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A LITERATURE SURVEY OF THE COMBINED EFFECTS OF STRAIN RATE AND ELEVATED TEMPERATURE ON THE MECHANICAL PROPERTIES OF METALS

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BY

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DIVISION OF ENGINEERING
BROWN UNIVERSITY
PROVIDENCE, RHODE ISLAND

TECHNICAL REPORT AFML-TR-72-125

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13. ABSTRACT

This report is a survey of the available literature on the observed effects of strain rate on the mechanical properties of metals at elevated temperatures. The range of strain rates included in this survey is from 10^{-4} sec^{-1} to 10^{-3} sec^{-1}, and the range of temperatures from room temperature up to the melting point.

The compiled data and the reference sheets included in this report should be useful as a quick reference on the experimental investigations carried out to date in this field, as well as a source for quantitative information on the rate dependence of the mechanical properties of metals at elevated temperatures.

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FOREWORD

This report was prepared by the Division of Engineering, Brown University, Providence, Rhode Island, under USAF Contract No. F33615-71-C-1308. The contract was initiated under Project No. 7353, "Characterization of Solid Phase and Interphase Phenomena in Crystalline Substances," Task No. 735303, "Surface Effects and Mechanical Response." Funds for this project were supplied to the Air Force Materials Laboratory by the Office of Aerospace Research. The work was administered by the Metals and Ceramics Division, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with Dr. T. Nicholas, AFML/LLD, as Project Acientist.

This report covers work conducted from October 1971 to June 1972. Manuscript was released by the author July 1972 for publication.

This technical report has been reviewed and is approved.

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This report is a survey of the available literature on the observed effects of strain rate on the mechanical properties of metals at elevated temperatures. The range of strain rates included in this survey is from 10^{-4} sec^{-1} to 10^{3} sec^{-1}, and the range of temperatures from room temperature up to the melting point.

The compiled data and the reference sheets included in this report should be useful as a quick reference on the experimental investigations carried out to date in this field, as well as a source for quantitative information on the rate dependence of the mechanical properties of metals at elevated temperatures.

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SECTION I

INTRODUCTION

This survey is a compilation of the experimental data available in the literature on the combined effects of strain rate and elevated temperature on the mechanical properties of metals. It is not intended as a critical survey but only as a list of references along with brief statements of materials, methods, and results.

As of this writing the state-of-the- art in high strain rate testing is well documented in the recent review article of Lindholm [1]* and in the literature survey of the rate dependent strength properties of metals by Lindholm and Bessey [2]. However, in [2], the survey is limited to room temperature work and for many purposes data are required on elevated temperature behavior as well. Accordingly the present survey was undertaken to provide data on the combined effects of elevated temperature and strain rate. The data collected are presented in tabular form for the convenience of the reader. The documentation should serve as a source for quantitative information as well as a guideline for further work.

*Number in brackets designate references in Section VI.

SECTION II

LIST OF INVESTIGATIONS ON THE COMBINED EFFECTS OF STRAIN RATE AND ELEVATED TEMPERATURE ON THE MECHANICAL PROPERTIES OF METALS

The investigations are listed chronologically in the following table, which also presents a list of the materials tested, the range of strain rates and temperatures covered and the maximum strain attained.

More details about each investigation are presented in Section III, while illustrative data for each material tested are gathered in Section IV.

LIST OF INVESTIGATIONS

Ref. No.	Investigators	Technique	Mode of Loading	Materials	Type	Range of Temp., °C	Range of St.Rate, Sec^{-1}	Max. True Strain	Ref. Sheet No.
27, 28	Nadai and Manjoine (1941)	High speed rotary impact machine	Tension	Aluminum Copper Iron Steel	Com. Pure Com. Pure Pure Low Carbon Stainless	25/600 25/1000 25/1200 25/1200 25/1200	100/1000	→fracture	25
36 40	Sokolov (1946-1950)	Modified Charpy impact machine	Compression	Aluminum Copper Brass Zinc Lead Tin Steel			120		—
17	Hughes (1951)	Special Torsion machine	Torsion	Steel	Mild High Carbon Chromium	950/1350	(12-600rpm)	→failure	33
44	Work and Dolan (1953)	Special Torsion machines	Torsion	Steel	SAE 1018	24/538 (75/1000°F)	10^{-4}/12.5		34
3	Alder and Phillips (1954)	Cam Plastometer	Compression	Aluminum Copper Steel	Com. Pure Phosphorous deoxidised 0.17%C	-190/550 18/900 930/1200	1/40	0.5 nominal	1
20	Leech et. al. (1954)	Izod Impact Machine	Tension	Copper Alloys	Brass Bronze Bismuth-Copper	24/900 24/900 350/750	250	→fracture	29
18	Inoue (1955)	Modified tension m.	Tension	Steel	15 types	730/1230	0.8/77	0.2	-

LIST OF INVESTIGATIONS, CONT'D

Ref. No.	Investigators	Technique	Mode of Loading	Materials	Type	Range of Temp., °C	Range of St. Rate, Sec^{-1}	Max. True Strain	Ref. Sheet No.
24	McDonald et al. (1956)	Hydraulic press and jig	Tension	Steel	Alum. killed	24/149 (75/300°F)	0.002/0.8	0.275	21
12	Cook (1957)	Cam Plastometer	Compression	Steel (12 types)	Carbon St. Stainless St. Chromium St.	900/1200	1.5/100	0.5	2
4	Arnold and Parker (1960)	Cam Plastometer	Compression	Alum. alloys	Com. Pure Al-Mn Al-Mg Al-Si-Mg	300/550	1/30	0.5	3
30	Ormerod and Tegart (1960)	Special torsion machine	Torsion	Aluminum	Super Pure	195/550	0.86/7.1 ($\dot{\gamma}$)	2.0(γ)	35
16	Hodierne (1962)	Special torsion machine	Torsion	Aluminum Copper Lead	-	700 max.	10/1000	3.0	36
31	Pugh et al. (1962)	Constant strain rate machine	Torsion	Iron	High Purity	-196/200	10^{-4}, 0.37	0.5	22
12	Chiddister and Malvern (1963)	Split Hopkinson Bar	Compression	Aluminum	1100 F	30/550	300/2000	0.25 (at highest strain rate)	13

