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BASIC PARAMETERS OF METAL BEHAVIOUR UNDER HIGH RATE FORMING

Fourth Interim Report to

U. S. ARMY MATERIALS RESEARCH AGENCY

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BASIC PARAMETERS OF METAL BEHAVIOR UNDER HIGH RATE FORMING

by

P. C. Johnson
B. A. Stein
R. S. Davis

Materials Description and High Strain Rate Stress-Strain Data

Fourth Interim Report to
U. S. Army Materials Research Agency
Watertown, Massachusetts

January 1962 - March 1962

Report No. WAL TR 111.2/20-3

OMS Code 5010.11.8430051

D/A Project 5B93-32-004

Contract No. DA-19-020-ORD-5239
Boston Procurement District, U. S. Army

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Technical Report No. WAL TR 111.2/20-3

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ABSTRACT

The free-expansion of a thin ring has been used to measure the dynamic flow curves of five materials at strain rates of the order of 5000 per second. The technique involves calculation of the second derivative of the strain-time record obtained by high-speed photography. This report contains the strain-time records and resultant flow curve equations for these five materials. This report also includes a summary of the treatment and properties at low strain rates of the ring materials used in this work and in the dynamic uniform elongation to failure work described in the Second Interim Report (WAL TR 111.2/20-1).

TABLE OF CONTENTS

	Page
List of Tables	vii
List of Figures	ix
I. INTRODUCTION	1
II. MATERIALS USED IN THE RING EXPANSION PROGRAMS	2
A. MATERIALS	2
B. TENSILE PROPERTIES	3
III. HIGH STRAIN RATE STRESS-STRAIN DATA	16

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LIST OF TABLES

Table No.		Page
I	Sources of Material	4
II	Heat Treatment	5
III	Material Hardnesses - Vickers Pyramid Number	6
IV	Mechanical Properties	15
V	Ring Diameter - Time Data - 99.99% Aluminum	17
VI	Ring Diameter - Time Data - 7075-T6 Aluminum	19
VII	Ring Diameter - Time Data - Titanium - 6 Aluminum - 4 Vanadium	21
VIII	Ring Diameter - Time Data - 304 Stainless Steel	22
IX	Ring Diameter - Time Data - Armco Iron	24
X	High Strain Rate Results	26

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LIST OF FIGURES

Figure No.		Page
1	Low Strain Rate Tensile Test Curve - 99.99% Aluminum	7
2	Low Strain Rate Tensile Test Curve - 7075-T6 Aluminum	8
3	Low Strain Rate Tensile Test Curve - 304 Stainless Steel	9
4	Low Strain Rate Tensile Test Curve - Armco Iron	10
5	Low Strain Rate Tensile Test Curve - Titanium - 6 Aluminum - 4 Vanadium	11
6	Low Strain Rate Tensile Test Curve - 1015 Steel	12
7	Low Strain Rate Tensile Test Curve - Annealed 4340 Steel	13
8	Low Strain Rate Tensile Test Curve - Hardened 4340 Steel	14

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I. INTRODUCTION

The behavior of materials in high energy rate forming operations is determined by two distinct factors. The first of these involves the deformation mechanics of the piece being formed; that is, it has to do with the propagation and interaction of the plastic strain waves by which deformation occurs. The second involves only the effect of rate of strain on the deformation of the material (in the microscopic sense) and the resultant changes in stress levels and ductility in the material.

The First Yearly Progress Report (WAL TR 111.2/20) describes a technique for measuring the high strain rate mechanical properties of materials under conditions where the first of these factors, the deformation mechanics, is greatly simplified. The technique involves the observation of a freely expanding ring of the material which has been given an initial radial velocity outward by an explosive-generated shock wave. High-speed photographic observation of the ring leads to a measurement of the strain in the ring as a function of time. The second derivative of this relation is directly proportional to the stress in the ring at any instant in time. (See WAL TR 111.2/20.)

The ring experiment represents a deformation system in which the stress in the ring is everywhere uniform and uniaxial. It thus provides a measure of the mechanical behavior of materials at high rates of strain in the absence of plastic waves.

We have used this technique to measure the high strain rate stress-strain relation for five materials. Included in this report is a detailed description of the materials used in this study. We have also included here the raw diameter-time data which were obtained from the photographic records in these tests, and the high strain rate stress-strain relations which have been calculated from these data. The details of the experimental technique and interpretation and discussion of these results will form the basis of a later report.

The Second Interim Report (WAL TR 111.2/20-1) for this program deals with the use of this ring technique to measure the uniform elongation to failure of a number of materials at high rates of strain. The ring represents a system which is deforming under a homogeneous, uniaxial stress system. By expanding the rings to failure with a grid on them, it is possible to measure the elongation in regions away from necks and failures. This measurement represents the usable ductility of a material at these strain rates under these loading conditions. The results of this program are given in detail in the Second Interim Report (WAL TR 111.2/20-1). This report contains a more detailed description of the properties of the materials that were used in this program.

II. MATERIALS USED IN THE RING EXPANSION PROGRAMS

Dynamic stress-strain measurements in the second series of experiments were made on five materials: 99.99% aluminum, 7075-T6 aluminum, Armco iron, 304 stainless steel, and titanium - 6 aluminum - 4 vanadium. The uniform elongation to failure tests were reported in the Second Interim Report (WAL TR 111.2/20-1) for seven materials: 7075-T6 aluminum, titanium - 6 aluminum - 4 vanadium, 304 stainless steel, 1015 steel, Armco iron, hardened and tempered 4340 steel, and annealed 4340 steel. There was a total of eight different materials used. Those which were used in both programs were used in identical conditions, so the properties given in this section for these materials apply to them for both the stress-strain work and for the uniform elongation to failure program.

A. MATERIALS

The sources of the rings and tensile specimens used are given in Table I. The rings were taken from transverse sections of bars or tubes. In general, it was not possible to obtain tensile specimens for the low strain rate comparisons whose axes lay in the transverse section. The source of the tensile specimens is therefore also indicated in Table I. In some cases, the tensile specimens were not taken from the same piece of stock. These cases are also indicated in Table I. Table II lists the treatments given the specimens after fabrication. The use of standard tensile specimens taken in directions other than that of the rings was necessitated by the lack of a method for expanding rings to failure at low rates of strain while measuring stress and strain values. The use of tensile specimens from directions other than the ring directions introduces the problem of material anisotropy. In order to measure differences due to anisotropy, hardness measurements were taken in the direction of major strain for the rings and tensile specimens before deformation. These hardnesses are given in Table III. They are the average of four readings for each specimen. Although these data are not complete, they do provide some indications as to the value of the tensile specimens for providing the low strain rate comparison data. The only two materials for which there are significant hardness differences between the ring and tensile specimens in the direction of major strain are the Titanium - 6 aluminum - 4 vanadium and the hardened 4340 steel. In the case of the high strain rate stress-strain measurements on the Ti-6Al-4V alloy, the increased stress level on rings at high strain rates cannot be a result of this anisotropy, since the tensile hardness number is the higher of the two. The hardness difference is in the wrong direction to account for a part of the high strain rate stress increase for this material

The hardness differences for both materials could possibly explain the increased ductility for the rings of both materials. The hardness differences are in the right direction. However, the magnitudes of the expected ductility changes due to these hardness differences are much lower than the differences which we have observed and ascribed to the strain rate effect. For example, the hardness difference for the 4340 steel would be expected to increase the total elongation to failure from 13% for the harder material to 13.5% for the softer material at low strain rates.[1]

In fact, we observed a change in the uniform elongation from 2% for the tensile specimen to 9% for the ring. This difference must be almost completely ascribed to the change in strain rate.

