GRAH-RA 68-0855

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SC-R-68-1857
October 1968

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R. A. Graham
O. E. Jones
Sandia Laboratories
Albuquerque, New Mexico

SANDIA LABORATORIES

OPERATED FOR THE UNITED STATES ATOMIC ENERGY COMMISSION BY SANDIA CORPORATION | ALBUQUERQUE, NEW MEXICO; LIVERMORE, CALIFORNIA

Published by
Sandia Corporation,
a prime contractor to the
U. S. Atomic Energy Commission

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ABSTRACT

A summary of Hugoniot elastic limit measurements published in the literature is presented. The summary, taken from about 60 references, includes about 120 entries describing metals, brittle single crystals, and polycrystalline ceramics. Geologic materials are not comprehensively surveyed. The tabulated data gives characteristic Hugoniot elastic limit values together with the experimental technique employed and critical comments concerning metallurgical condition, sample thickness and departures from simple time-independent behavior.

INTRODUCTION

The response of solids subjected to high-pressure shock-wave loading has been extensively investigated both theoretically and experimentally.[1-8] The presence of elastic precursor waves was first reported by Pack, et al.[9] in 1948, and the first quantitative measurements of precursor amplitude, i. e., the Hugoniot elastic limit (HEL), were reported by Minshall[10] in 1955. Although these early elastic wave measurements date from the same time as the more extensive studies of higher pressure shock-wave behavior,[11] comprehensive measurements and the study of the physical processes involved are of more recent origin. This is immediately apparent from the summary presented herein, which shows that one-half of the HEL values were reported within the last three years. The lower stress levels involved in HEL measurements and the time-dependent character of dynamic yield phenomena required the development of new measurement techniques with enhanced sensitivity and improved time-resolution.

The concept of a unique HEL value implies that rate effects are negligible and equilibrium is achieved. Under these conditions shock-wave propagation is steady and the value of the HEL will be time-independent, i. e., its value will not depend on propagation distance or driving stress amplitude. The experimental results given in the summary show that, in fact, many materials exhibit time-dependent unsteady behavior. Thus, the concept of a unique HEL value for a material is often an oversimplification; nevertheless, characteristic values can be assigned within limits, and these are the values given in the summary. Although the summary is a reasonably complete compendium of experimental results, individual references should be consulted for specific details.

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SUMMARY OF HUGONIOT ELASTIC LIMIT MEASUREMENTS

Material	Condition (a)	σ_{HEL} (kbar) (b)	Remarks (c)	Technique (d)	Reference
		METALS			
		Iron Alloys			
o iron	annealed	7	25 mm	E-1	Bancroft, et al. (195
o iron	AR, annealed	15-7	25-133 mm	E-1, 14	Minshall (1961)
o iron	normalized	8-7	20-51 mm^{+*}	E-5	Jones, et al. (1962)
o iron	annealed	11-7	6-51 mm^{+*}	E-6	Taylor, et al. (196
o iron	-	10	25-60 mm^{+*}	E-7	Ivanov, et al. (196
o iron	annealed	12-6	6-40 mm^{+*}	E-12	McQueen (1964)
o iron	-	11-8	4-18 mm^{+}	E-12	Peyre, et al. (1965
vac E iron	varied	12-6	12 mm*	E-5	Holland (1967)
vac E iron	annealed	10	13 mm*, temp 76-573°K	E-5	Rohde (1968a)
018	normalized	13-10	20-51 mm^{+*}	E-5	Jones, et al. (1962)
018	annealed - cold rolled	16-9	19 mm	E-5	Jones, et al. (1964)
018	varied	12	19 mm*	E-5	Jones, et al. (1968)
020	-	10-12	127 mm	E-1	Minshall (1955)
020	AR, annealed	15-11	50-127 mm	E-1	Minshall (1961)
020	AR	10	51-76 mm	E-1	Costello (1957)
040	-	11	127 mm	E-1	Minshall (1955)
040	AR, annealed	6-14	127 mm	E-1	Minshall (1961)
055	AR, annealed	13-15	125-127 mm	E-1, 14	Minshall (1961)
055	varied	8-15	25 mm	E-14	Loree, et al. (1966)

