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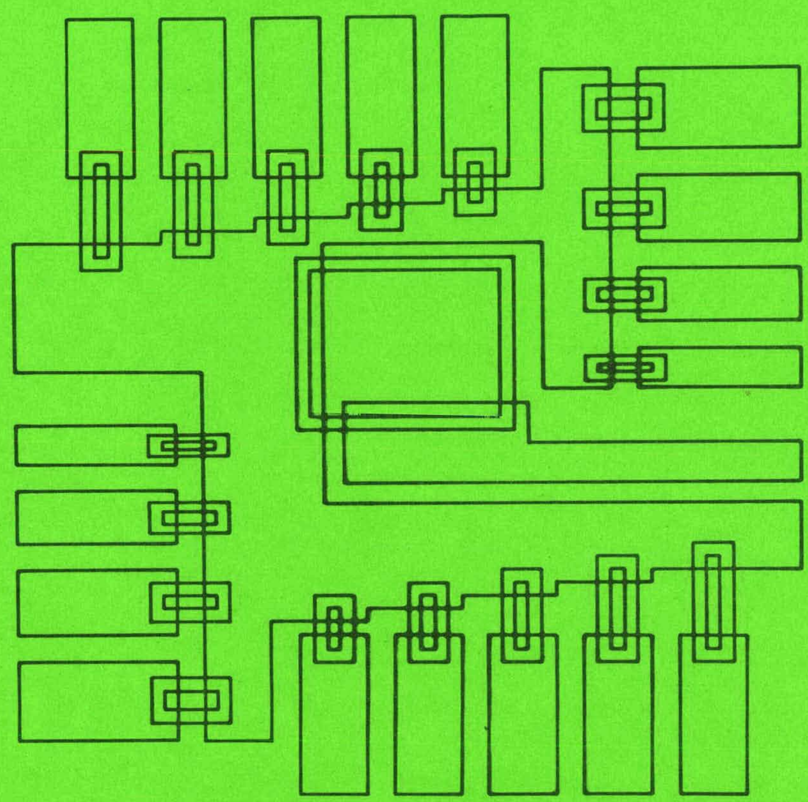
Strain Hardening Exponent for 17-4 PH Stainless Steel



BDX-613-577

An AEC Research and Development Report

Published:
October, 1971

Prepared by:
J. R. Mulkey
Materials Test Laboratory

PDO 6984735
Topical Report

Prepared for the U. S. Atomic Energy Commission Albuquerque Operations Office under Contract Number AT(29-1)-613 USAEC.

Bendix Kansas City Division

Printed in the United States of America

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy $3.00; Microfiche $0.95

Prepared for the U. S. Atomic Energy Commission
Albuquerque Operations Office Under Contract
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by:

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ABSTRACT

Strain hardening exponents were measured on three thicknesses of 17-4 PH stainless steel sheets. Based on these results, published values for strain hardening exponents were rejected and a range of 0.2 to 0.24 established at the Bendix Kansas City Division was recommended. This range is consistent with the experience of Bendix material and test engineers.

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SUMMARY

Strain hardening exponents were measured on 17-4 PH stainless steel aged one hour at 900°F. The exponents were measured at material thicknesses of 1/16, 1/8, and 1/4 inch, and the specimens were of rectangular cross section. Test results indicated the exponent to be a function of specimen thickness up to approximately 1/4 inch. The 1/4-inch specimens were sufficiently thick to relieve geometric effects. This fact was determined by comparing Bendix rectangular data with data from cylindrical specimens tested by Battelle Memorial Institute (BMI).

Bendix testing indicated the true material exponent, independent of geometric effects, to be in the range of 0.2 to 0.24. The geometric effects on the 1/16-inch-thick specimen caused the exponent to appear higher (0.45). The exponent in the 0.2 range was considerably different from published values. BMI reported an exponent of 0.05 for 17-4 PH aged at 900°F. A review of BMI test results revealed the testing procedures to be of high quality. The exponent, recomputed at Bendix using BMI data, however, was found to be about 0.24.

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DISCUSSION

SCOPE AND PURPOSE

In the manufacture of miniature parts and assemblies, the design of tooling and processing techniques has undergone several magnitudes of refinement. The advance in theory of material forming and removal requires the definition of new material parameters such as strain hardening exponents. The strain hardening exponent is a factor in predicting the energy required for formation of a chip or energy of cold drawing. This increased knowledge of material properties generates better tool designs and manufacturing techniques.

This investigation was initiated because of a lack of testing data regarding strain hardening exponents in the literature. Sufficient data has not been published to allow cross-checking sources. The strain hardening exponent, 0.05, published by two separate sources did not appear consistent with the experience of Bendix material and test engineers.