LIST OF INVESTIGATIONS, CONT'D

Ref. No.	Investigators	Technique	Mode of Loading	Materials	Type	Range of Temp., °C	Range of St.Rate, Sec^{-1}	Max. True Strain	Ref. Sheet No.
6, 7	Bailey and Singer (1963)	Cam Plastometer	Plane Strain Compression	Aluminum Lead	Super Purity Dural. 4.2%Cu High Str. 5.7%Zn High Purity	$0.95\ T_m$ (max.)	0.4/311 (plane strain rate)	2.0 (plane strain)	19
25	Mahtab et al. (1965)	Air Gun	Indentation	Aluminum Copper	Alloy BS 1476 Alloy BS 1433	24/550 24/600	10^3-10^4 (mean $\dot{\varepsilon}$)	-	10
8	Baraya et al. (1965)	Drop Hammer	Compression	Aluminum	Super Pure	20/500	650 (Max. mean $\dot{\varepsilon}$)	0.7	11
14	Hockett (1966)	Cam Plastometer	Compression	Aluminum	Com. Pure	-50/400	0.05/200	0.7	4
13	Green and Babcock (1966)	Constant strain rate machine Split Hopkinson bar	Compression and Tension Compression	Aluminum Titanium Beryllium	6061-T6 7075-T6 6Al-4V I-400	22/316 (72/600°F)	$10^{-3}/10^2$	0.1	7, 15
5	Bailey (1967)	Hydraulic Press	Plane Strain Compression	Aluminum	Pure 4.2%Cu	22/600 300/500	0.65/8 (Initial $\dot{\varepsilon}$)	2.5	20
35	Slater and Johnson (1967)	Blanking Press	Shear	Aluminum Copper Mild Steel	B.S. 1470 B.S. 1432 EN 2	20/500 20/800 20/1100	$10^3/4 \times 10^3$ ($\dot{\gamma}$)	→Rupture	30

LIST OF INVESTIGATIONS, CONT'D

Ref. No.	Investigators	Technique	Mode of Loading	Materials	Type	Range of Temp., °C	Range of St.Rate, Sec^{-1}	Max. True Strain	Ref. Sheet No.
41	Suzuki et al. (1968)	Cam Plastometer Drop Hammer	Compression	Aluminum Copper Zinc Titanium Magnesium Steel	Com. Pure Duralumin Com. Pure Copper alloys Pure Low Carbon High Strength Stainless	75/650 200/500 18/900 18/900 75/300 18/900 18/500 800/1200 800/1200 800/1200	C.1/100	0.5 (nominal)	5, 6
32, 33	Samanta (1968) (1969)	Drop Hammer	Compression	Aluminum Copper Steel	Com. Pure 99.9%Cu Low Carbon Alloy Steel	250/550 450/900 20/1055 20/1055	110/260 155/600 430(mean) 430(mean)	0.5 0.5 0.8 0.8	9
14	Hawkyard et al. (1968)	Speciman fired on hard anvil	Compression	Copper Steel	BS 1432 Mild St.	20/700	5×10^3 (mean $\dot{\varepsilon}$)	-	12
21, 22	Lindholm and Yeakley (1968)	Split Hopkinson bar	Compression and Tension	Aluminum	1100	27/427	10^3	C.15	16
34	Schultz (1969)	Transverse impact on wire specimen	Tension	Aluminum Steel	1100 2024 C1010	93/426 (200/800°F) 93/315 (200/600°F) 221/760 (430/1400°F)	10^2-10^3 mean	-	28

LIST OF INVESTIGATIONS, CONT'D

Ref. No.	Investigators	Technique	Mode of Loading	Materials	Type	Range of Temp., °C	Range of St.Rate, Sec^{-1}	Max. True Strain	Ref. Sheet No.
29	Nagata et al. (1969)	Split Hopkinson bar	Compression	Iron	0.002-0.05 wt % C	-196/300	4×10^3 (max.)	0.19	17
9	Campbell and Briggs (1969)	Universal rapid load machine	Compression	Niobium Molybdenum		-196/324 -196/324	$10^{-3}/10^2$ (mean)	0.1	6
43	Watson and Ripperger (1969)	Split Hopkinson bar	Compression	Copper Iron	High Purity Armco	25/538 (78/1000°F)	10^3	0.006	14
	Campbell and Ferguson (1970)	Rapid load machine Modified Split Hopkinson bar	Double Shear	Steel	Mild St.	-78/440	10^{-3}–4×10^4	0.2	31, 32
19	Kendall (1970)	High Strain rate machine	Tension	Steel	Mild St. 1018 Alloy St 4340 Tool St. Grade 300 St.	315 max. (600°F)	10 max. (elastic $\dot{\varepsilon}$)	0.002 (at yield)	2-
23	Lindholm and Yeakley (1971)	Biaxial machine and Split Hopkinson bar	Compression, tension and biaxial	Titanium Beryllium	6Al-4V S-200E	21/538 (70/1000°F)	10^3 max.	0.08 at max. temp.	26
42	Thiruvengadam and Conn (1971)	Split Hopkinson bar	Tension	Steel Titanium	316 Stainless TI-6-2-4-2	24, 704 (75, 1300°F) 24, 482 (75, 900°F)	10^3	-	22
26	Muller	Split Hopkinson bar	Compression	Iron Nickel	99.95% pure	RT, 100,200 300,400,500	$500/10^4$	0.1	18

SECTION III

REVIEW OF EXPERIMENTAL INVESTIGATIONS

For quick reference, and to supplement the illustrative data in Section IV, the investigations at high strain rates and elevated temperatures referred to in this survey are summarized in the present section in a much reduced form.

Each reference sheet in this section presents details concerning the test technique adopted, materials tested, specimen shapes, dimensions and heat treatment, lubrication and methods of heating and stress and strain measurement. Illustrations and graphs, reproduced from the original publications, are also presented. The reference sheets are classified with respect to the mode of loading used in each investigation, and further as to whether the experiments conducted were of the dynamic type (strain rate range : 0.1 to 100/sec) or of the impact type (strain rate over 100/sec).