B. TENSILE PROPERTIES

The tensile properties at low strain rates were carried out on specimens having 3/8-inch diameter threaded ends and a 0.125-inch square cross section over a 1-1/2-inch gauge length. The specimens were approximately 3 inches in over-all length. (See Figure 4, Second Interim Report, WAL 111.2/20-1) They were pulled in an Instron machine at strain rates of the order of 10^{-3} per second. Uniform and total elongation measurements were made on the specimen itself by means of a photo-deposited grid. The strain axis on the stress-strain curves was adjusted for the measured total elongation

The tensile stress-strain curves for the eight materials are given in Figures 1 - 8. In addition, Table IV lists the values of the yield and tensile strengths, and the uniform and total elongations.

---

1. Metal Data, Samuel L. Hoyt, Reinhold Publishing Corporation (New York, 1952) p. 123.

TABLE I

SOURCES OF MATERIAL

MATERIAL	SOURCE OF RING SPECIMENS	SOURCE OF TENSILE SPECIMENS
99.99 Aluminum	Transverse - bar	Longitudinal - bar
7075-T6 Aluminum	Transverse - bar	Longitudinal - bar
304 Stainless Steel	Transverse - Seamless tube	Longitudinal - from 1/2 diameter bar
Armco Iron	Transverse - from 2-1/4 inch diameter bar	Longitudinal - from 1/2 diameter bar
Titanium 6 Aluminum 4 Vanadium	Transverse - bar	Transverse - bar
1015 Steel	Transverse - Seamless tube	Plate
4340 Steel	Transverse - bar	Longitudinal - bar

TABLE II

HEAT TREATMENT

MATERIAL	TREATMENT
99.99 Aluminum	Forged from high purity Al ingot. Annealed at 500°C for 20 minutes.
7075-T6	Used as received in the T6 condition.
304 Stainless Steel	Annealed at 1925°F, 1/2 hour; water quenched.
Armco Iron	Annealed at 1700°F, 1/2 hour; furnace-cooled.
Ti-6Al-4V	Used as received from Watertown Arsenal (Solution treated, aged at 1100°F).
1015 Steel	Annealed at 1600°F, 1/2 hour; furnace-cooled.
4340 Steel (annealed)	Annealed at 1350°F, 1/2 hour; furnace-cooled.
4340 Steel (hardened)	Austenitized at 1600°F, oil quenched; tempered at 800°F, 1 hour.

TABLE III

MATERIAL HARDNESSES - VICKERS PYRAMID NUMBER

Taken on ring and tensile specimen cross-section surfaces

MATERIAL	RING	TENSILE
99.99 Aluminum	---	---
7075-T6 Aluminum	187	205
304 Stainless Steel	282	271
Armco Iron	---	---
Ti-6Al-4V	383	415
1015 Steel	124	133
4340 (A)	277	275
4340 (H)	463	494