ACTIVITY

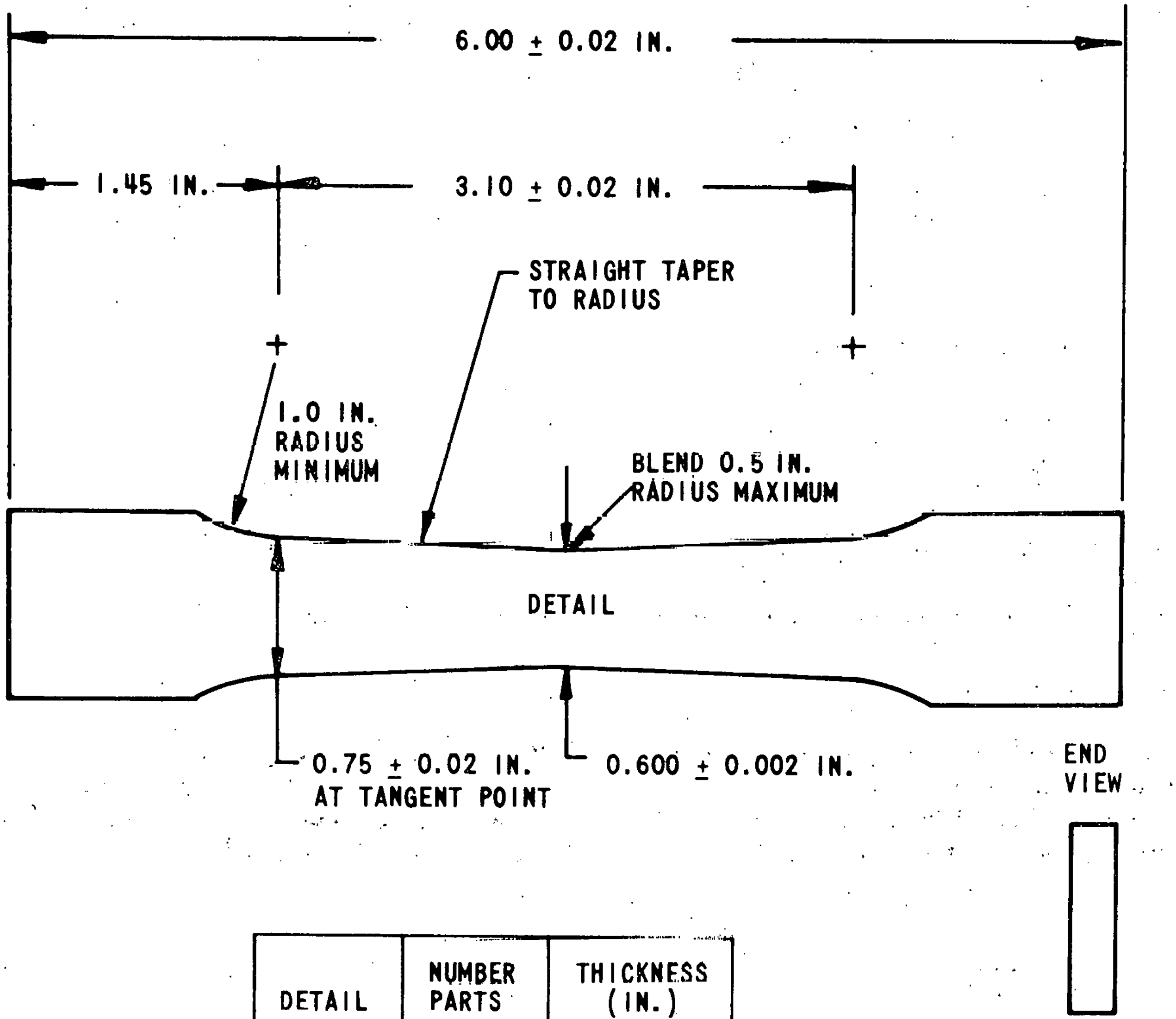
Test Procedure

Tensile tests were conducted at a crosshead speed of 0.04 inch per minute. Load, thickness, and width were recorded throughout the test to failure. The instantaneous area allowed the plotting of true stress versus true strain tensile curves. Electronic strain gage transducers were used to measure the dimensional change. The Wheatstone bridge circuit was used to compensate for temperature and to ensure accurate calibration. The dimensional change was measured with an estimated accuracy of ±0.0001 inch.

Tests were conducted on nine specimens: three in Group A, each 0.062 inch thick; three in Group B, each 0.120 inch thick; and three in Group C, each 0.240 inch thick. Data from Specimens A-3, B-3, C-1, and C-2 are presented in this report. Data from the five remaining specimens were incomplete and would require additional study. The specimen design is shown in Figure 1.

Theory

The plastic region of a structural metal is becoming more important as higher working stresses are demanded, and studies of advanced manufacturing techniques consequently require further definition of plastic flow properties. Strain hardening exponents can also be used to compare the work hardening properties of different materials.



DETAIL	NUMBER PARTS	THICKNESS (IN.)
A	3	1/16
B	3	1/8
C	3	1/4

Figure 1. Bendix Sheet Tensile Specimen (Part 707: Grind Machine Marks From Detail 3)

Equation Development

The symbols used in the equations are as follows:

σ_t = True or natural stress:

ϵ_t = True or natural strain;

L_o = Original length;

L = Instantaneous length;

A_o = Original area;

A = Instantaneous area;

M = Strain hardening exponent;

σ_o = Proportionality constant with units of psi (stress); and

P = Load.

The strain hardening exponent (M) is based on the true or natural stress versus true or natural strain curve. According to Fitzpatrick, Ludwig suggested as early as 1909 that a more profitable method of characterizing a material would be to plot the true stress as a function of the true strain where[1]

$$\epsilon_t = \int_{L_o}^{L} \frac{dL}{L} = \mathrm{Ln}\,\frac{L}{L_o}\,. \qquad (1)$$

Little was done with this suggestion until 1937 when C. W. MacGregor pointed out that, in this form, Equation 1 could not be used after necking of the bar begins because the length (L) is indeterminant.[2] Assuming the volume to be constant, he expressed true strain in terms of area in the necked-down region.

$$A_o L_o = AL,$$

$$\frac{L}{L_o} = \frac{A_o}{A}\,, \text{ and}$$

$$\epsilon_t = \mathrm{Ln}\,\frac{A_o}{A}$$

The true stress is defined as the load divided by the instantaneous area:

$$\sigma_t = \frac{P}{A}.$$

The equation for true stress versus true strain in the plastic region is written:

$$\sigma_t = \sigma_o e_t^M.$$

This is the modified Ramberg-Osgood relationship in the theory of plasticity which describes most metals very well in the plastic strain region.[3] (σ_o) is a proportionality constant which may be obtained by setting $\epsilon_t = 1.0$.[4]

$$\text{Ln } \sigma_t = M \text{ Ln } 1.0 + \text{Ln } \sigma_o$$

Ln 1.0 = 0, and

$$\sigma_o = \sigma_t \quad (\text{at } \epsilon_t = 1.0)$$

The constant (σ_o) is numerically equal to the true stress corresponding to a true strain of 1.0.

J. H. Holloman is generally credited with the concept of using the exponent (M) as a basic material parameter. Holloman presented a paper on this new concept to the American Society for Metals in 1944.[3] The total lack of information in the literature between 1944 and 1963 suggests that very little work was done during this period. G. R. Halford presented a paper in 1963 to the American Society for Metals restating the Holloman theory with little alteration.[5] Halford states: "Holloman's equation, $\sigma_t = \sigma_o \epsilon_t^M$, has become widely accepted, and when the term strain-hardening exponent is used, it is generally assumed to refer to this formula."[5] Values of (M) are normally determined by measuring the slope of a log-log plot of the true-stress and true-strain.

The first linear portion is the elastic region and the second is the plastic region. The second portion will be linear if there is no previous history of cold working as Datsko points out.[6] (M) is the slope of the logarithmic plot in the plastic zone (Figure 2).

True strain, ϵ_t equal to 1.0, is not 100 percent elongation as in the classical engineering definition of strain, but actually corresponds to an engineering strain of 271.8 percent elongation or 63.2 percent reduction in area. Since most materials will not strain 271.8 percent before failure, the value for (σ_o) must be obtained by extrapolation as shown in Figure 2.[4]

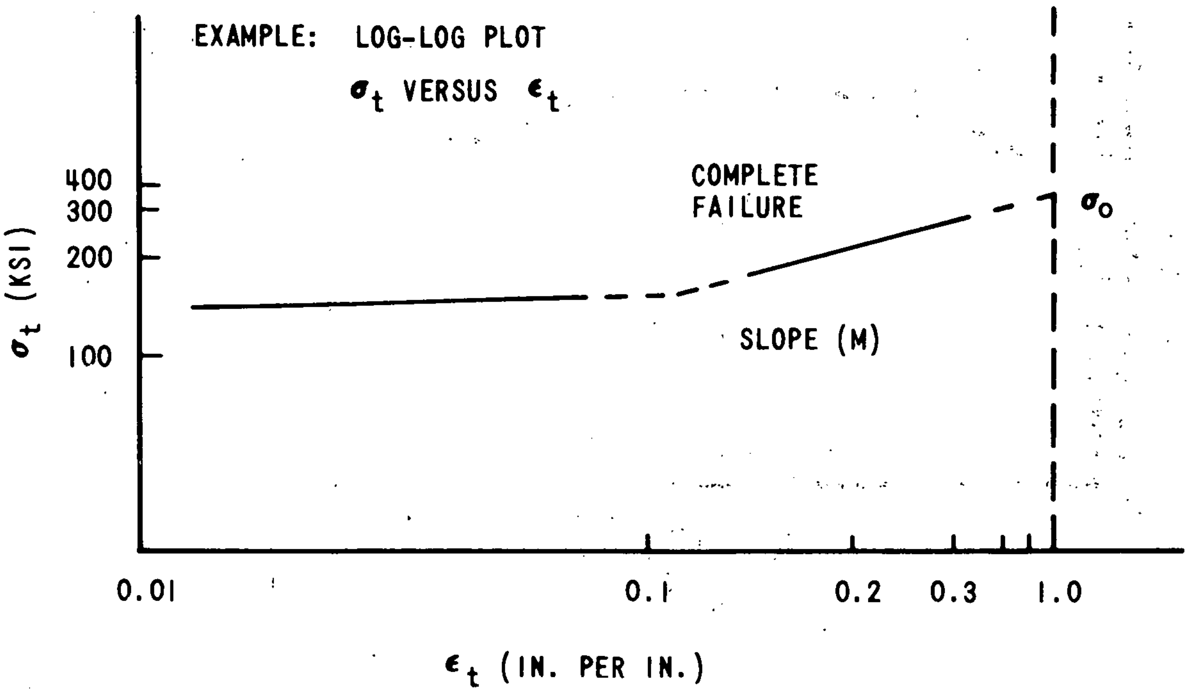


Figure 2. Example of Log Stress Versus Log Strain Plot

Having found (σ_o), the strain hardening exponent (M) may be calculated.

$$M = \frac{\text{Ln}\,\frac{\sigma_t}{\sigma_o}}{\text{Ln}\,\epsilon_t} \tag{2}$$

Relation Between (M) and (ϵ_u)[4]

An interesting relation exists between (M) and (ϵ_u). The strain corresponding to the maximum load is designated (ϵ_u). It will be shown that this quantity is numerically equal to the strain hardening exponent (M). If the load is plotted against true strain, a curve similar to the one in Figure 3 is obtained.