List of Experimental Investigations Reviewed in Section III

Reference Sheet No.	Mode of Loading	Investigator	Ref. No.	Page
1	Dynamic* Compression	Alder & Phillips (1954)	3	11
2		Cook (1957)	12	13
3		Arnold & Parker (1960)	4	15
4		Hockett (1957)	15	17
5		Suzuki et al. (1958)	41	19
6		Campbell & Briggs (1969)	9	21
7		Green & Babcock (1966)	13	23
8	Impact* Compression	Suzuki et al. (1958)	41	25
9		Samanta (1968, 1969)	32 33	27
10		Mahtab et al. (1965)	25	29
11		Baraya et al. (1965)	8	31
12		Hawkyard et al.	14	33
13		Chiddister & Malvern (1963)	11	35
14		Watson & Ripperger (1969)	43	37
15		Green & Babcock (1966)	13	39
16		Lindholm & Yeakley (1968) Lindholm (1968)	22 21	41
17		Nagata et al. (1969)	29	43
18		Muller (1971)	26	45

Reference Sheet No.	Mode of Loading	Investigator	Ref. No.	Page
19	Dynamic Plane Compression	Bailey & Singer (1963)	6, 7	47
20		Bailey (1967)	5	49
21	Dynamic Tension	MacDonald et al. (1956)	24	51
22		Pugh et al. (1961)	31	53
23		Green & Babcock (1966)	13	55
24		Kendall (1970)	19	57
25	Impact Tension	Nadai & Manjoine (1941)	27, 28	59
26		Lindholm & Yeakley (1971)	23	61
27		Thiruvengadam & Conn (1971)	42	63
28		Schultz (1969)	34	65
29		Leech et al (1954)	20	67
30	Impact Shear	Slater & Johnson (1967)	35	69
31	Dynamic Double Shear	Campbell & Ferguson (1970)	10	71
32	Impact Double Shear	Campbell & Ferguson (1970)	10	73
33	Dynamic Torsion	Hughes (1951)	17	75
34		Work & Dolan (1953)	44	77
35		Ormerod & Tegart (1960)	30	79
36	Impact Torsion	Hodierne (1962)	16	81

* Dynamic strain rate range : 0.1 - 100 sec^{-1}.

Impact range : above 100 sec^{-1}.

Dynamic Compression	ALDER and PHILLIPS (1954), [3]	1

<u>Apparatus</u>: Cam Plastometer: 10 tons capacity; Log. cam: 12.5 mm x 90°
Max. ϵ = 0.5 (nominal); $\dot{\epsilon}$: constant true $\dot{\epsilon}$ = 1/40 sec^{-1}

<u>Mat.</u>: Aluminum - commercial purity; as extruded 3/4" diameter
Copper - phosphorous deoxidized; cold drawn 3/4" diameter
Steel - 0.17% C; hot rolled 1" diameter

<u>Spec.</u>: Cylinders, axis parallel to extrusion or rolling direction
Aluminum - D = 12 or 18 mm, L = 25 mm; Annealed 400° C x 1 hour
Copper - 12 or 18 x 25 mm; Annealed 600 x 2 hours in vacuo
Steel - 12 or 18 x 25 mm; not annealed

[<u>Lubr.</u>: on 2 ends before heating; θ = Rm temp., Petroleum jelly;
θ = Rm/450°C, Graphite in Alcohol; θ > 450°C, Glass + Alcohol;
when barrelling occurred in a test, results were discarded.]

<u>Heat</u>: Spec. in guarding box heated in resistance furnace (+ argon for steel spec.), then tested quickly; maximum temperature drop = 5°C.
Test temperature: Aluminum, -190/550; Copper, 18/900; Steel, 930/1200°C.
Glass lubricants prevented oxidation.

<u>Meas. Instr.</u>: - Load - Calibrated optical dynamometer, change in birefringence created in two glass blocks was recorded on rotating drum.
- Displ.: from cam design (allowance made for elastic distortion)

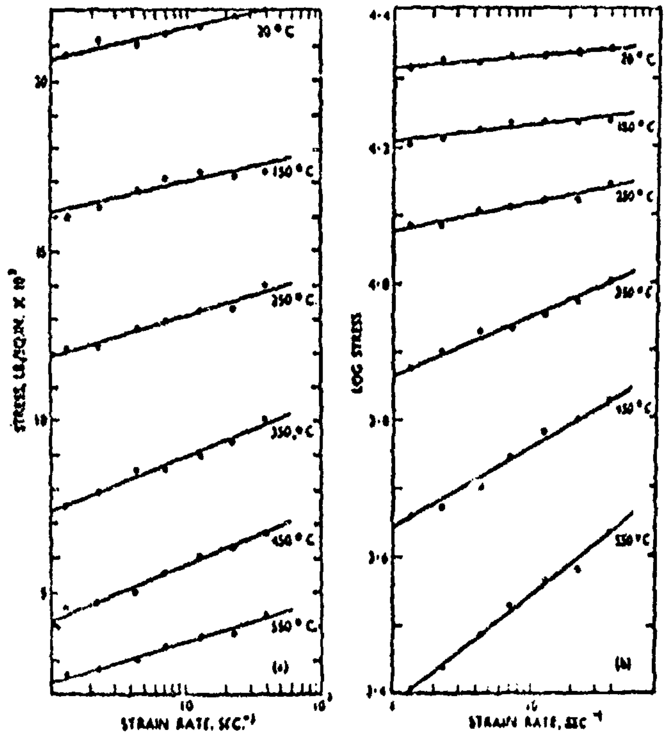


FIG. 6.—Effect of Strain Rate on the Stress Required to Compress Aluminium to 40% Reduction at Various Temperatures.
(a) σ v. $\log_{10} \dot{\epsilon}$; (b) $\log_{10} \sigma$ v. $\log_{10} \dot{\epsilon}$.

