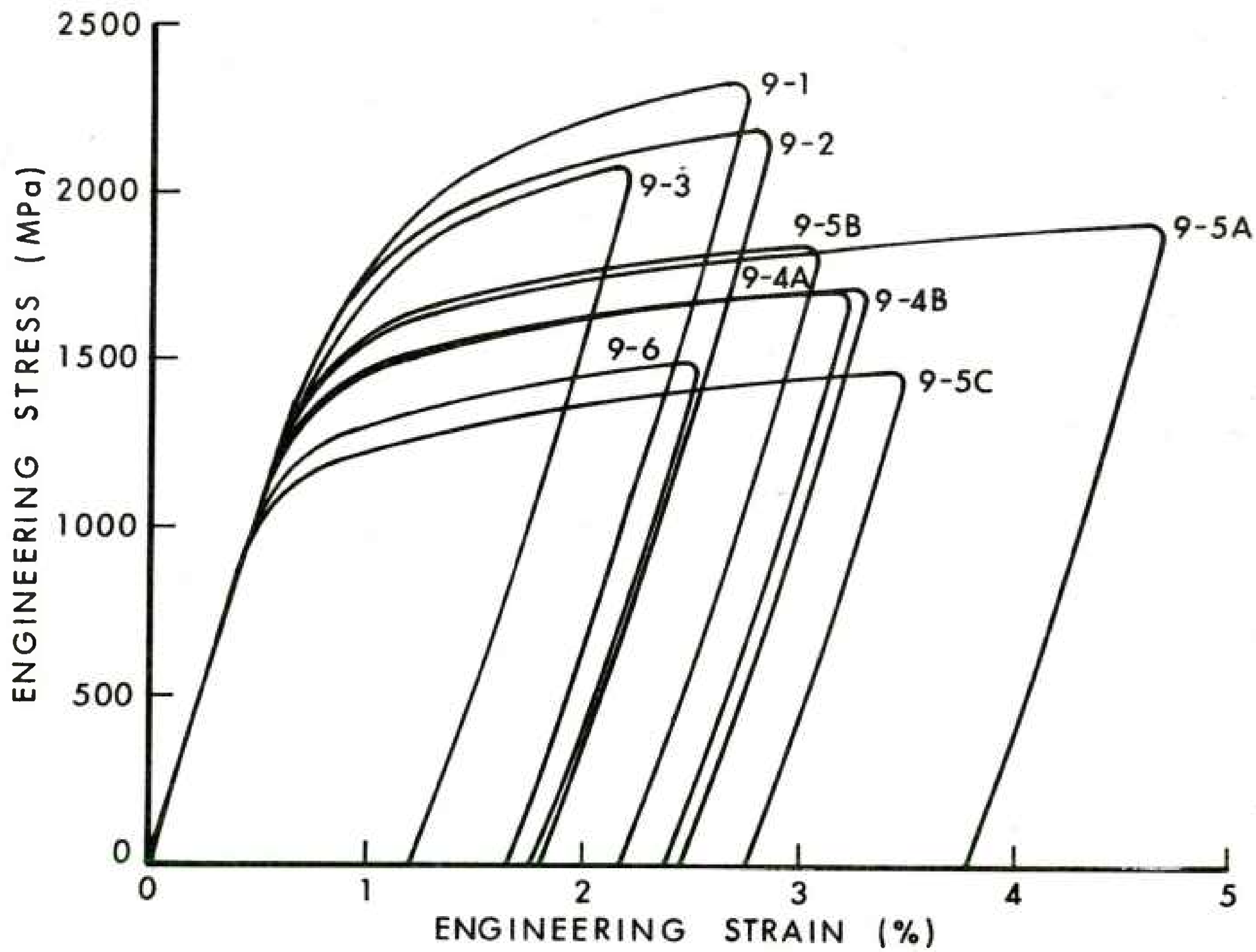

Figure 5: Engineering Stress Versus Engineering Strain, Test Series 9.