The load on a tensile specimen is equal to the product of the true stress and the instantaneous area.

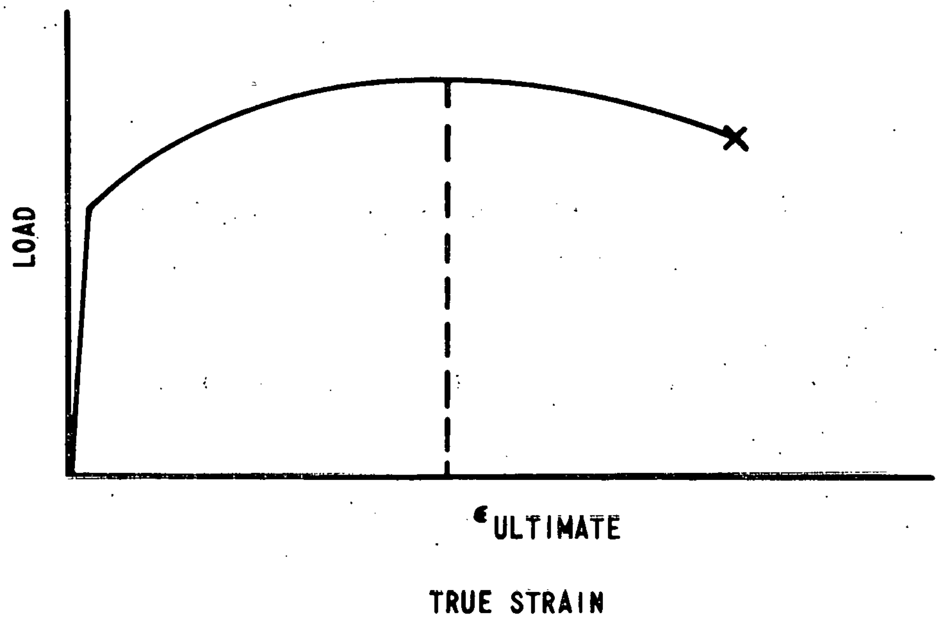


Figure 3. True Strain Versus Load

$$P = \sigma_t A$$

since

$$\sigma_t = \sigma_o \epsilon_t^M$$

$$P = \sigma_o \epsilon_t^M \times A$$

$$\epsilon = Ln \frac{A_o}{A}$$

or

$$e^{\epsilon_t} = \frac{A_o}{A}$$

$$A = \frac{A_o}{e^{\epsilon_t}}$$

therefore

$$P = \sigma_o A_o \epsilon_t^M e^{-\epsilon_t}$$

Since the slope (M) of the load versus true strain curve is zero at maximum load, another relationship can be obtained.

$$\frac{dP}{d\epsilon_t} = -\sigma_o A_o \left(\epsilon_t^M\right)\left(e^{-\epsilon_t}\right) + \sigma_o A_o \left(e^{-\epsilon_t}\right) M \left(\epsilon_t^{M-1}\right) = 0$$

cancel

$$\sigma_o A_o e^{-\epsilon_t}$$

$$\epsilon_t^M = M \epsilon_t^{M-1}$$

The strain at maximum load is designated as ϵ_u.

$$(\epsilon_u)^M = M(\epsilon_u)^{M-1}$$

$$1 = M(\epsilon_u)^{-1}$$

and

$$M = \epsilon_u$$

The value for (M) may, therefore, be found directly from the load versus true strain curve. This is interesting, but in reality few materials exhibit such a pronounced maximum load that ϵ_u may be determined accurately. (M) is usually obtained by the log-log slope method for this reason.[4]

Strain Hardening and Strain Softening

Strain hardening exponents give a quantitative indication of material hardenability. Values for (M) range from about 0.04 for martensitic high strength steels (exhibiting little strain hardening) to about 0.5 for copper and some austenitic stainless steels.[7] Table 1 from the Datsko text lists a few materials for general comparison. The published values for 17-4 PH will be challenged later in the paper.[4] High strength alloys with high reduction of area yield values of (M) which are very small.[8]

Table 1. Materials and Values From Datsko Text*

TABLE 1-1. Some Typical Values of σ_o, m and ϵ_f
(All Values Are for Longitudinal Specimens Except as Noted)[1]

Material	*Treatment*	σ_o (psi)	m	ϵ_f
1100 aluminum	900°F 1 hr ann	26,000	0.20	2.30
2024 aluminum	T-4	100,000	0.15	0.13
Copper	1000°F 1 hr ann	78,000	0.55	1.19
Copper	1250°F 1 hr ann	72,000	0.50	1.21
Copper	1500°F 1 hr ann	68,000	0.48	1.26
70-30 leaded brass	1250°F 1 hr ann	105,000	0.50	1.10
70-30 brass	1000°F 1 hr ann	110,000	0.56	1.50
70-30 brass	1200°F 1 hr ann	105,000	0.52	1.55
1002 steel	Annealed	80,000	0.32	1.20
1018 steel	Annealed	90,000	0.25	1.05
1020 steel	Hot rolled	115,000	0.22	0.90
1212 steel	Hot rolled	110,000	0.24	0.85
1045 steel	Hot rolled	140,000	0.14	0.58
1144 steel	Annealed	144,000	0.14	0.49
1144 steel[2]	Annealed	144,000	0.14	0.05
4340 steel	Hot rolled	210,000	0.09	0.45
52100 steel	Spher. ann	165,000	0.18	0.58
52100 steel	1500°F ann	210,000	0.07	0.40
18-8 stainless	1600°F 1 hr ann	210,000	0.51	1.08
18-8 stainless	1800°F 1 hr ann	230,000	0.53	1.38
304 stainless	Annealed	185,000	0.45	1.67
303 stainless	Annealed	205,000	0.51	1.16
202 stainless	1900°F 1 hr ann	195,000	0.30	1.0
17-4 PH stainless	1100°F age	260,000	0.01	0.65
17-4 PH stainless	Annealed	173,000	0.05	1.20
Molybdenum	Ext. ann	105,000	0.13	0.38
Cobalt base alloy[3]	Solution H.T.	300,000	0.50	0.51
Cobalt base alloy[2,3]	Solution H.T.	300,000	0.50	0.40
Vanadium	Annealed	112,000	0.35	0.90

[1] These are values obtained from only one or two different heats. The values will vary from heat to heat because of differences in composition and annealing temperature. ϵ_f may vary by 100%.

[2] Tensile specimen machined from 4 in. diameter bar transverse to rolling direction.

[3] 20 Cr, 15 W, 10 Ni, 3 Fe, 0.1C, Balance Cobalt.