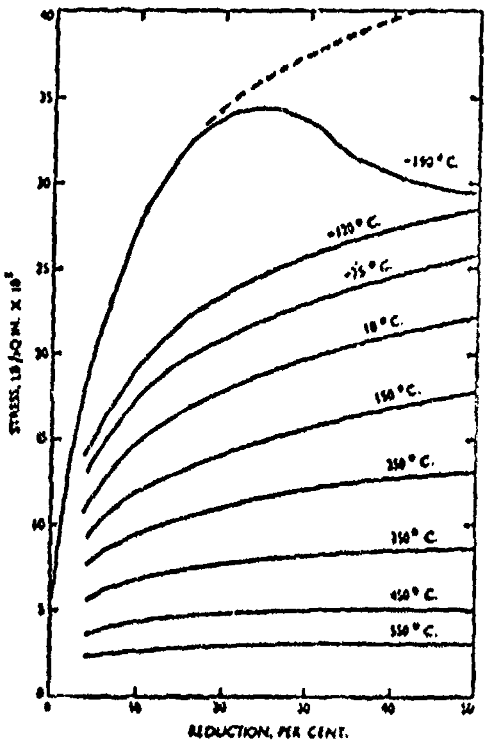


FIG. 4.—Effect of Temperature on the Stress/Strain Curve for Aluminium. Strain rate = 4·38 sec.$^{-1}$

Table V.—*Values of the Index n in the Equation* $\sigma = \sigma_0 \dot{\epsilon}^n$.

Metal	Temp., °C.	Value of n for a Compression of: 10%	20%	30%	40%	50%
Al	18	0·013	0·018	0·018	0·018	0·020
	150	0·022	0·022	0·021	0·024	0·026
	250	0·026	0·031	0·033	0·041	0·041
	350	0·055	0·061	0·073	0·084	0·088
	450	0·100	0·098	0·100	0·116	0·130
	550	0·130	0·130	0·141	0·156	0·155
Cu	18	0·010	0·001	0·002	0·006	0·010
	150	0·014	0·016	0·020	0·023	0·026
	300	0·016	0·018	0·017	0·025	0·024
	450	0·010	0·004	0·008	0·014	0·031
	600	0·050	0·043	0·041	0·056	0·078
	750	0·096	0·097	0·128	0·180	0·182
	900	0·134	0·110	0·154	0·193	0·190
Fe	930	0·088	0·054	0·094	0·099	0·105
	1000	0·108	0·100	0·090	0·093	0·122
	1060	0·112	0·107	0·117	0·127	0·150
	1135	0·123	0·129	0·138	0·159	0·198
	1200	0·116	0·122	0·141	0·173	0·196

Table VII.—*Values of* σ_0 *in the Equation* $\sigma = \sigma_0 \dot{\epsilon}^n$.

Metal	Temp., °C.	Value of σ_0 for a Compression of: 10%	20%	30%	40%	50%
Al	18	14·6	17·1	18·9	20·6	22·0
	150	11·4	13·5	15·0	16·1	17·0
	250	9·1	10·5	11·4	11·9	12·3
	350	6·3	6·9	7·2	*7·3	7·4
	450	3·9	4·3	4·5	4·4	4·3
	550	2·2	2·4	2·5	2·4	2·4
Cu	18	26·3	40·3	49·0	54·1	53·7
	150	23·1	32·4	37·8	41·5	43·5
	300	20·2	26·5	30·2	32·2	34·4
	450	17·0	22·5	25·1	26·6	26·8
	600	12·7	16·8	18·9	19·4	19·0
	750	7·6	9·7	10·0	8·5	8·2
	900	4·7	6·3	6·1	5·5	5·2
Fe	930	16·3	19·4	20·4	20·9	20·9
	1000	13·0	15·6	17·3	18·0	16·9
	1060	10·9	12·9	14·0	14·4	13·6
	1135	9·1	10·5	11·2	11·0	9·9
	1200	7·6	8·6	8·8	8·3	7·6

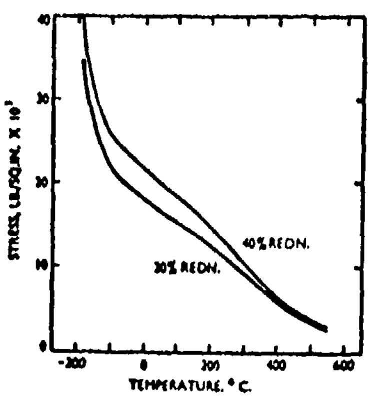


Fig. 6.—Effect of Temperature on the Stress Required to Compress Aluminium to 20% and 40% Reduction. Strain rate = 4·38 sec.$^{-1}$.

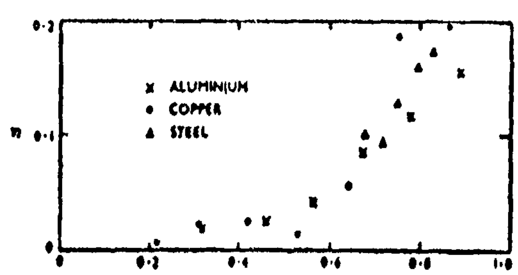


Fig. 7.—Dependence of the Strain-Rate Effect on the Homologous Temperature for 40% Reduction.

Table VI.—*Values of the Slopes of the* n/T_H *Curve for Various Compressions.*

Compression, %	10	20	30	40	50
m_1 *	0·045	0·050	0·055	0·060	0·065
m_2 †	0·36	0·38	0·41	0·46	0·52

* m_1 is the slope for $0 < T_H < 0{\cdot}55$.
† m_2 is the slope for $T_H > 0{\cdot}55$.

Dynamic Compression	COOK (1957), [12]	2

Apparatus: Cam Plastometer: 10 tons capacity; Log. cam: 1/4" lift x 35°
Max. $\varepsilon = 0.5$ (nominal); $\dot{\varepsilon}$: constant true $\dot{\varepsilon} = 1.5/100\ sec^{-1}$

Mat.: Twelve steels; hot rolled bars up to 1 1/4" diameter, annealed before machining specimens.