1% carbon-iron	varied	12-17	25 mm	E-14	Loree, et al. (1966)
1.5% carbon-iron	varied	16-19	25 mm	E-14	Loree, et al. (1966)
2% carbon-iron	varied	15-21	25 mm	E-14	Loree, et al. (1966)
SAE 4340	annealed	19-14	6-50 mm[+*]	G-5	Butcher, et al. (1968a)
SAE 4340	annealed	23-21	3-6 mm	G-8	Graham, et al. (1967b)
SAE 4340	RC-15	17	25 mm	E-14	Minshall (1961)
SAE 4340	RC-15	17-19	12 mm	G-2	Butcher, et al. (1964)
SAE 4340	RC-30	16	23 mm	E-5	Jones, et al. (1962)
SAE 4340	RC-32	16-20	12 mm	G-2	Butcher, et al. (1964)
SAE 4340	RC-35	25	25 mm	E-14	Minshall (1961)
SAE 4340	RC-40	20-18	20-51 mm	E-5	Jones, et al. (1962)
SAE 4340	RC-50	22	23 mm	E-5	Jones, et al. (1962)
SAE 4340	RC-54	14-31	12 mm	G-2	Butcher, et al. (1964)
Hampden tool steel	RC-20	14	19 mm	E-5	Jones, et al. (1962)
Hampden tool steel	RC-62	~22	19 mmϕ	E-5	Jones, et al. (1962)
Hampden tool steel	RC-66	>24	19 mmϕ	E-5	Jones, et al. (1962)
SAE 347 stainless steel	AR	6	127 mm	E-1,14	Minshall (1961)
3% silicon-iron crystal	-	~7	13 mm[*]	G-6	Taylor (1968)
3.34% silicon-iron	annealed	10-9	6-25 mm[+*]	E-5	Mote (1968)
Invar, 36% nickel - 64% iron	AR	13	wedge	E-10	Curran (1961)
Invar, 36% nickel - 64% iron	annealed	5	13 mm	G-5	Graham, et al. (1967a)
30% nickel - 70% iron	annealed	5-3	10-13 mm	G-5	Graham, et al. (1967a)
30% nickel - 70% iron	martensitic	~20 (ramp)	13 mmϕ	G-5	Graham, et al. (1967a)
Russian steel 3	AR	13-6	20-120 mm[+*]	E-7	Ivanov, et al. (1963)
Russian steel 30khGSA	annealed	17	60 mm[+*]	E-7	Ivanov, et al. (1963)
Russian steel 30khGSA	hardened	18	60 mm[+*]	E-7	Ivanov, et al. (1963)
Austenitic manganese steel	RB93	8	6 mm	E, G-5	Champion (1968)

SUMMARY OF HUGONIOT ELASTIC LIMIT MEASUREMENTS (cont)

Material	Condition (a)	σ_{HEL} (kbar) (b)	Remarks (c)	Technique (d)	Reference
304 stainless steel	RB77	6	6 mm	G-5	Butcher (1968b)
Vibrac	RC36	21	51-76 mm	E-1	Costello (1957)
Aluminum Alloys					
2024	T-4	5	wedge	E-10	Fowles (1961)
2024	annealed	1	wedge	E-10	Fowles (1961)
2024	-	4	25 mm	E-5	Jones, et al. (1962)
2024	-	6	-	E-6	McQueen (1964)
2024	T-4	-	13 mm	G-6	Taylor (1968)
6061	T-6	6	13-25 mm	G-1	Lundergan, et al. (1963)
6061	T-6	5	6 mm	G-5	Halpin, et al. (1963)
6061	T-6	5-7	25 mm	G-2	Barker, et al.(1964b)
6061	T-6	5	13 mm	G-4	Barker (1967)
6061	T-6	6	13-64 mm	G-2	Butcher, et al. (1966)
1060	annealed	0.3-0.5	25 mm[*]	G-4,5	Barker, et al. (1966)
1060	annealed	0.6-0.2	6-24 mm[+*]	G-4	Karnes (1967)
Russian alloy D-1	annealed	2-1	40-120 mm[+]	E-7	Novikov, et al. (1966)
Russian alloy D-16	annealed	3-2	30-80 mm[+] temp 283-473°K	E-7	Novikov, et al. (1966)
Russian alloy D-16	hardened	5	30 mm	E-7	Novikov, et al. (1966)
French alloy AU4G	-	8	-	E-12	Peyre, et al. (1965)