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*Reprinted from Material Properties and Manufacturing Process by Joseph Datsko. New York: John Wiley & Sons, Inc., p 21.

The direction in which the slope (k) changes, on the true stress versus true strain tensile curve, yields useful information. The material is considered strain hardening when (k) is increasing and strain softening when (k) is decreasing. Both the 18- and 12-percent-nickel maraging steels exhibit strain softening. The austenitic stainless steels exhibit strain hardening.[8]

Test Results

The values for (M) are calculated by:

$$M = \frac{\mathrm{Ln}\,\frac{\sigma_t}{\sigma_o}}{\mathrm{Ln}\,\epsilon_t} .$$

Bendix Results

Material: 17-4 PH stainless steel aged 1 hour at 900°F.

Specimen: sheet specimen as shown in Figure 1.

Test Speed: 0.04 inch per minute.

Specimen C-1, (0.239 thick) as shown in Figures A-1 and A-5.

σ_o = 328,000

σ_t = 280,000

ϵ_t = 0.493

M = 0.224

Specimen C-2, (0.239 thick) as shown in Figures A-1 and A-4.

σ_o = 310,000

σ_t = 275,600

ϵ_t = 0.502

M = 0.170

Specimen B-3, (0.120 thick) as shown in Figures A-2 and A-5.

σ_o = 345,000

σ_t = 276,900

ϵ_t = 0.30

M = 0.183

Specimen A-3, (0.060 thick) as shown in Figure A-3.

σ_o = 266,000

σ_t = 237,500

ϵ_t = 0.11

M = 0.457

Battelle Memorial Institute Results[9]

Testing was performed by J. G. Dunleavy and J. W. Spretnak. The value of (σ_o) is obtained by extrapolating the log-log plot of stress and strain in the plastic region. The scatter in the data forms a narrow band rather than a line. Because of the data spread, any line drawn through the data plot points would be arbitrary. Considering this problem, the highest and lowest values which likely would be chosen are presented.

Material: 17-4 PH stainless steel aged 1 hour at 900°F.

Specimen: 1/4 inch diameter, cylindrical.

Test Speed: 0.01 inch per minute

The BMI published value for (M) is 0.068.

Calculations using BMI data given in Figure A-7 yield:

σ_o = 330,000 psi, MAX

σ_t = 275,000 psi

ϵ_t = 0.500

M = 0.263

σ_o = 320,000 psi, MIN.

σ_t = 275,000 psi

ϵ_t = 0.500

M = 0.218

Discussion of Results

The true stress versus true strain plots are shown in Figures A-1 and A-2. The two thicker specimens (Figure A-1) showed very similar curves until the later portion of the curve. Specimen C-2 failed at a lower load but the strain was nearly the same. This variation causes a significant difference in the strain hardening exponent. Specimen C-1 continues to increase in true stress to failure. C-1 correlates very well with the data for a 1/4-inch-diameter specimen tested by BMI (Figures A-6 and A-7).

The BMI exponent is 0.218 to 0.263 (calculated by author using BMI data).

The Bendix specimen C-1 exponent is 0.224, and the specimen C-2 exponent is 0.170.

The ultimate failure true stress was also very close. For BMI (σ_u) is 305,000 psi, and for Bendix, (σ_u) is 300,000 psi.

Specimen A-3 (0.060 inch thick) showed a higher value for (M) than any other test, M = 0.457. The ultimate true strain for A-3 can only be estimated (ϵ_t = 0.30 ±0.1) because of equipment malfunction (Figure 6). Specimen B-3 in Figure A-2 (0.120 inch thick) failed at a true stress 296,000 psi, but the ultimate true strain was 0.40 compared to 0.65 for the thicker specimens. This decreased ductility must be attributed to specimen geometry and processing.

BMI published a value of 0.068 for (M) using the data presented in Figures A-6 and A-7.[9] The value for (M) published by Datsko for 17-4 PH annealed is 0.05. Bendix findings differ significantly from these figures. Typical log-log curves are shown in Figure A-8 (reproduced from Datsko).[4] These plots are made in the same manner as those from BMI and Bendix data (Figures A-5 and A-7). (M) is the slope of the log stress-log strain curve in the plastic region. Bendix and BMI plots are very similar. Bendix calculation on BMI data yields over 0.2 for (M) rather than 0.05. The difference is apparently not in the definition of (M). The equation used by Bendix may be applied to materials shown in Figure A-8 from the Datsko test to duplicate Datsko's numbers.

CONCLUSIONS

Specimen C-1 compared closely to the results on round specimens tested by BMI. The rectangular cross-section Bendix specimens were expected to yield a lower total strain because of reinforcement from edges. This edge effect must be considered negligible on the 0.239-inch-thick-specimens. The thinner specimens (0.120 inch thick) exhibited roughly half the strain of the thicker ones. The value for (M) tends to increase as the specimen is made thinner. This is caused by a decrease in apparent ductility because of reinforcement from the edges.

The cylindrical specimen is recognized as the best specimen configuration for determining the true material parameter (M). There are no edge constraints or stress concentrations to affect results. If the material is ductile enough to relieve the edge constraint by plastic deformation, the rectangular specimen yields equally valid results. This was the case in the thickest specimens tested by the Bendix Laboratory.

As a result of the investigations reported here, it must also be concluded that the true value of (M) for 17-4 PH stainless steel should be approximately 0.170 to 0.263.

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[1] J. M. Fitzpatrick, "Strain Hardening Characteristics of Four New Steels and a Titanium Alloy," JMLSA, Volume 3, Number 4 (December, 1968), pp. 977-982.

[2] C. W. MacGregor, American Institute of Mining and Metallurgical Engineers: Transactions, Volume 124 (1937), p. 208.

[3] "The Effect of Heat Treatment and Carbon Content on the Work Hardening Characteristics of Several Steels," American Society for Metals: Transactions, Volume 32 (1944), pp. 123-133.

[4] Joseph Datsko, Material Properties and Manufacturing Processes. New York: John Wiley, pp. 1-40.

[5] "The Strain Hardening Exponent: A New Interpretation and Definition," American Society for Metals, Volume 56 (1963), pp. 787-788.

[6] Datsko, pp. 14-16.

[7] T. Baumeister and L. S. Marks, Standard Handbook for Mechanical Engineers. New York: McGraw-Hill, pp. 5-73.

[8] E. A. Steigewald and G. L. Hanna, "Influence of Work Hardening Exponent on the Fracture Toughness of High Strength Materials," AIME: Transactions of the Metallurgical Society, Volume 242 (February, 1968), pp. 320-328.

[9] J. G. Dunleavy and J. W. Spretnak, "A Definitive Study of the Characteristic of Toughness of Engineering Materials," Air Force Military Literature: AFML-TR-68-353, (September, 1968).