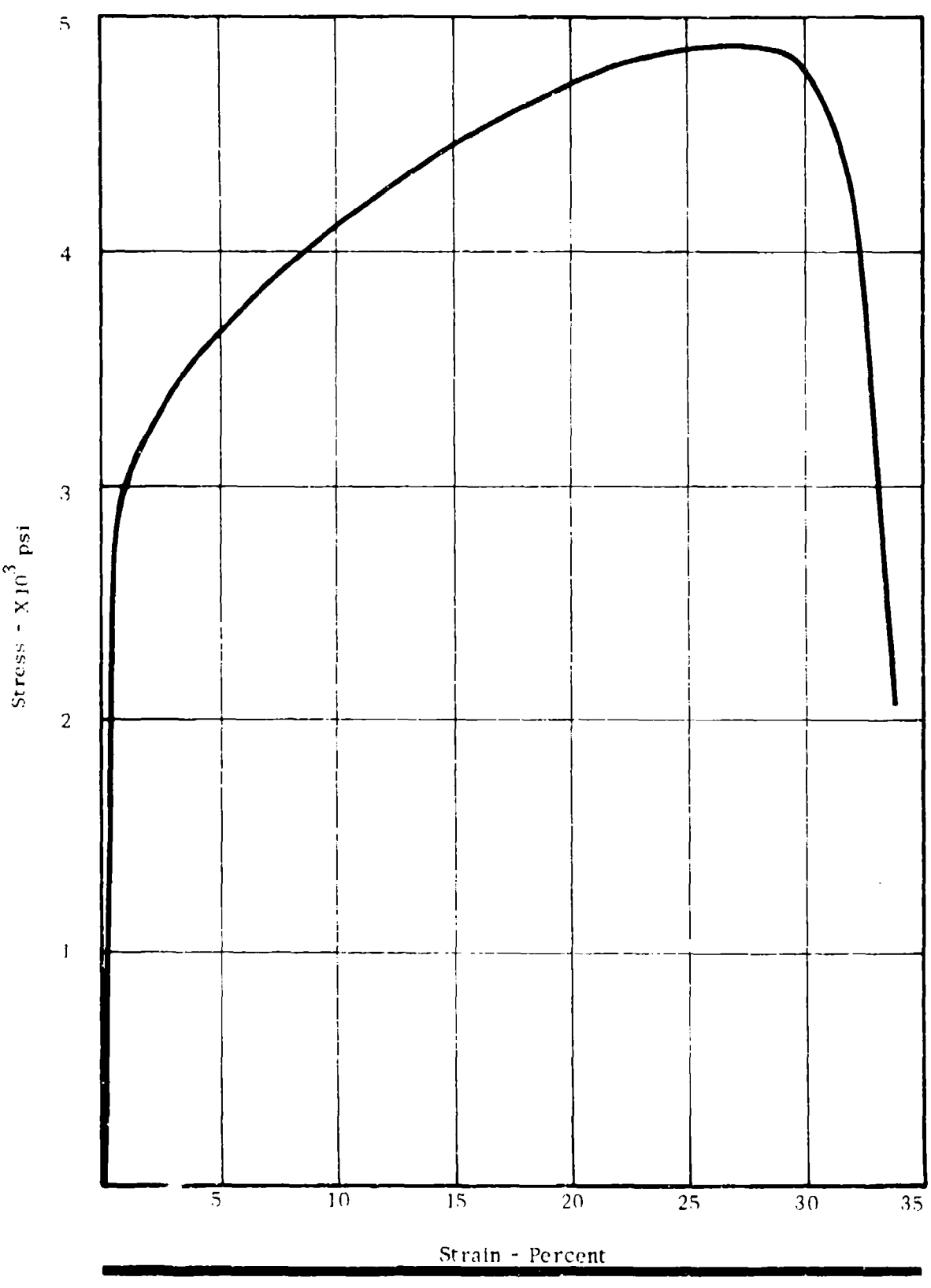

FIGURE 1 LOW STRAIN RATE TENSILE TEST CURVE
99.99% ALUMINUM

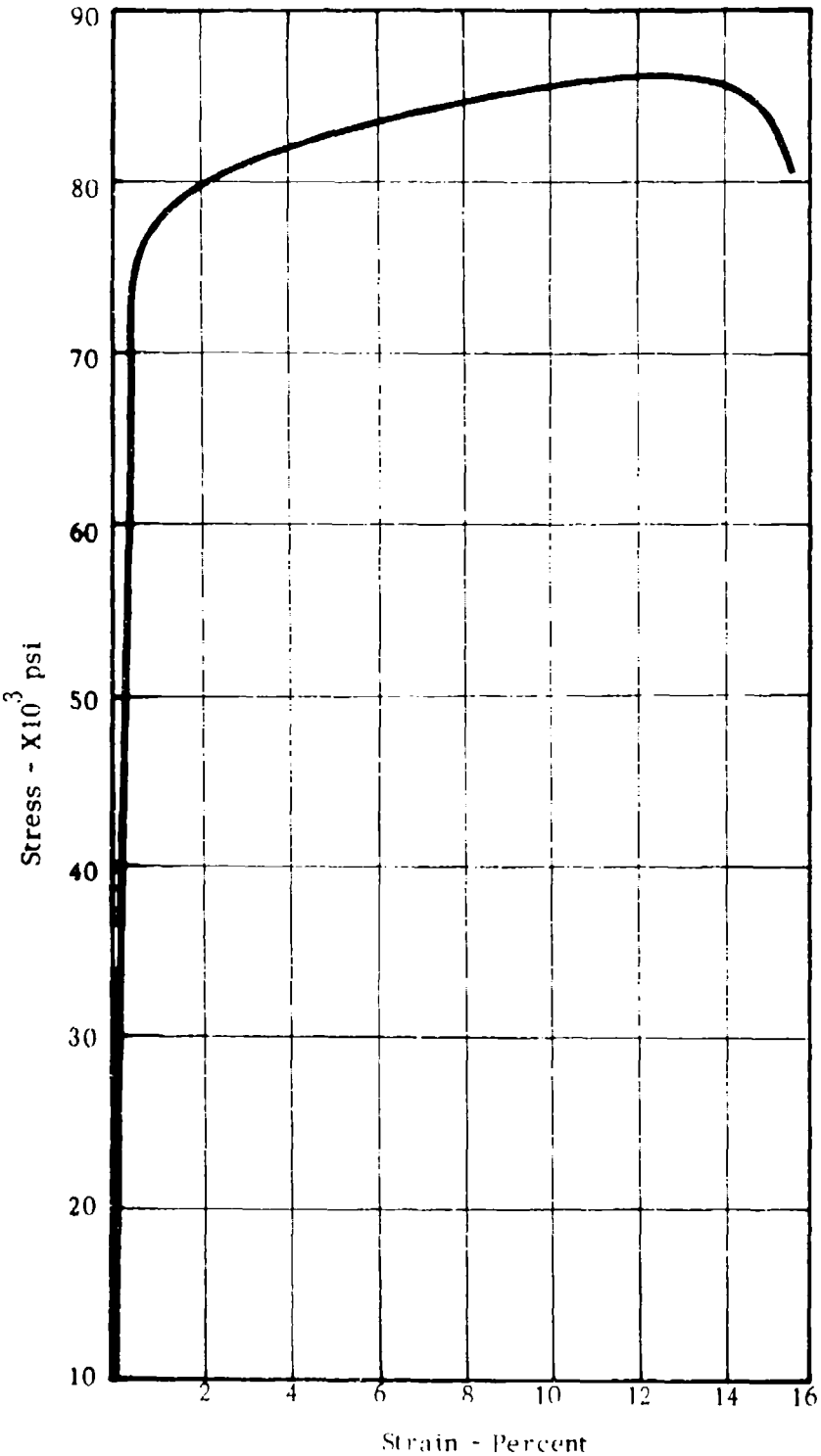

FIGURE 2 LOW STRAIN RATE TENSILE TEST CURVE 7075-T6 ALUMINUM