Spec.: Cylinders; D = 3/8"., L = 1/2"

[Lubr.: on 2 ends before heating, powder glass in alcohol. Different types of glass used at different temperatures. Very slight barreling, neglected in analysis. ($\mu < 0.1$)]

Heat: Spec. in guarding box heated in resistance furnace, then compressed quickly. Test temperature: 900/1200° C.

Meas. Instr.: - Load - Calibrated optical dynamometer, change in birefringence created in two glass blocks recorded on rotating drum.
- Displ.: From cam design (allowance made for elastic distortion)

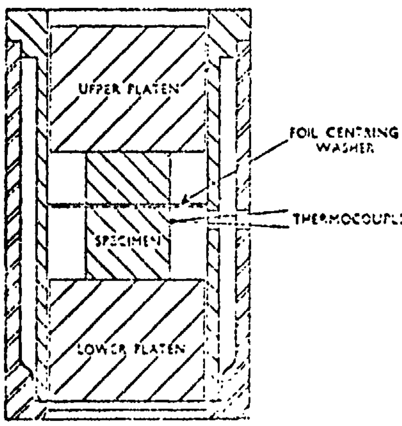
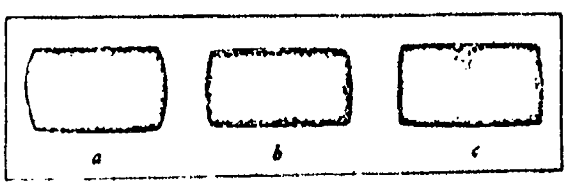


Fig. 3.17. Section Through Guard-ring Box, with Specimen in Position

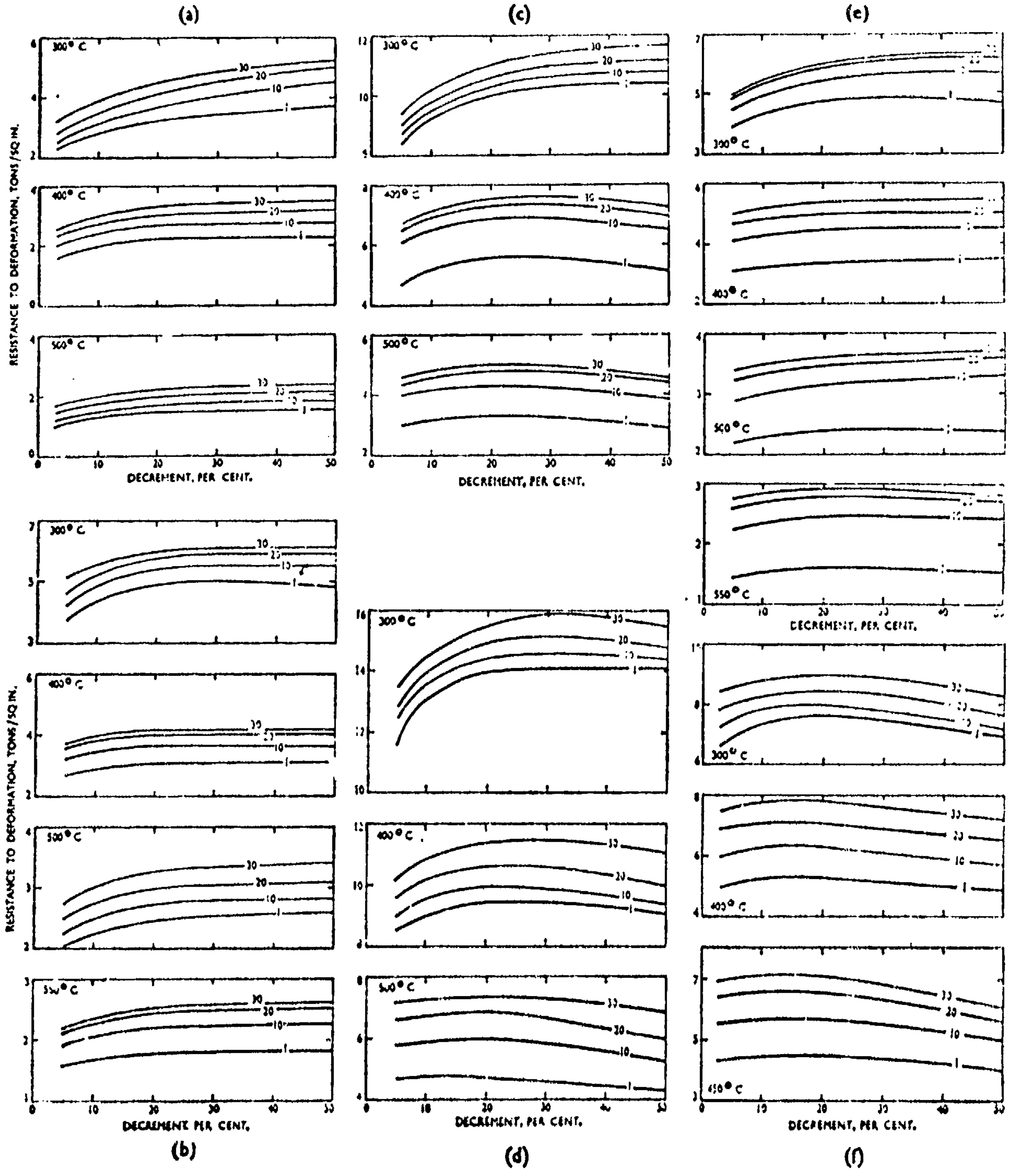


a Lubricated with Pyrex glass.
b Lubricated with hard flint glass.
c Lubricated with lead borate glass.
} See Table 3.3.

Fig. 3.19. Specimens Compressed 50 per cent at 1000 deg. C (1832 deg. F.)