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Appendix

GRAPHS

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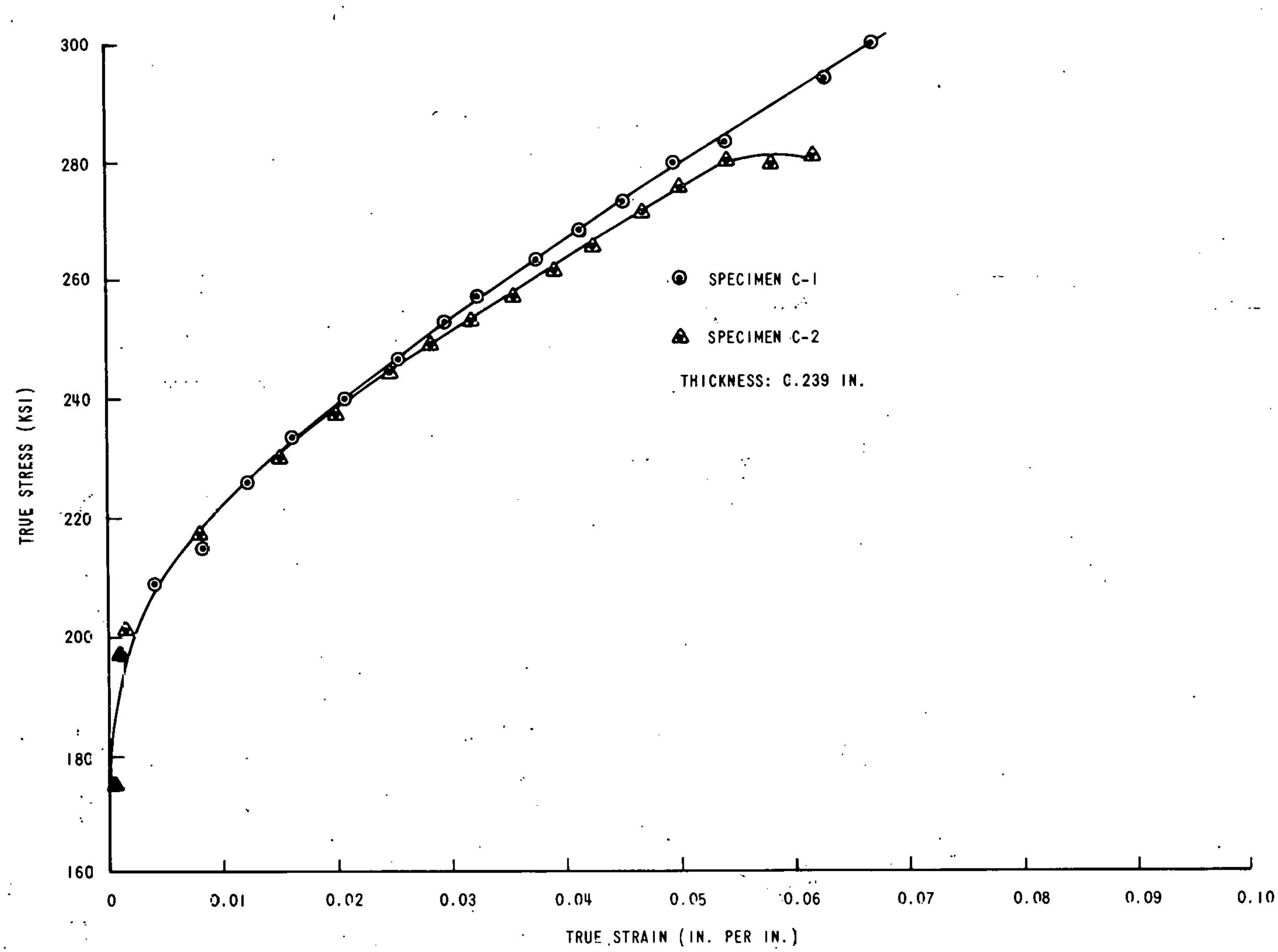

Figure A-1. Bendix Specimens C-1 and C-2: True Stress Versus True Strain (17-4 PH Steel Aged 1 Hour at 900°F)

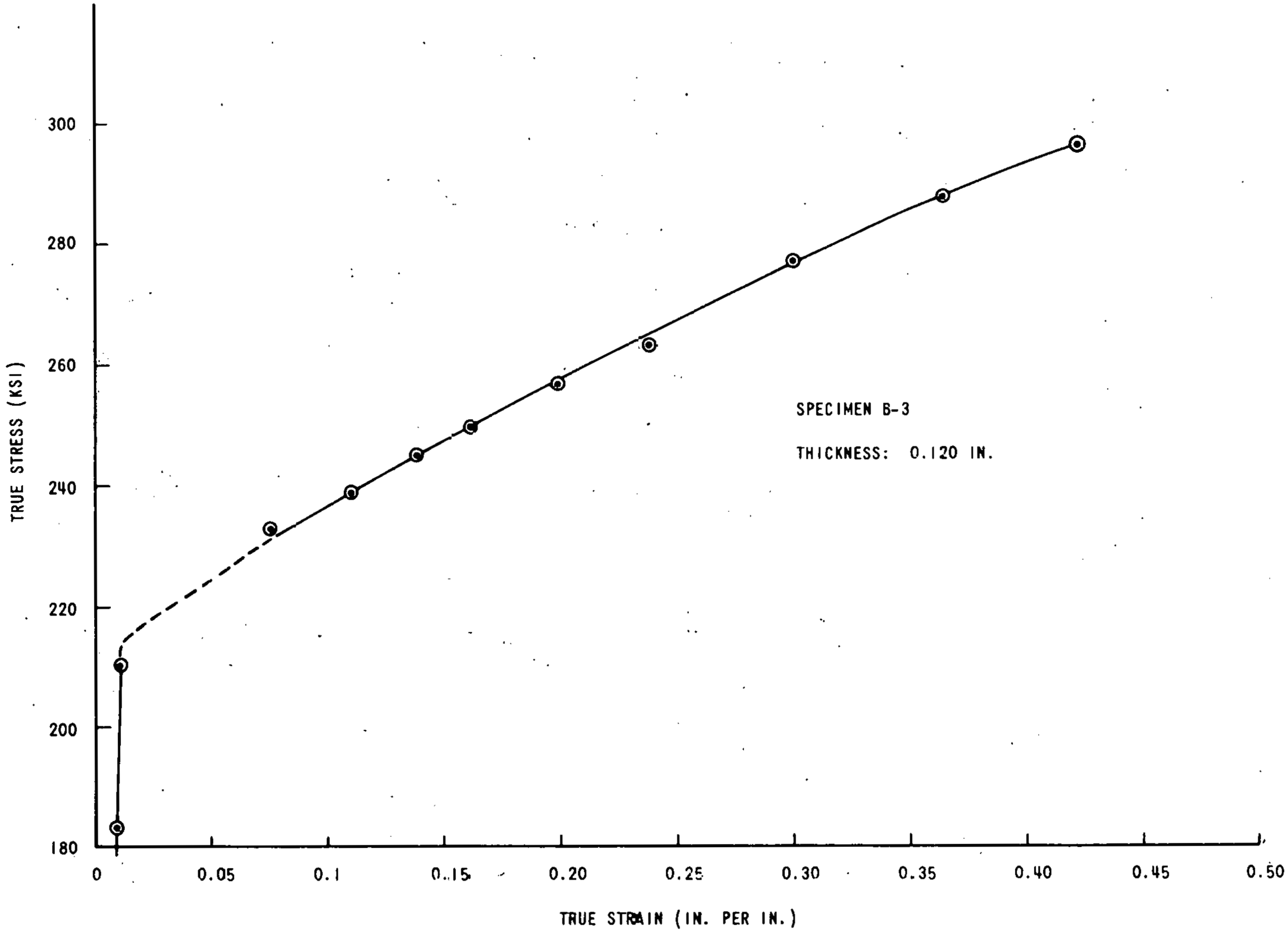

Figure A-2. Bendix Specimen B-3: True Stress Versus True Strain (17-4 PH Steel Aged 1 Hour at 900°F)