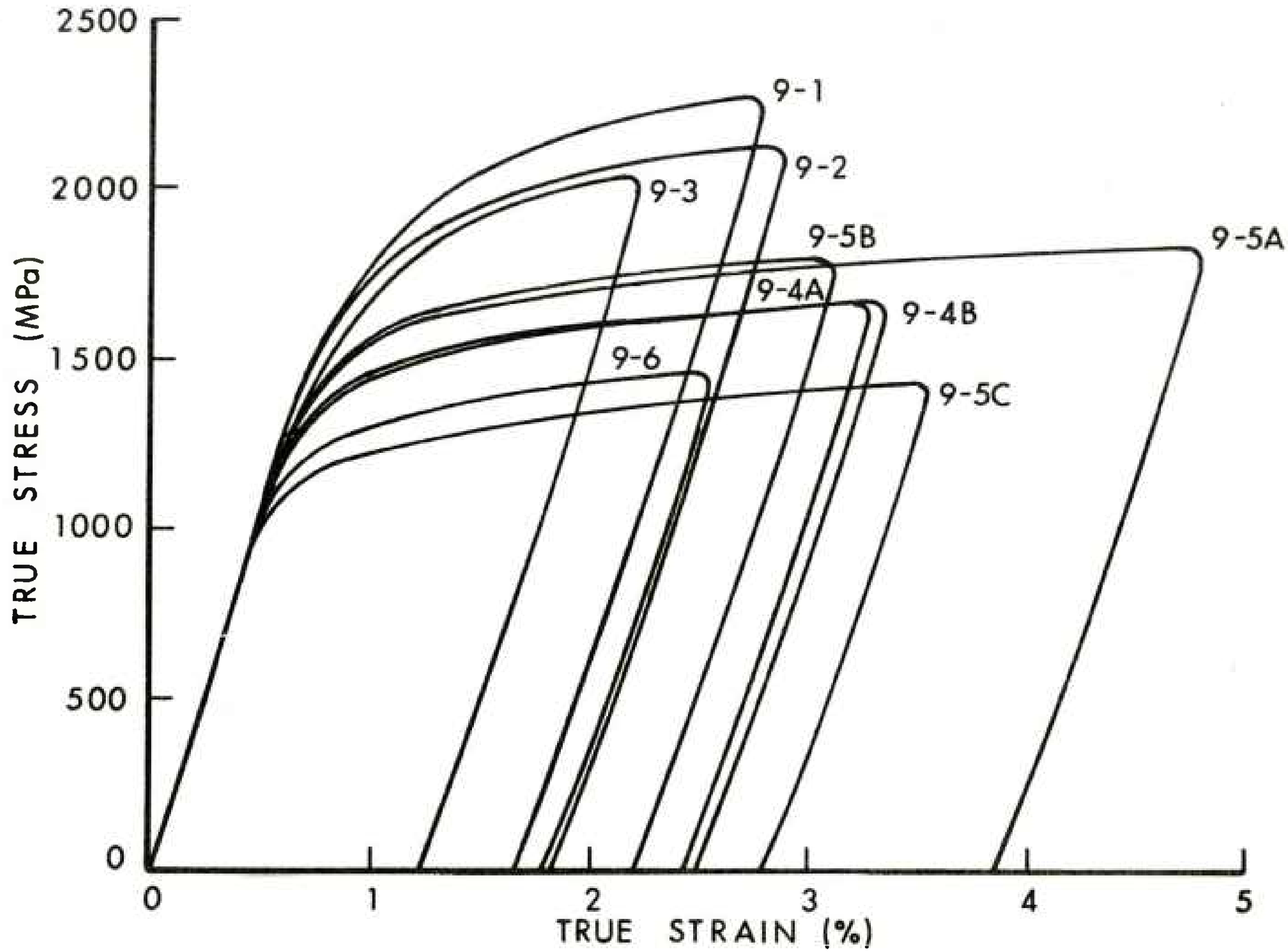

Figure 6: True Stress Versus True Strain, Test Series 9.

REFERENCES

1. "Bearcat Tool Steel", Engineering Alloys Digest, Inc., Upper Montclair, N.J.

2. ASTM E8-69 "Standard Methods of Tension Testing of Metallic Materials", Figure 8, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

3. R. F. Benck and G. L. Filbey, Jr., BRL Memorandum Report #2649, "Elastic Constants of Aluminum Alloys, 2024-T3510, 5083-H131 and 7039-T64 as Measured by a Sonic Technique", Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1976. (AD #B012953L)

4. G. C. Rauch and W. C. Leslie, "The Extent and Nature of the Strength-Differential Effect in Steels", Met. Trans. 3, 373-385, Feb 1972.

APPENDIX

It is well known that the gage factor of resistance strain gages appears to change at high strains. One gage manufacturer[A1] has stated that the gage factor for high elongation gages should probably be $2+\varepsilon$ where ε is the measured strain. In order to determine whether this factor should be used, some compression tests on 7039-T64 aluminum specimens were performed. Nominal 1/8-inch long resistance strain gages were attached to the midpoint of 9.5mm diameter, 28.6mm long aluminum right circular cylinders. Four thin lines were scribed 6.35 and 12.7mm apart, surrounding the gages, as shown in Figure A1. The specimens were placed in the testing machine and simultaneous resistance strain gage and optical traveling microscope measurements were made. The results of one such test using the lines that were initially 6.35mm apart are given in Figure A2. Figure A2 shows the strains calculated using the manufacturers gage factor plotted against the strains calculated using $2+\varepsilon$ as the gage factor. The optical measurements are marked by crosses, the size of the crosses indicate the approximate experimental uncertainty. It can be seen that the $2+\varepsilon$ gage factor gives a good fit to the optical data.