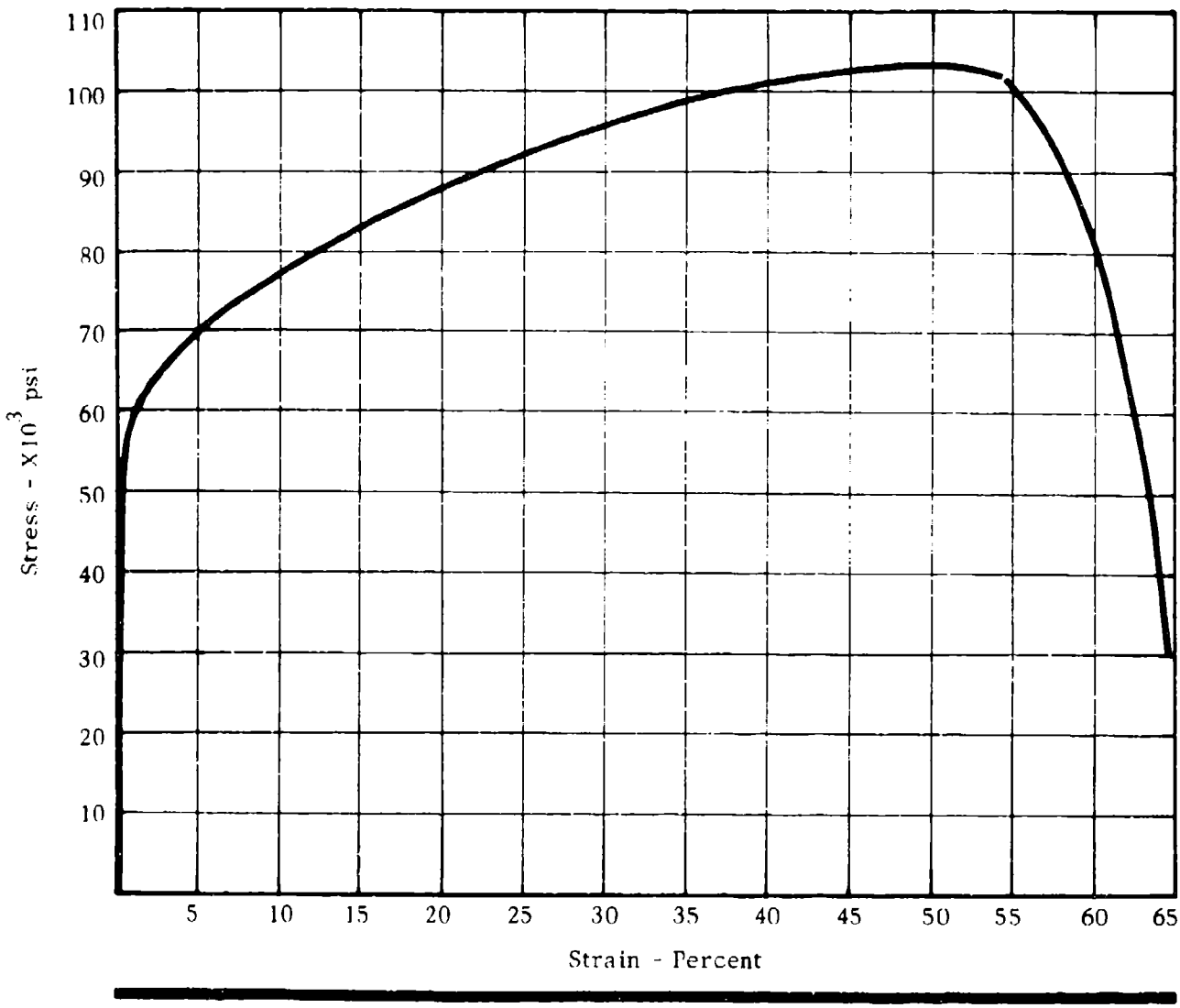

FIGURE 3 LOW STRAIN RATE TENSILE TEST CURVE
304 STAINLESS STEEL

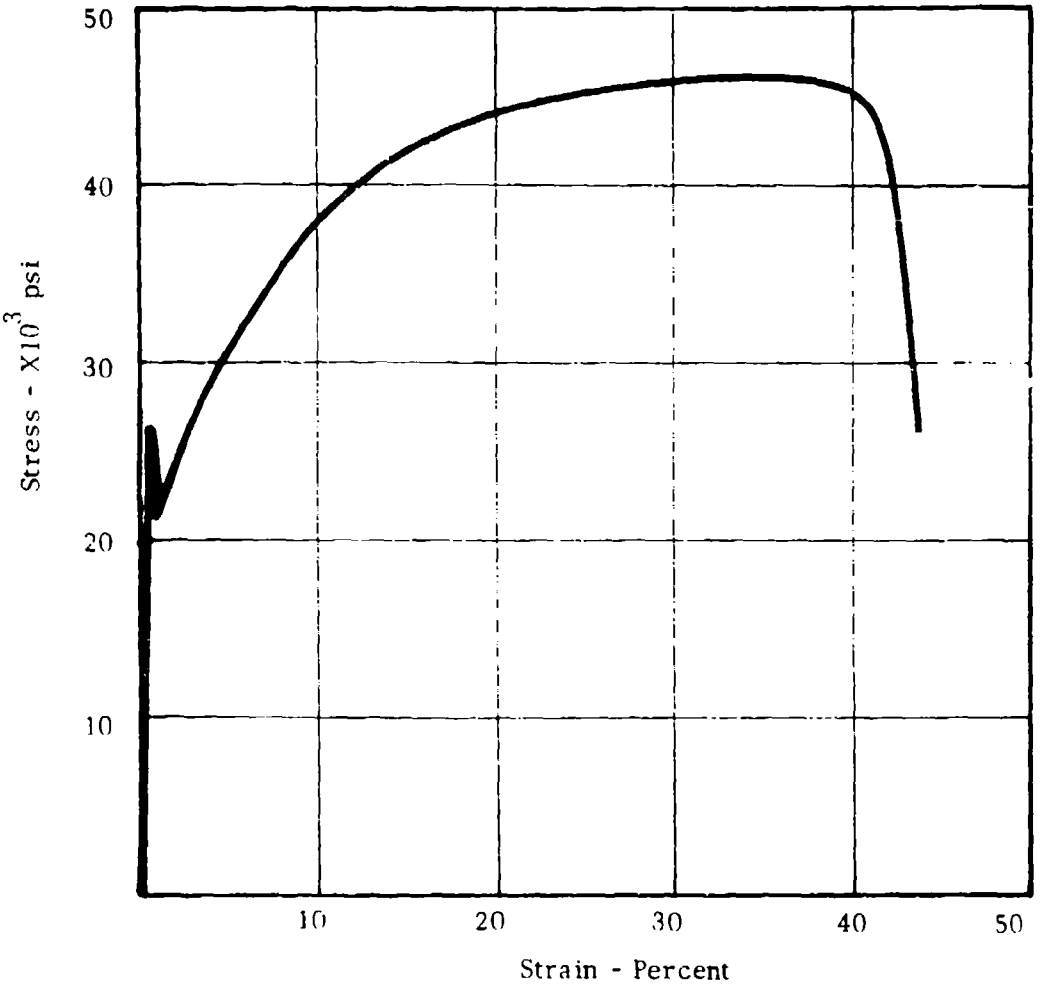

FIGURE 4 LOW STRAIN RATE TENSILE TEST CURVE
ARMCO IRON

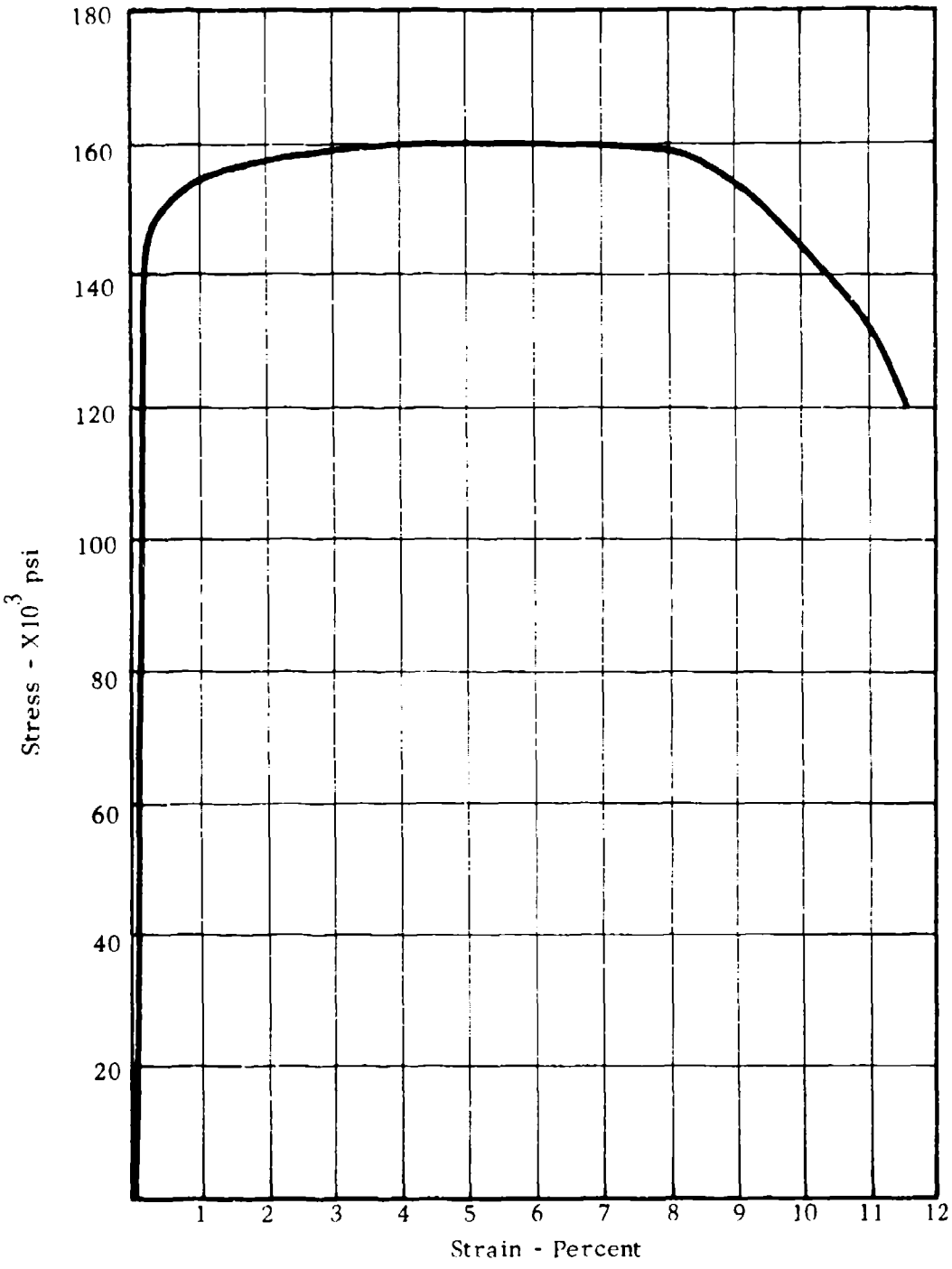