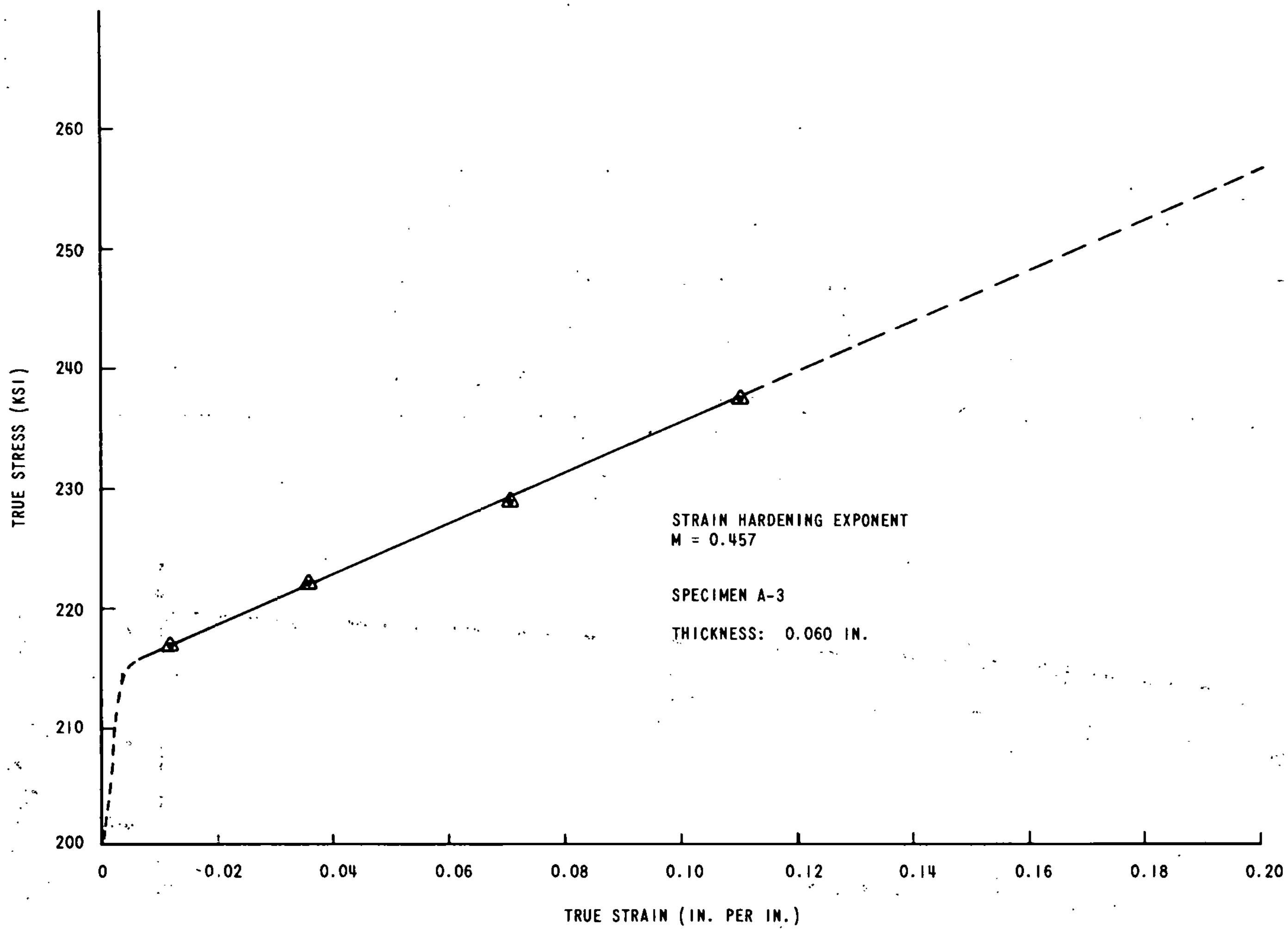

Figure A-3. Bendix Specimen A-3: True Stress Versus True Strain (AISI 17-4 PH Steel Aged 1 Hour at 900°F: No Specimen Failure, Equipment Malfunction)

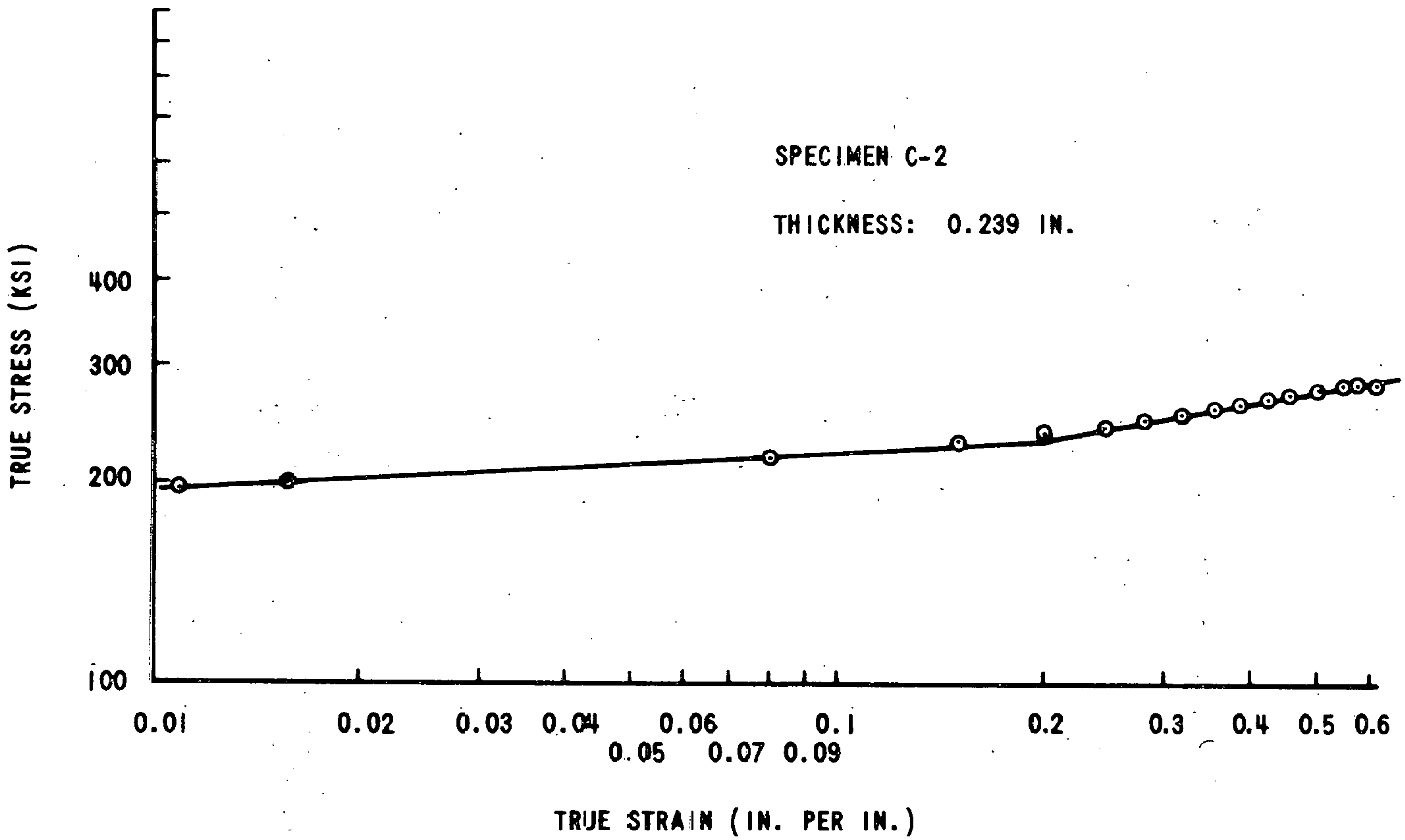

Figure A-4. Bendix Specimen C-2: Log Stress Versus Log Strain (17-4 PH Steel Aged 1 Hour at 900°F)