Table 3.3. Percentage Glass Compositions

Type	Lead borate	Hard flint	Pyrex
Used at, deg. C.	900 and 1000	1100	1200
deg. F.	1652 and 1832	2012	2192
Silicon dioxide		66·4	80
Boric oxide	20		12
Barium oxide		5·2	
Aluminium oxide		4·3	3.
Calcium oxide		7·8	
Lead oxide	80		
Sodium oxide		12·3	4
Potassium oxide		4·0	0·3



Figs. 3 (a)–(f) Resistance to homogeneous deformation of various materials at strain rates of 1, 10, 20, and 30 in./in./sec. (a) Commercially pure aluminium; (b) Al-Mn alloy; (c) Al-2½% Mg alloy; (d) Al-5% Mg alloy; (e) Al-Si-Mg alloy; (f) Al-Cu-Si-Mg alloy.

Dynamic Compression	ARNOLD and PARKER (1969), [4]	3

Apparatus: Cam Plastometer, Const. vel. cams; upward displ. of lower
platen is prop. with cam ang. rotation; effective lifts = 1/2, 1/4, 1/8"
Max. ε = 0.5 (nominal); $\dot{\varepsilon}$: 1/30 sec^{-1}

Mat.: C. P. Alum. and 5 Alum. alloys;
hot rolled slabs 1 3/4 - 2" thick → ht treated → cold rolled to 1 1/4" thick

Spec.: Cylinders, axis in dir. of slab thickness: D = 0.5", L = 1.0, 0.5, 0.25".
Annealed: Al - Mn alloy: 500° C x 1 hr, all others: 400° C x 1 hr,
Hardness measured after annealing.

[Lubr.: For T < 500° C: Colloidal graphite suspended in alcohol.
For T ≥ 500° C: Glass suspended in alcohol.]

Heat: Spec. in guarding box heated in resistance furnace, soaking time: 1/2 hr,
then quickly tested.
Lubricants prevented oxidation.
Test temp.: 300, 400, 450, 500° C

Meas. Instr.: - Load: calibrated wire str. g. dynamometer → CRO → photo.
- Displ: from cam design (allowance made for elastic distortion)

[Correction for frictional effects considered in analysis.
Strain rate was defined as $\dot{\varepsilon} = \Delta h/h_0 t$]

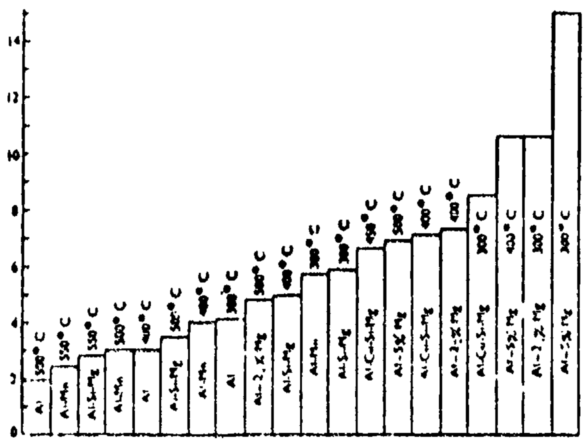


Fig. 4 Comparison of resistance to homogeneous deformation of aluminium and five aluminium alloys. Values refer to a decrement of 20% and a strain rate of 30 in./in./sec. The ordinate shows resistance to deformation (tons/in²).

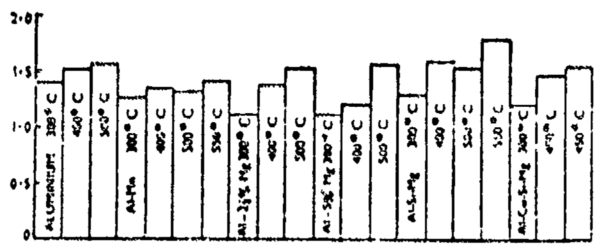
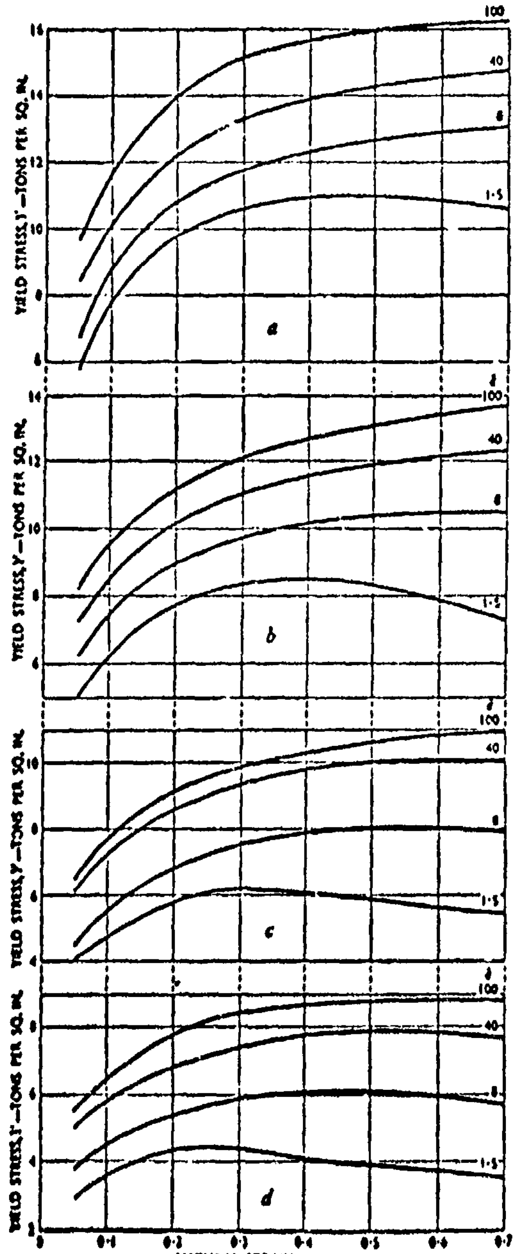
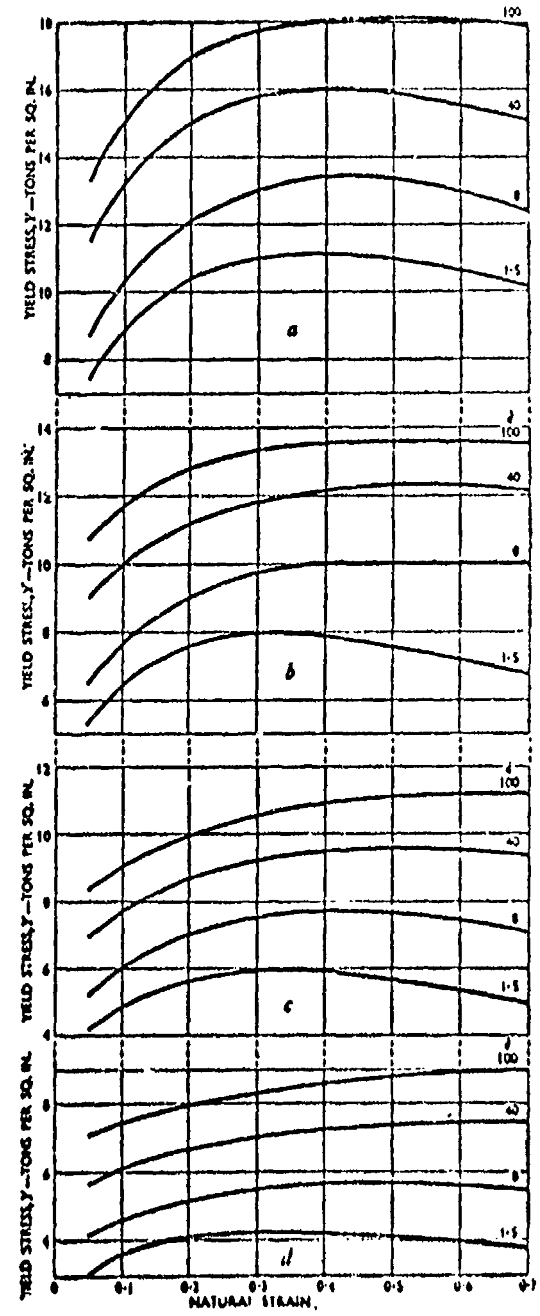