An explanation of this effect was given in a recent article in the Journal of Applied Physics[A2]. For gages with gage factors of approximately 2 (the gages used here had gage factors that ranged from 1.98 to 2.04) the resistance of the gage depends only on the length of the gage grid. Specifically, the resistance, R, of the strain gage is proportional to ℓ^2 as is shown in expression A1

$$R = K\ell^2 \tag{A1}$$

where K is a constant that depends on the gage material, and ℓ is the length of the grid.

In resistance strain gage experiments, $\frac{\Delta R}{R_o}$ is measured and $\varepsilon = \frac{\Delta \ell}{\ell_o}$ is calculated using the basic strain gage equation

$$\frac{\Delta R}{R_o} = (G.F.)\varepsilon \tag{A2}$$

where G.F. is the gage factor, and R_o and ℓ_o are the original resistance and length of the strain gage.

Now

$$\frac{\Delta R}{R_o} = \frac{R}{R_o} - 1$$

using equation (A1)

$$\frac{\Delta R}{R_o} = \left(\frac{\ell}{\ell_o}\right)^2 - 1$$

$$= \left(\frac{\Delta \ell}{\ell_o} + 1\right)^2 - 1 \qquad (A3)$$

$$= (2+\varepsilon)\,\varepsilon$$

Therefore from equation (A2)

$$G.F. = 2+\varepsilon .$$

It is noted in Reference A2 that this equation holds for both elastic and plastic strains and can be used in the entire experimental range.

Solving for ε in equation (A3) gives

$$\varepsilon = -1 + \sqrt{R/R_o} \; .$$

GAGE FACTOR EXPERIMENT

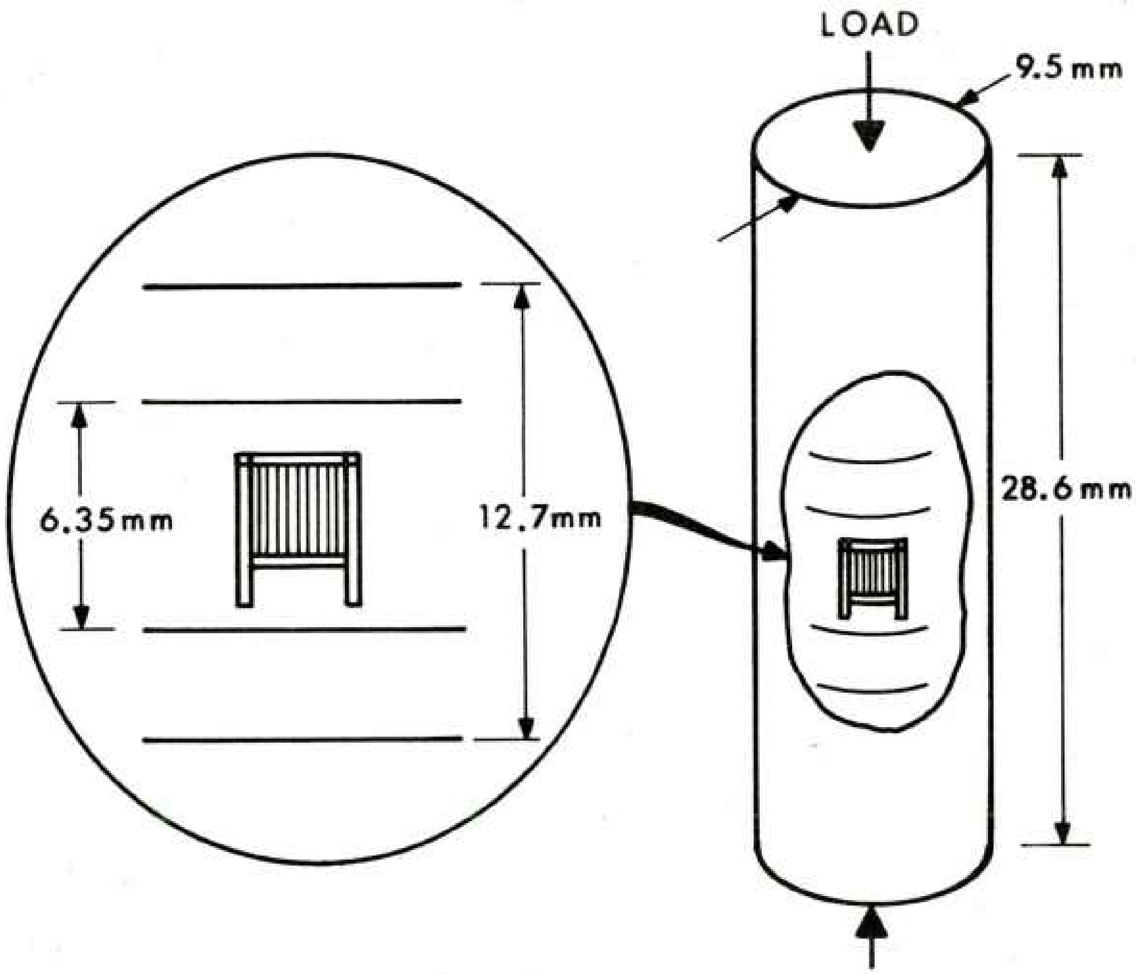

Figure A1: Experimental Setup of Gage Factor Experiment.