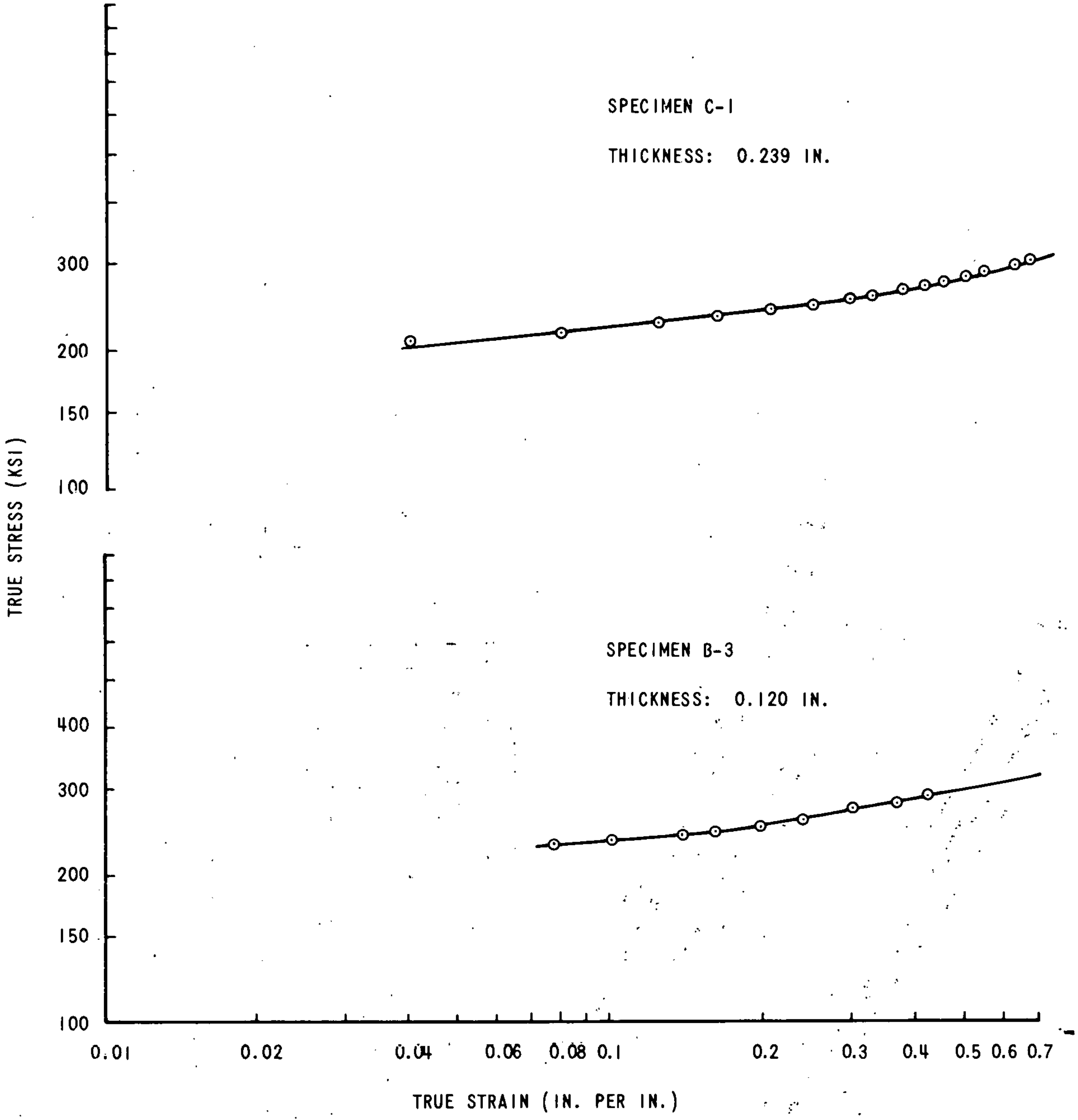

Figure A-5. Bendix Specimens C-1 and B-3: Log Stress Versus Log Strain (17-4 PH Steel Aged 1 Hour at 900°F)

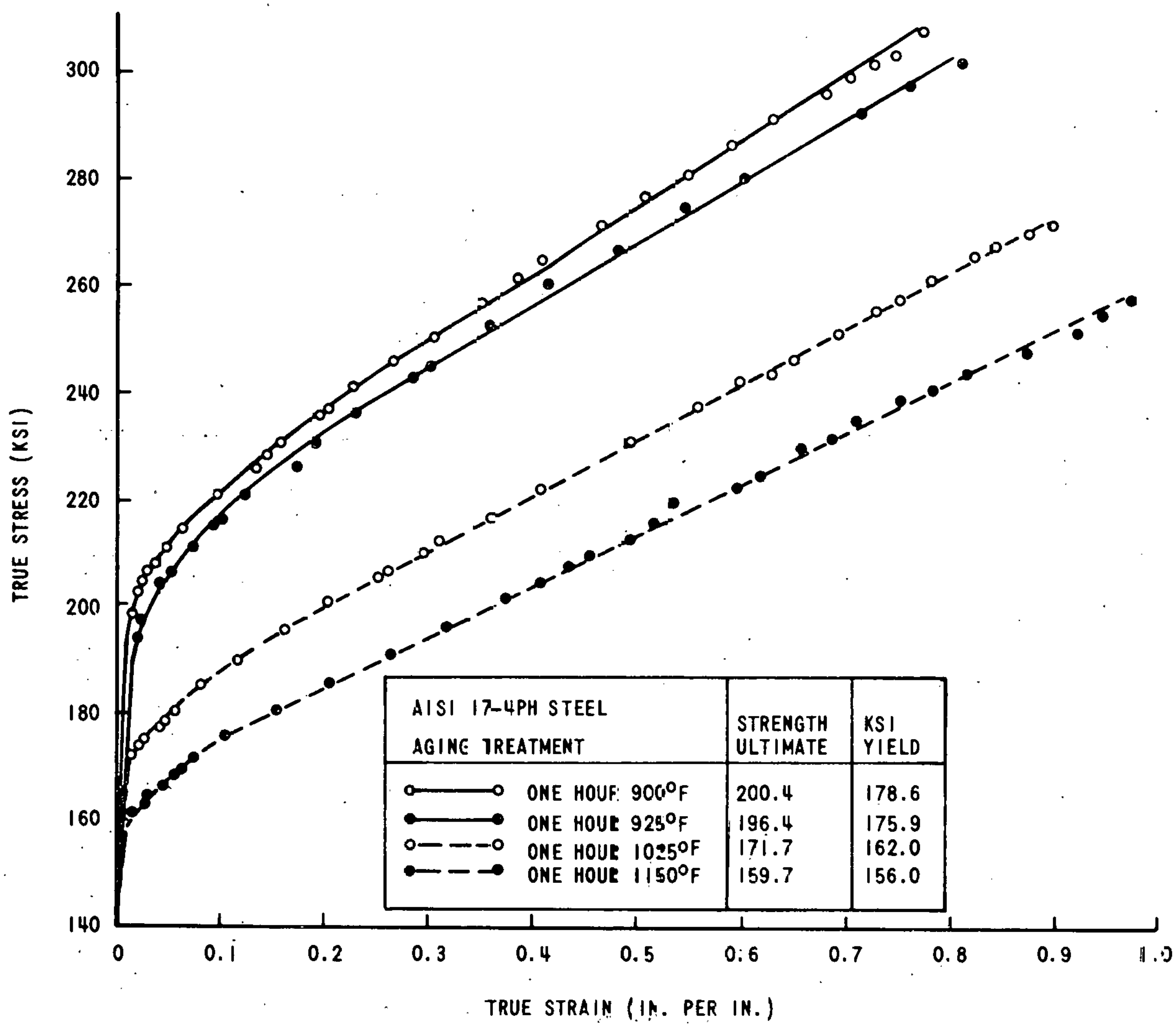

Figure A-6. BMI Results: True Stress Versus True Strain for AISI 17-4 PH Steel at Various Aging Treatments