FIGURE 5 LOW STRAIN RATE TENSILE TEST CURVE
TITANIUM - 6 ALUMINUM - 4 VANADIUM

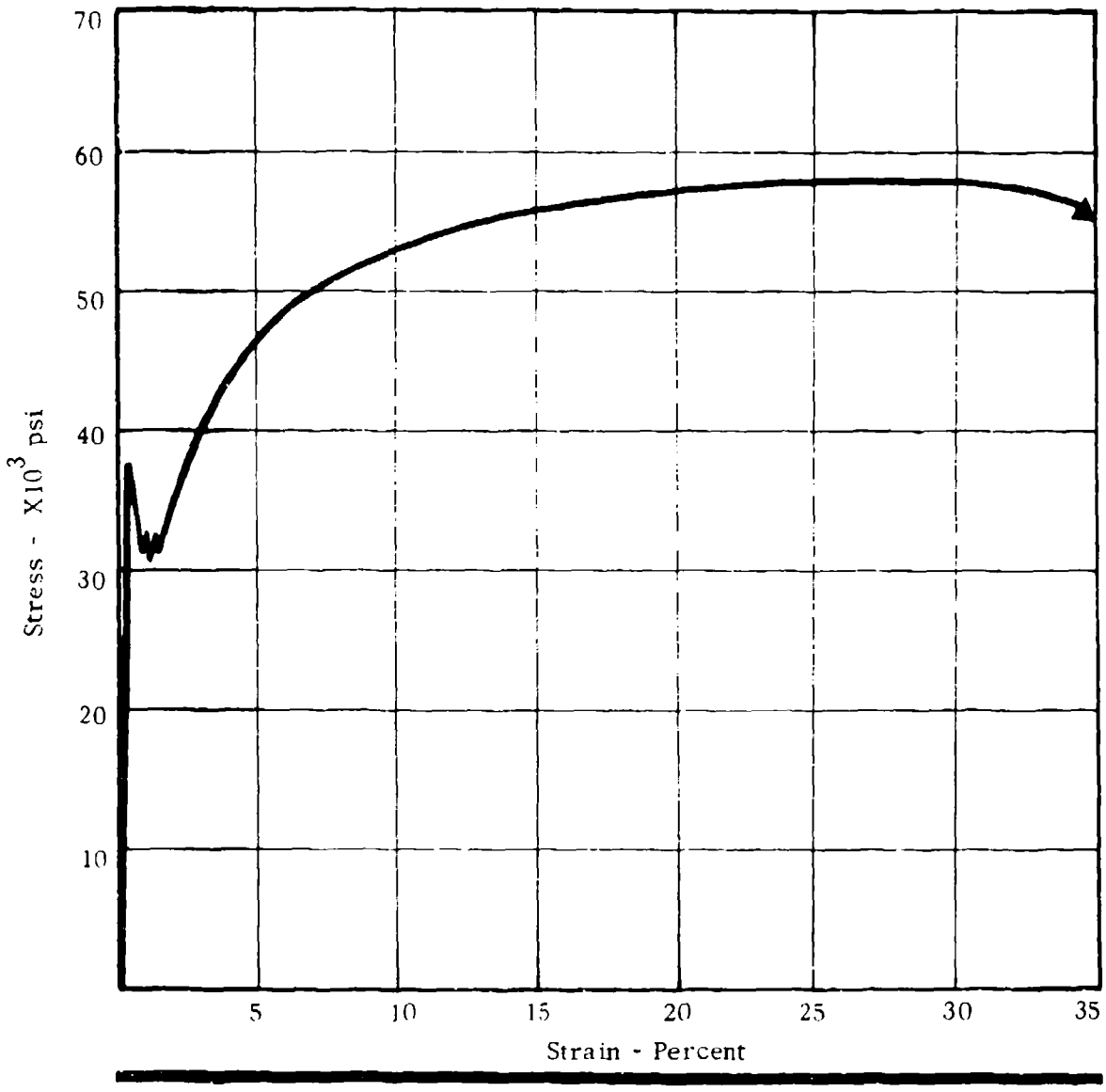

FIGURE 6 LOW STRAIN RATE TENSILE TEST CURVE
1015 STEEL

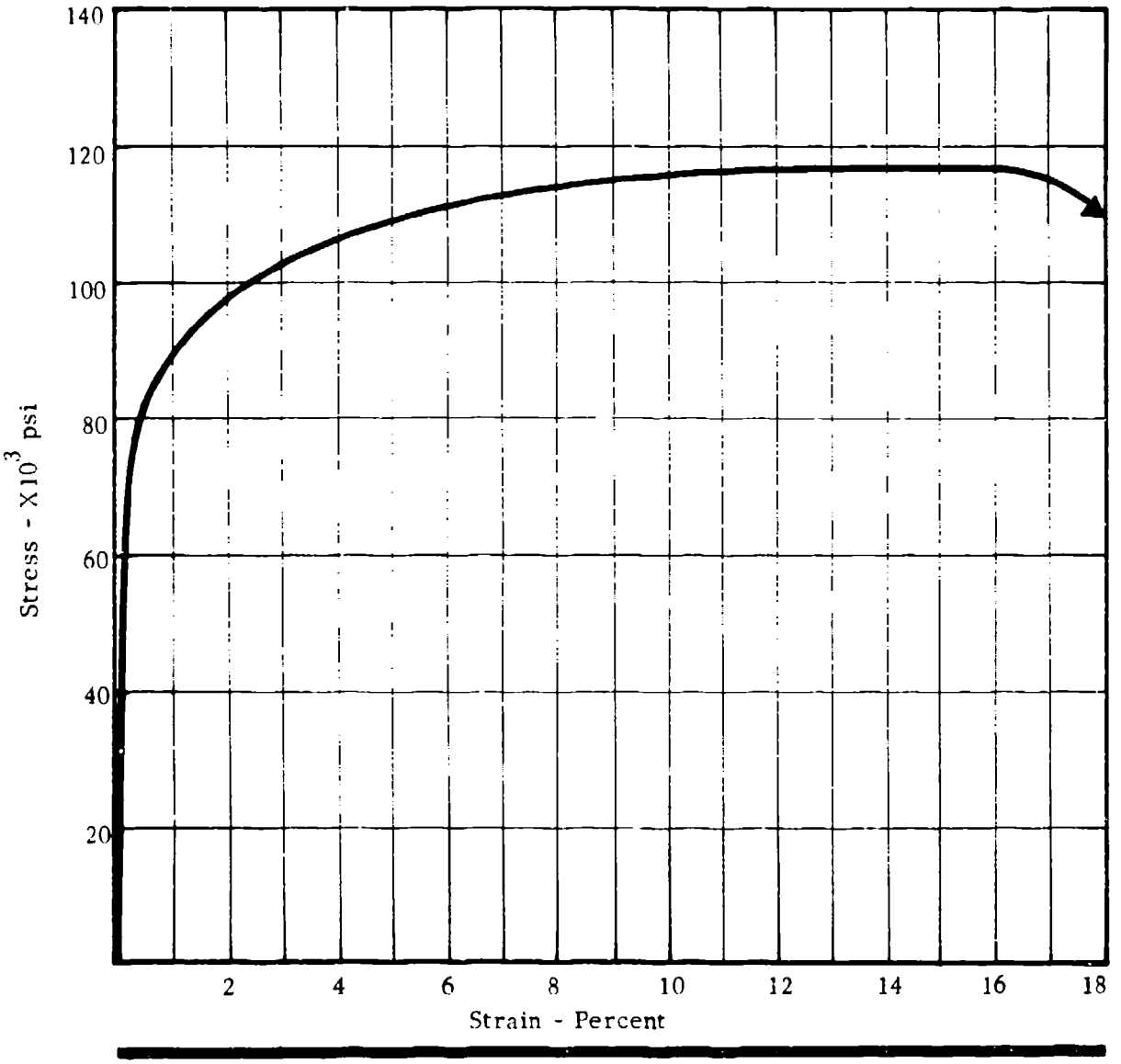