Fig. 5 Comparison of the effect of strain rate on the resistance to deformation of aluminium and five aluminium alloys. The ordinate shows the ratio of the resistance to deformation at a strain rate of 30 in./in./sec. to that at 1/3 in./in./sec.





a 900 deg. C. (1652 deg. F.) *b* 1000 deg. C. (1832 deg. F.)
c 1100 deg. C. (2012 deg. F.) *d* 1200 deg. C. (2192 deg. F.)

Yield-stress Against Natural-strain Curves for

Low-carbon Steel *Medium-carbon Steel*

Figures under $\dot{\varepsilon}$ are $sec.^{-1}$

Dynamic Compression	HOCKETT (1967), [15]	4

Apparatus: Cam Plastometer
$\dot{\varepsilon}$: constant true $\dot{\varepsilon}$ = 0.05/200 sec^{-1}

Mat.: CP Alum. 1100 F (as fabricated temper)

Spec.: Cylinders. no particulars concerning dim. reported.
Annealed: 773°K x 30 min., furnace cooled

Heat: Done in seatu in a heater. Test temp.: 223, 293, 473, 673° K

Meas. Instr.: - Load: Load cell → oscillograph
- Cam position and time: Counter used to adjust time base of a time mark generator, then registers count of 60 pips per rev. generated by the cam in each sec. Pips and time base applied to oscillograph.
Load, time and cam position are then recorded simultaneously.

[NB. Def. assumed homogeneous and verified by rm.temp microhardness surveys of sections of spec. tested at various θ & $\dot{\varepsilon}$, and optically by high speed photography compared with grid def. on specimen.]

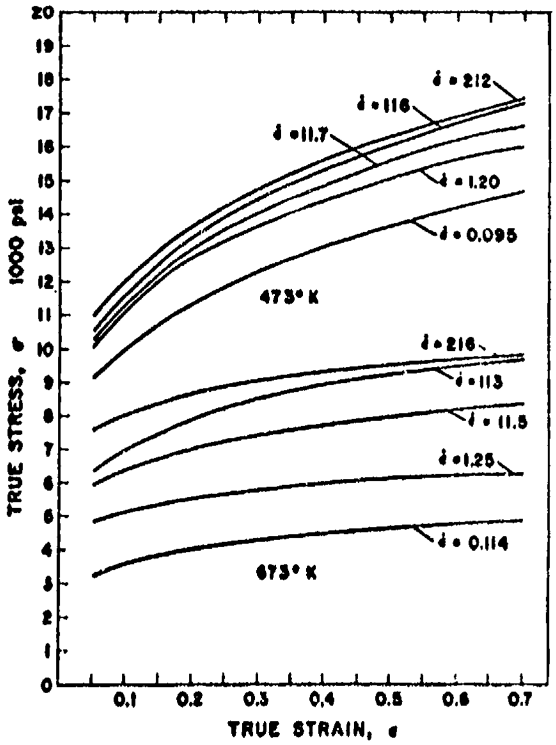


Fig. 4—True-stress vs true-strain curves for 1100-O aluminum at two temperatures. True-strain rates, ε̇, and temperatures as indicated.