Other Metals

Copper, crystal	[001]	2	5 mm*	E-5	Mote (1968)
	[011]	1	5 mm*	E-5	Mote (1968)
	[111}	1	5 mm* (relaxation suppressed by prestrain)	E-5	Mote (1968)
Copper, polycrystal	-	~0.5 (ramp)	5 mmϕ	E-5	Mote (1968)
Copper	annealed	0.6-0.4	20-30 mm temp. 283-473°K	E-7	Novikov et al. (1966)
Copper	annealed	~0.4 (ramp)	13 mmϕ	G-6	Taylor (1968)
Copper	annealed	~0.5 (ramp)	ϕ	E-2,3	Munson, et al. (1966)
Copper	cold worked	-	ϕ	G-6	Taylor (1968)
Lead	annealed	<0. 2	-	E-2	Munson, et al. (1966)
Brass	annealed	3-2	30-80 mm$^+$	E-7	Novikov, et al. (1966)
Brass	-	~8	6 mmϕ	E-5	Benedick (1965)
Beryllium, crystal	c-axis	40	*	G-6	Taylor (1968)
Beryllium, crystal	a-axis	4	*	G-6	Taylor (1968)
Beryllium, sintered	-	~2 (ramp)	ϕ	G-6	Taylor (1968)
Tantalum	annealed	-	-	G-6	Taylor (1968)
Niobium	annealed	-	-	G-6	Taylor (1968)
Thorium	-	-	-	G-6	McQueen (1964)
Uranium	-	-	ϕ	G-6	Taylor (1968)
Bismuth, crystal	-	3	1-3 mm	E,G-5	Larson (1967)
Bismuth, polycrystal	cast	~2 (ramp)	2-13 mmϕ	E, G-5	Larson (1967)
Bismuth, polycrystal	cast	~4 (ramp)	2 mmϕ	G-5	Present work
Tungsten	annealed	38	10 mm	G-5	Rohde (1968b)
Antimony	cast	17-2	5-49 mm$^+$	E-1	Warnes (1967)

SUMMARY OF HUGONIOT ELASTIC LIMIT MEASUREMENTS (cont)

Material	Condition (a)	σ_{HEL} (kbar) (b)	Remarks (c)	Technique (d)	Reference
BRITTLE SINGLE CRYSTALS					
Quartz (SiO_2)	x-cut	94-48	5-25 mm^{+*}	E-9	Wackerle (1962)
Quartz (SiO_2)	x-cut	66-55	6 mm*	E-11	Fowles (1967)
Quartz (SiO_2)	y-cut	110-82	10 mm*	E-9	Wackerle (1962)
Quartz (SiO_2)	y-cut	86-65	3-6 mm*	E-11	Fowles (1967)
Quartz (SiO_2)	z-cut	145-120	10 mm*	E-9	Wackerle (1962)
Quartz (SiO_2)	z-cut	148-100	3-6 mm*	E-11	Fowles (1967)
Quartz (SiO_2)	z-cut	145-60	-	E-12	Peyre, et al. (1965)
Quartz (SiO_2)	fused	98 (ramp)	10-13 mmϕ	E-9	Wackerle (1962)
Sapphire (Al_2O_3)	60° cut	120-170	10-13 mm	E-9	Brooks, et al. (1966)
Sapphire (Al_2O_3)	z-cut	120-200	10-13 mm	E-9	Brooks, et al. (1966)
Sapphire (Al_2O_3)	x-cut	135-180	10-13 mm	E-9	Brooks, et al. (1966)
Germanium	[111]	44	8 mm	G--	Graham, et al. (1966)
Germanium	[111]	41-35	6-12 mm*	E-12	McQueen (1964)
Germanium	[100]	53-46	6-12 mm*	E-12	McQueen (1964)
Germanium	[100]	45	7 mm*	E-5	Kennedy (1968)
Germanium	[100]	47	6 mm*	G-8	Graham (1967b)
Germanium	[114]	-	6-12 mm*	E-12	McQueen (1964)
Silicon	crystal	free surface velocities 50% higher than Ge values.		E-12	McQueen (1964)
Cadmium sulfide (CdS)	c-axis	>32	*	E-5	Kennedy, et al. (1966)
Cadmium sulfide (CdS)	a-axis	>28	*	E-5	Kennedy, et al. (1966)
Indium antimonide (InSb)	[100]	>20	-	E-5	Kennedy, et al. (1965)