FIGURE 7 LOW STRAIN RATE TENSILE TEST CURVE
ANNEALED 4340 STEEL

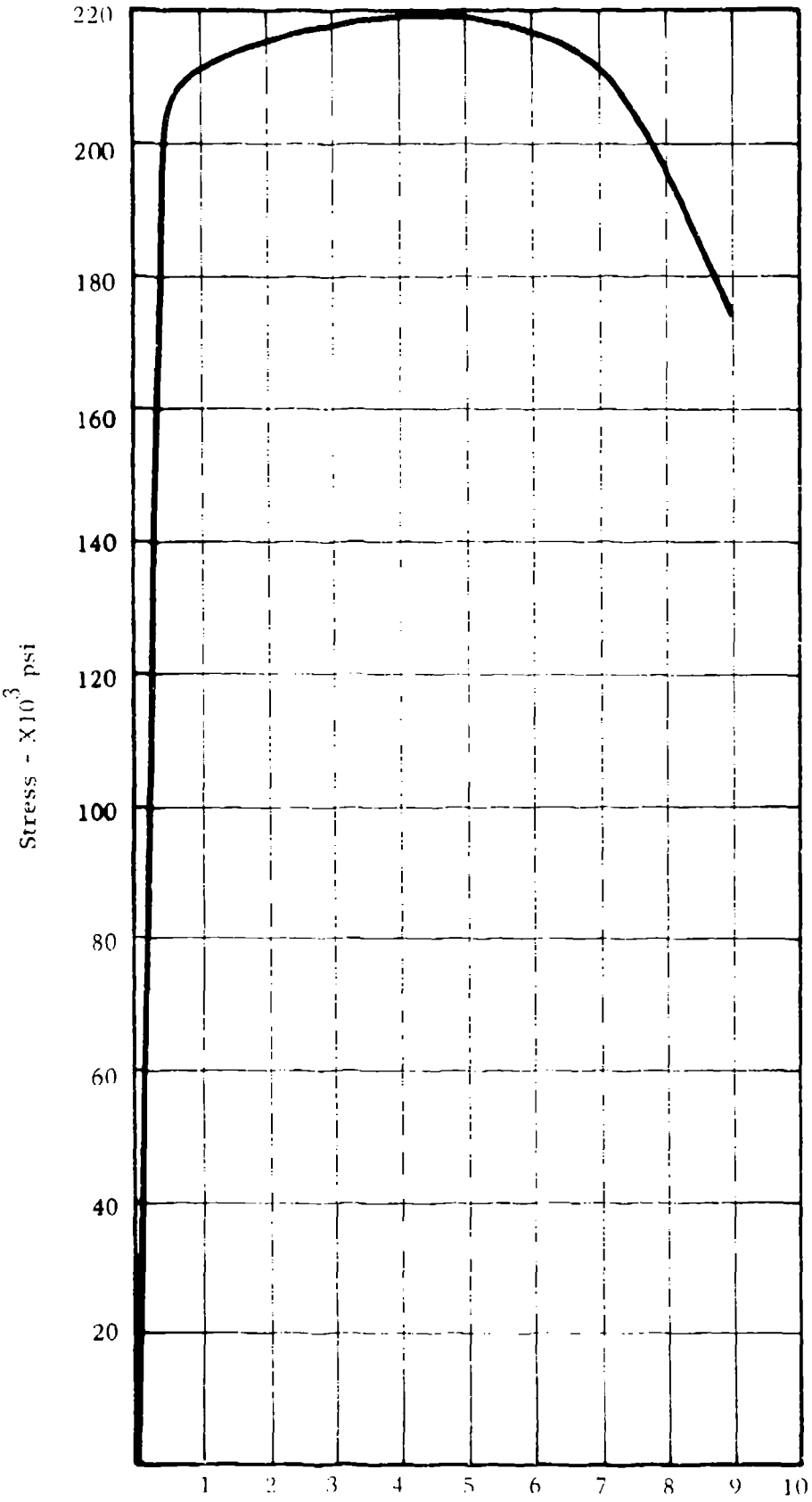

FIGURE 8 LOW STRAIN RATE TENSILE TEST CURVE
HARDENED 4340 STEEL

TABLE IV

MECHANICAL PROPERTIES
(Quasi-Static Tests)