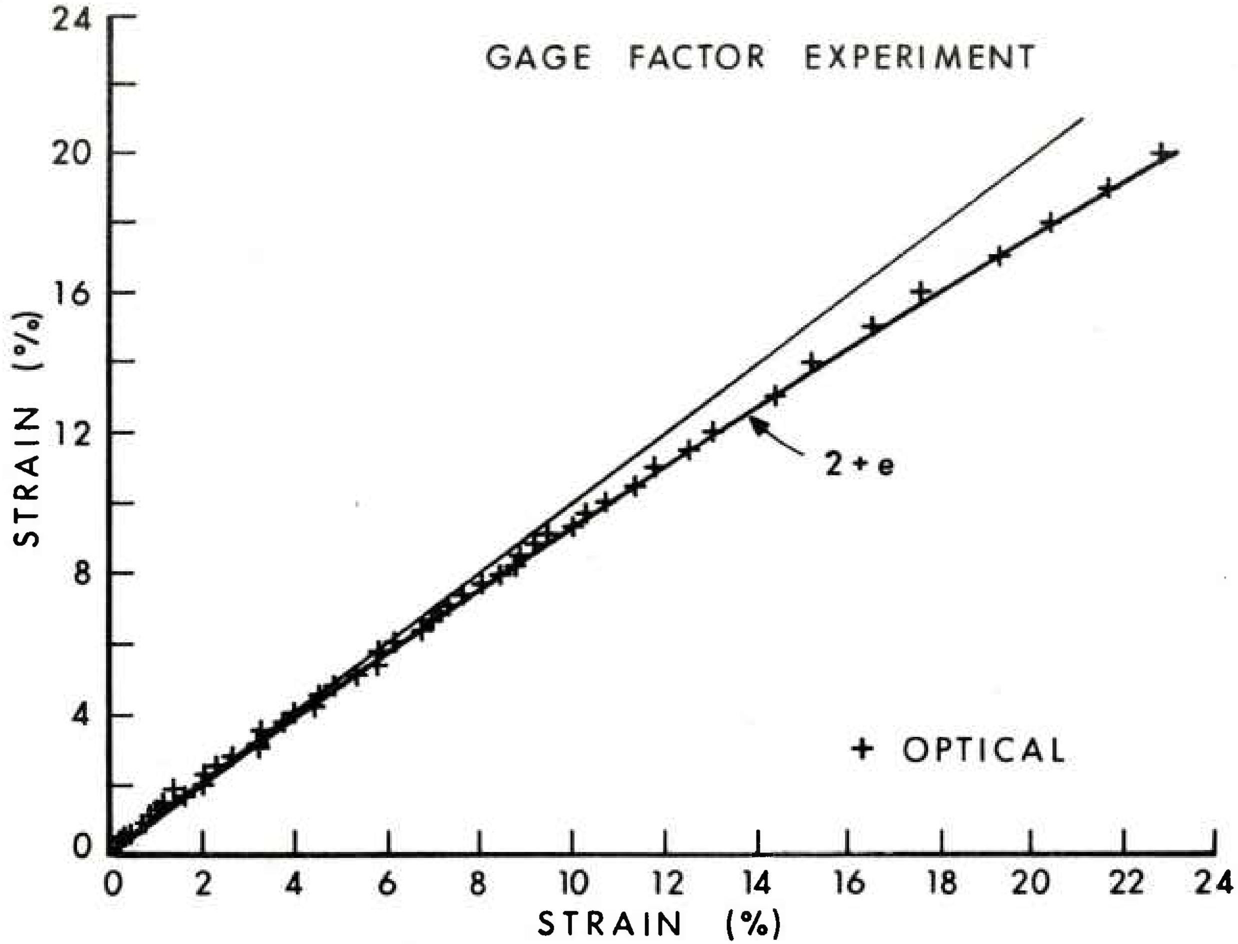

Figure A2: Results of Gage Factor Experiment.

REFERENCE

A1. Micro-Measurements Instruction Bulletin TT-133, 1976. Measurements Group, Vishay Intertechnology, Inc.

A2. G. Arit, "The Sensitivity of Strain Stages", J. Appl. Phys. 49 (7), July 1978.

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