Indium antimonide (InSb)	[111]	>17	-	E-5	Kennedy, et al. (1965)
Indium antimonide (InSb)	[110]	>20	-	E-5	Kennedy, et al. (1965)
Titania (TiO_2)	[100]	70	6 mm	E-13	Linde, et al. (1968)
Titania (TiO_2)	[001]	100	6 mm	E-13	Linde, et al. (1968)
Sodium chloride (NaCl)	[100]	~ 0. 3	5-14 mm*	E-5	Benedick (1968)

POLYCRYSTALLINE CERAMICS

Lucalox (Al_2O_3, $\rho_o = 3.98$)	-	99-123	3-13 mm	E-11	Ahrens, et al. (1968)
Alumina (Al_2O_3, $\rho_o = 3.92$)	-	140	-	E-11	Gust, et al. (1968)
Alumina (Al_2O_3, $\rho_o = 3.81$)	-	67-100	6 mm	E-11	Ahrens, et al. (1968)
Alumina (Al_2O_3, $\rho_o = 3.76$)	-	58-72	13 mmϕ	G-5, 9	Present work
Alumina (Al_2O_3, $\rho_o = 3.72$)	-	80	-	E-11	Gust, et al. (1968)
Magnesium oxide (MgO, $\rho_o = 3.58$)	-	89-35	4-10 mm	E-11	Ahrens (1966)
Boron carbide (B_4C, $\rho_o = 2.50$)	-	150	-	E-11	Gust, et al. (1968)
Barium titanate ($BaTiO_3$)	-	25	13 mm	E-9	Reynolds, et al. (1962)
Barium titanate ($BaTiO_3$)	-	~30	3-13 mm+	E-10	Doran (1968)
Lead zirconate titanate (PZT 95/5)	-	~40	4-13 mm+	E-10, 11	Doran (1968)
Lead zirconate titanate (PZT 52/48)	-	19	13 mm	E-9	Reynolds, et al. (1962)
Manganese-zinc ferrite	-	23	14 mmϕ	E-5	Present work
Yttrium iron garnet ($\rho_o = 5.07$)	-	>60	8 mm	G-5	Present work
Polycrystal quartz rocks	-	47-130	3-13 mm+	E-11	Ahrens, et al. (1966)
Titania (TiO_2, $\rho_o = 4.24$)	-	75	6 mm	E-13	Linde, et al. (1968)

(a) AR denotes as-received.

(b) When a range of sample thicknesses is given and + is noted in remarks, the larger HEL value corresponds to the smaller sample thickness, and vice versa.

(c) Numbers refer to sample thickness. Symbols: + sample thickness effect observed; * stress relaxation observed; ϕ poorly defined elastic wavefront.

(d) Letters denote method of loading: E explosive loading, and G gun impact. Numbers denote measurement techniques:

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3. Interferometer, Barker et al. (1965).
4. Velocity interferometer, Barker (1967).
5. Quartz gauge, Graham et al. (1965).
6. Capacitor, Rice (1961).
7. Capacitor, Ivanov et al. (1963).
8. Solid dielectric capacitor, Graham et al. (1967).
9. Optical knife-edge, Davis et al. (1961).
10. Optical lever-oblique shock, Fowles (1961).
11. Inclined mirror, Doran (1963).
12. Optical lever, McQueen (1964).
13. Manganin wire, Keough et al. (1964).
14. Capacitor, Hughes et al. (1961).

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