MATERIAL	YIELD STRENGTH PSI	TENSILE STRENGTH PSI	Uniform Elongation Percent	Total Elongation Percent
99.99 Aluminum	2,900	4,860	26	33.0
7075-T6	77,000	86,000	9	11.6
304 Stainless Steel	58,000	103,000	46	64.5
Armco Iron	22,000	46,000	31	43.4
Ti-6Al-4V	150,000	160,000	3	11.6
1015 Steel	32,000	57,000	26	38.9
4340 Steel (A)	76,000	117,000	11	20.4
4340 Steel (H)	208,000	219,000	2	9.0

III HIGH STRAIN RATE STRESS-STRAIN DATA

High speed photography was used to measure the displacement-time behavior of rings of five materials in the second series of tests to measure high strain rate plastic flow parameters. The second derivative of the displacement-time curve can be used to calculate the stress as a function of strain by the equation:

$$\sigma = \rho r \ddot{r}_0 \ddot{\varepsilon}$$

where σ is the stress, ρ is the density, r is the instantaneous radius, r_0 is the original radius, and $\ddot{\varepsilon}$ is the instantaneous rate of change of strain rate. The derivation of this equation can be found in the First Yearly Progress Report (WAL TR 111.2/20)

The raw displacement-time data for these tests are given in Tables V through IX. The values of the diameters are given in terms of measurements on magnified images of the high speed photographs, and as such are in arbitrary units. It will be noted that the first few frames of each test give approximately constant diameter values. These are frames of the ring before expansion begins. The original diameter of the ring in the arbitrary unit system is calculated by averaging the values in these first frames. There were 25 frames in each test; measurements which are missing represent frames in which the image was fuzzy or obscured by gas clouds.

In the first series of tests, reported in WAL TR 111.2/20, numerical techniques were used to fit curves to the raw data for each test. Stress, strain, and strain-rate were calculated numerically from the equations for these curves. In this latter series, it was found that the displacement-time curves were too complex to be approximated by simple polynomial expressions, so graphical techniques were used to fit the curves and obtain the second derivatives. Within the accuracy of our data and the graphical techniques, we were able to obtain only average stress levels or, at best, linear stress-strain relations. The results for each test are given in Table X. A more complete description of the experimental technique, and a comparison of the results with low strain rate results will be given in the Fifth Interim Report (WAL TR 111.2/20-4)

TABLE V

RING DIAMETER - TIME DATA

99.99% ALUMINUM

Frame No.	Test No. 121 Frame Separation 4.00 Microseconds Diameter	Test No. 128 Frame Separation 4.00 Microseconds Diameter	Test No. 129 Frame Separation 4.00 Microseconds Diameter
1	30.00	30.00	30.00
2	30.15	30.05	30.10
3	30.35	30.40	30.45
4	30.65	30.70	30.70
5	31.00	31.00	31.00
6	31.25	31.25	31.30
7	31.40	31.45	31.50
8	31.65	31.65	31.65
9	31.85	31.90	31.80
10	32.00	32.10	32.00
11	32.15	32.30	32.15
12	32.25	32.40	32.25
13	32.35	32.50	32.35
14	32.45	32.65	32.40
15	32.50	32.70	32.45
16	32.55	32.80	32.50
17	32.50	32.85	32.50
18	32.50	32.85	32.40
19	32.50	32.85	32.50
20	32.50	32.85	32.50
21	32.50	32.80	32.45
22	32.50	32.85	32.50
23	32.50	32.85	32.50
24	↓	32.90	32.50
25	Gas	32.85	32.50

TABLE V (Continued)

99.99% ALUMINUM (Cont.)

Frame No.	Test No. 130 Frame Separation 4.00 Microseconds Diameter	Test No. 131 Frame Separation 4.00 Microseconds Diameter	Test No. 146 Frame Separation 4.00 Microseconds Diameter
1	30.05	29.95	30.00
2	30.10	30.00	30.00
3	30.35	30.35	30.30
4	30.60	30.55	30.70
5	30.85	30.80	31.10
6	31.10	31.10	31.35
7	31.25	31.25	31.65
8	31.45	31.55	31.85
9	31.65	31.65	32.10
10	31.80	31.95	32.35
11	32.00	32.10	32.60
12	32.10	32.20	32.75
13	32.20	32.30	32.95
14	32.25	32.40	33.10
15	32.30	32.45	33.15
16	32.30	32.50	33.25
17	32.30	32.55	33.25
18	32.30	32.55	33.30
19	32.30	32.60	33.30
20	32.30	32.60	33.30
21	32.30	32.60	33.30
22	32.30	32.60	33.30
23	32.30	32.60	33.35
24	32.30	32.65	33.35
25	32.30	32.60	↓ Gas

TABLE VI

RING DIAMETER - TIME DATA

7075 - T6 ALUMINUM

Frame No.	Test No. 137 Frame Separation 2.67 Microseconds Diameter	Test No. 140 Frame Separation 2.67 Microseconds Diameter	Test No. 141 Frame Separation 2.67 Microseconds Diameter
1	30.00	30.00	30.00
2	29.90	29.95	30.00
3	29.90	30.25	30.30
4	30.15	30.70	30.65
5	30.70	31.00	31.05
6	31.10	31.20	31.25
7	31.45	31.25	31.35
8	31.65	31.35	31.40
9	31.85	31.35	31.45
10	32.00	31.40	31.40
11	32.25	31.60	31.40
12	32.50	31.70	31.40
13	32.75	31.80	31.45
14	33.30	31.90	31.50
15	33.55	32.00	31.45
16	33.90	32.10	31.50
17	34.20	32.20	31.60
18	34.50	32.30	31.60
19	34.50	32.50	31.70
20	34.50	32.60	31.85
21	34.50	32.75	31.95
22	34.50	32.85	32.00
23	34.50	33.00	32.05
24	34.50	-	32.10
25	34.50	-	32.10

TABLE VI (Continued)

7075-T6 ALUMINUM (Cont.)