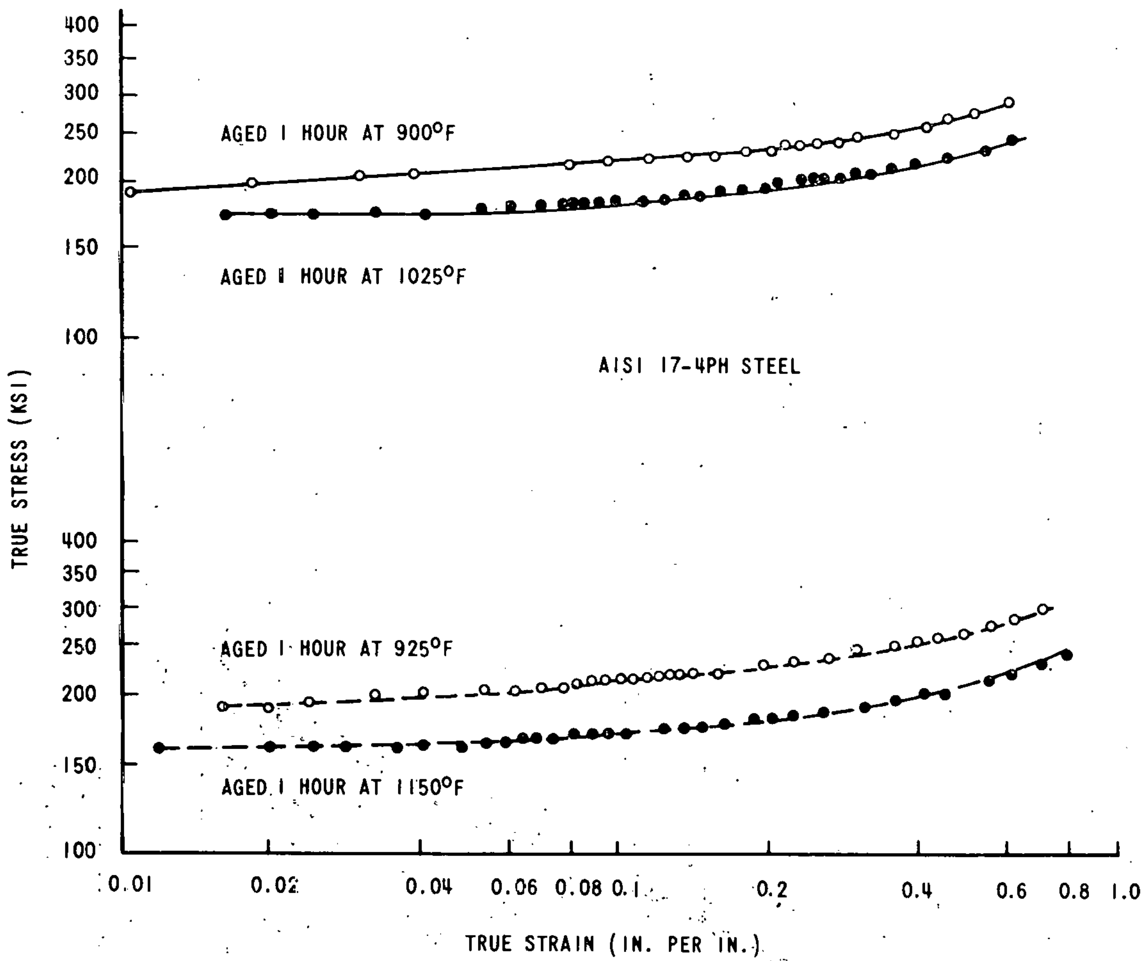

Figure A-7. BMI Results: True Stress Versus True Strain for AISI 17-4 PH Steel

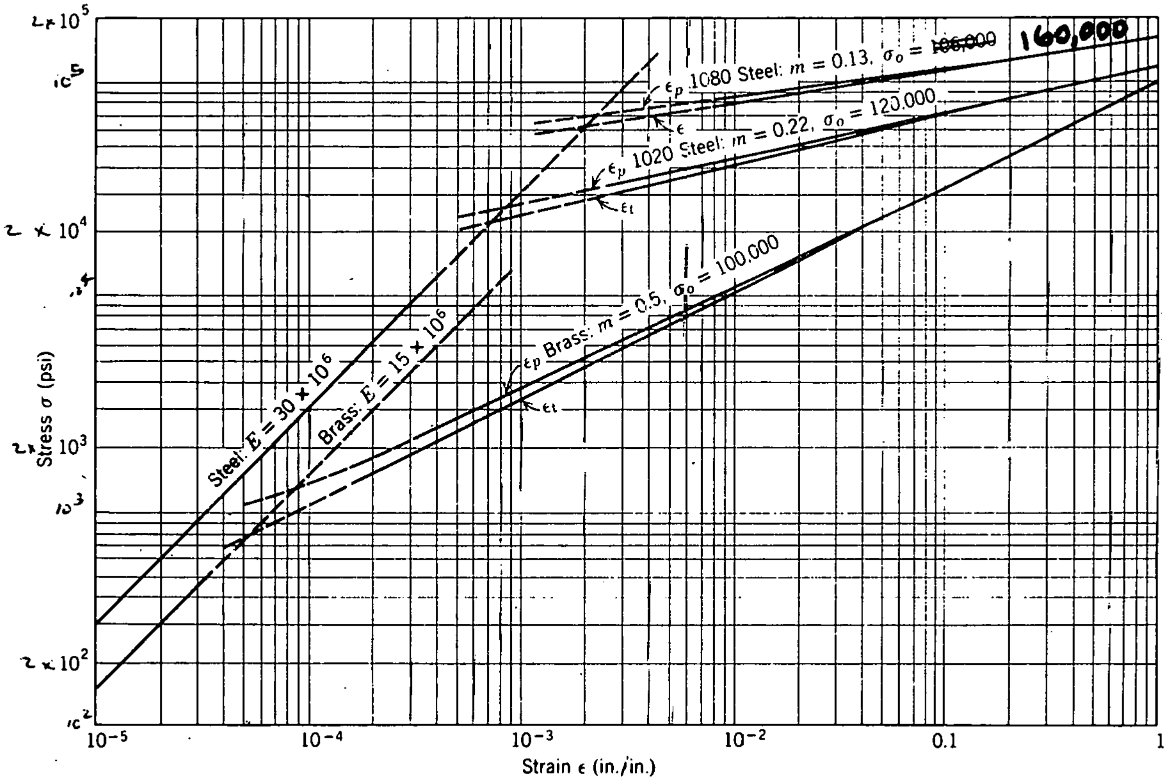

Figure 1-5. Comparison of strain-hardening curves on the basis of both the plastic strain ϵ_p only and the total (elastic plus plastic) strain ϵ_t.

Figure A-8. Datsko Comparison of Strain Hardening Curves*

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*Reprinted from Material Properties and Manufacturing Processes by Joseph Datsko. New York: John Wiley & Sons, Inc., p 17.