Frame No.	Test No. 142 Frame Separation 2.67 Microseconds Diameter
1	30.00
2	29.95
3	30.00
4	30.35
5	30.75
6	31.15
7	31.35
8	31.50
9	31.60
10	31.65
11	31.85
12	32.15
13	32.30
14	32.45
15	32.60
16	32.75
17	32.95
18	33.10
19	33.30
20	33.50
21	33.60
22	33.70
23	33.90
24	34.10
25	34.35

TABLE VII

RING DIAMETER - TIME DATA

TITANIUM - 6 ALUMINUM - 4 VANADIUM

Frame No.	Test No. 123 Frame Separation 2.67 Microseconds Diameter	Test No. 138 Frame Separation 2.00 Microseconds Diameter
1	30.00	29.90
2	30.00	30.00
3	30.00	30.00
4	30.10	30.15
5	30.60	30.45
6	31.00	30.75
7	31.25	31.10
8	31.45	31.30
9	31.65	31.40
10	31.85	31.55
11	32.20	31.95
12	32.35	32.15
13	32.45	32.25
14	32.60	32.50
15	32.65	32.65
16	32.75	32.80
17	32.80	32.90
18	32.75	33.00
19	32.80	33.15
20	32.85	33.25
21	32.80	33.25
22	32.85	33.30
23	32.85	33.35
24	32.85	33.35
25	32.85	33.35

TABLE VIII

RING DIAMETER - TIME DATA

304 STAINLESS STEEL

Frame No.	Test No. 112 Frame Separation 4.00 Microseconds Diameter	Test No. 114 Frame Separation 2.67 Microseconds Diameter	Test No. 115 Frame Separation 2.67 Microseconds Diameter
1	30.10	-	30.05
2	30.50	-	29.95
	30.75	30.15	30.05
	31.15	30.15	30.35
5	31.50	30.15	30.80
6	31.75	30.40	31.25
7	31.95	30.75	31.55
8	32.15	31.15	31.90
9	32.20	31.45	32.25
10	32.25	31.75	32.60
11	32.25	32.05	32.90
12	32.15	32.30	33.15
13	32.15	32.55	33.40
14	32.10	32.75	33.65
15	32.05	32.95	33.85
16	32.05	33.15	34.00
17	32.10	33.25	34.15
18	32.05	33.40	34.25
19	32.10	33.55	34.45
20	32.15	33.60	34.55
21	32.20	33.65	34.65
22	32.20	33.65	34.70
23	32.15	33.65	34.80
24	32.20	33.65	34.90
25	32.20	33.65	34.95

TABLE VIII (Continued)

304 STAINLESS STEEL (Cont.)

Frame No.	Test No. 116 Frame Separation 2.67 Microseconds Diameter	Test No. 124 Frame Separation 2.67 Microseconds Diameter	Test No. 125 Frame Separation 2.67 Microseconds Diameter
1	30.15	30.00	29.90
2	30.10	29.95	29.95
3	30.15	30.10	30.00
4	30.40	30.50	30.15
5	30.90	31.00	30.50
6	31.25	31.30	30.80
7	31.50	31.55	31.10
8	31.75	31.80	31.40
9	32.10	32.00	31.65
10	32.30	32.25	31.85
11	32.60	32.50	32.15
12	32.75	32.70	32.35
13	33.00	32.85	32.55
14	33.15	33.00	32.75
15	33.25	33.10	32.85
16	33.35	33.20	32.95
17	33.40	33.25	33.05
18	33.40	33.20	33.10
19	33.50	33.25	33.15
20	33.50	33.20	33.15
21	-	33.10	33.05
22	-	33.10	33.05
23	-	33.10	33.00
24	-	33.10	33.00
25	-	33.10	32.85

TABLE IX

RING DIAMETER - TIME DATA

ARMCO IRON

Frame No.	Test No. 117 Frame Separation 2.67 Microseconds Diameter	Test No. 122 Frame Separation 2.67 Microseconds Diameter	Test No. 127 Frame Separation 2.67 Microseconds Diameter
1	30.05	30.00	30.00
2	30.00	30.00	29.95
3	30.10	30.15	30.00
4	30.35	30.45	30.15
5	30.65	30.80	30.50
6	30.95	31.15	30.95
7	31.15	31.40	31.35
8	31.40	31.65	31.70
9	31.50	31.85	32.10
10	31.60	32.05	32.30
11	31.75	32.25	32.55
12	31.85	32.40	32.65
13	31.95	32.50	32.80
14	32.00	32.60	32.95
15	31.95	32.65	33.15
16	31.95	32.65	33.35
17	31.85	32.65	33.45
18	31.80	32.65	33.60
19	31.85	32.65	33.75
20	31.90	32.60	33.85
21	31.90	32.65	-
22	31.90	32.65	-
23	31.90	32.60	-
24	31.90	32.65	-
25	31.90	32.65	-

TABLE IX (Continued)

ARMCO IRON (Cont.)

Frame No.	Test No. 134 Frame Separation 2.67 Microseconds Diameter	Test No. 135 Frame Separation 2.67 Microseconds Diameter
1	30.00	30.00
2	29.95	30.00
3	29.95	30.10
4	30.10	30.40
5	30.55	30.95
6	30.80	31.30
7	31.25	31.60
8	31.55	31.80
9	31.85	32.00
10	32.10	32.20
11	32.35	32.35
12	32.60	32.50
13	32.70	32.65
14	32.95	32.75
15	33.05	32.95
16	33.20	33.10
17	33.30	33.15
18	33.40	33.15
19	33.50	33.20
20	33.55	33.30
21	33.55	33.25
22	33.60	33.25
23	33.55	33.25
24	33.50	33.20
25		33.20

TABLE X

HIGH STRAIN RATE RESULTS

MATERIAL	TEST NO.	INITIAL STRAIN RATE SEC^{-1}	STRESS-STRAIN RELATION σ = PSI, ϵ = PERCENT	RANGE PERCENT STRAIN
99.99% Aluminum	121	2960	$\sigma_{avg} = 10,500$	1 - 10
	128	2560	$\sigma = 807\epsilon + 4,970$	
	129	2660	$\sigma = 800\epsilon + 7,600$	
	130	2180	$\sigma = 1,000\epsilon + 4,300$	
	131	2500	$\sigma = 740\epsilon + 6,500$	
	146	3100	$\sigma_{avg} = 10,700$	
7075-T6 Aluminum	137	7420	$\sigma_{avg} = 140,000$	1 - 7
	140	6680	$\sigma_{avg} = 155,000$	
	141	5710	$\sigma_{avg} = 109,000$	
	142	6550	$\sigma_{avg} = 119,000$	
Titanium - 6 Aluminum 4 Vanadium	123	7500	$\sigma_{avg} = 258,000$	1 - 6
	138	8850	$\sigma_{avg} = 298,000$	

TABLE X (Continued)

MATERIAL	TEST NO.	INITIAL STRAIN RATE SEC^{-1}	STRESS-STRAIN RELATION σ = PSI, ϵ = PERCENT	RANGE PERCENT STRAIN
304 Stainless Steel	112	3110	$\sigma = 12,700\epsilon + 14,500$	1 - 10
	114	4610	$\sigma = 5,100\epsilon + 57,500$	
	115	5000	$\sigma = 7,520\epsilon + 33,400$	
	116	5150	$\sigma_{avg} = 74,700$	
	124	5120	$\sigma_{avg} = 70,300$	
	125	4200	$\sigma = 3,780\epsilon + 38,600$	
Armco Iron	117	4760	$\sigma = 4,100\epsilon + 70,400$	1 - 7
	122	4800	$\sigma_{avg} = 90,000$	
	127	6120	$\sigma_{avg} = 176,000$	
	134	3930	$\sigma_{avg} = 69,200$	
	135	6520	$\sigma_{avg} = 170,000$	

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