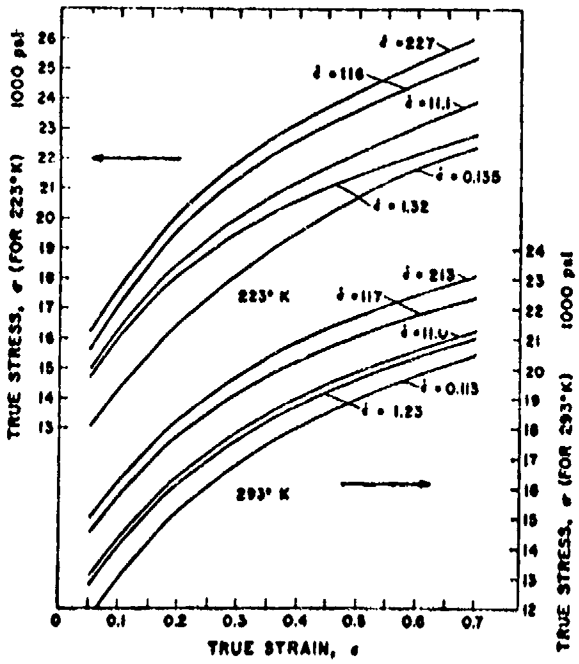
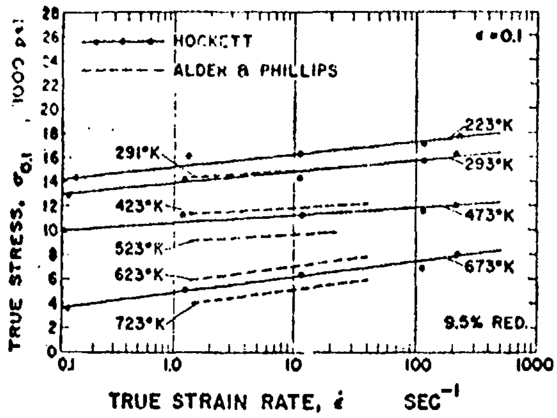
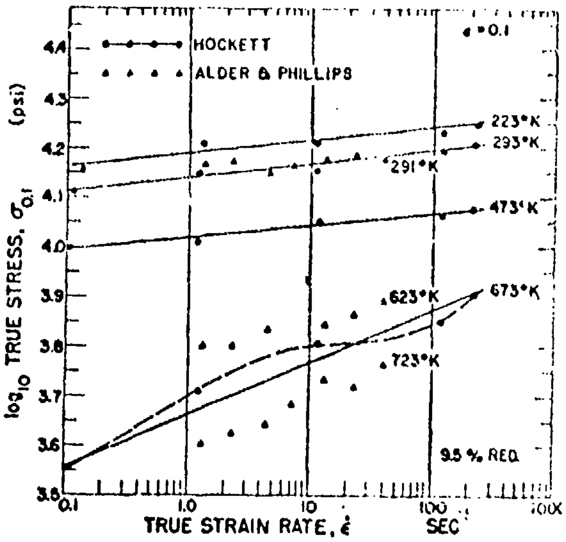
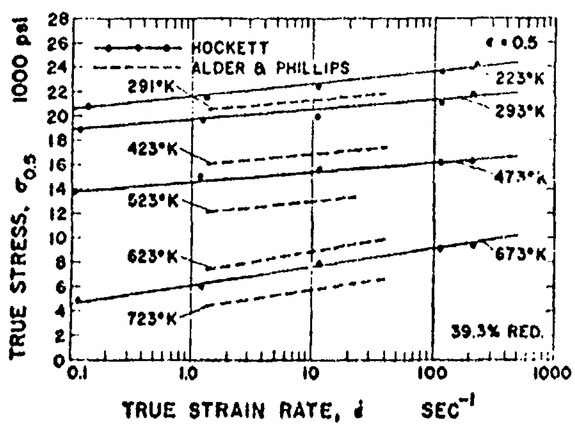
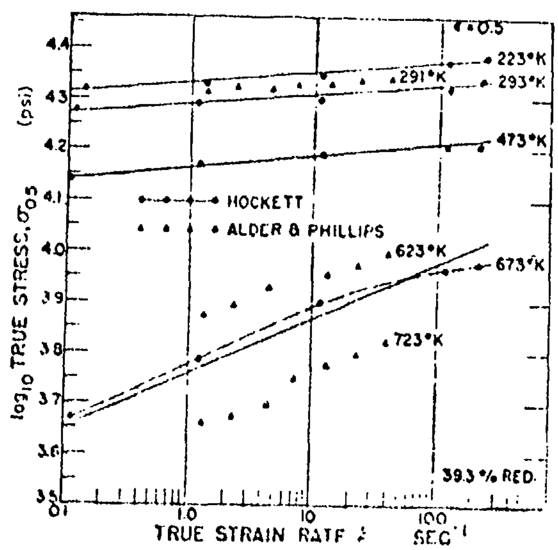


Fig. 5—True-stress vs true-strain curves for 1100-O aluminum at two lower temperatures. True-strain rates, ε̇, and temperatures as indicated.









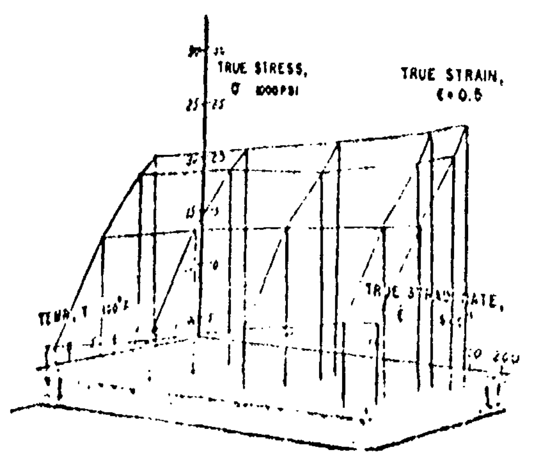


Fig. 14—True-stress vs log true strain rate vs temperature 1100-O aluminum. True strain, ε = 0.5.

Dynamic Compression	SUZUKI et al (1968), [41]	5

Apparatus: Cam Plastometer, 15 tons capacity; Log. cams: included angle 36°, 72°. Max. ϵ = 0.5 nominal ; $\dot{\epsilon}$ = const. true $\dot{\epsilon}$ = 0.1/100 sec^{-1}.

Mat.: Aluminum, Duralumin, Zinc, Magnesium, Titanium, Copper and its alloys, Different kinds of steel.

Spec.: Cylinders, D = 12, L = 18 mm and D = 8, L = 12 mm.

[Lubr.: θ < 600: Colloidal Graphite; 600 < θ < 800: Lead Glass ; θ > 1000° C: Pyrex glass. Degree of barrelling very small.]

Heat: Spec. in a subpress heated in Nichrome furnace for T < 600 or a Silicon carbide furnace for T > 600, then transferred quickly to m/c. Effect of lubricants at various temps. studied.
Test temp.: Alum., 75/650; Duralumin, 200/500; Zinc, 75/300; Magnesium, 18/500; Titanium, 18/900; Copper, 18/900; Steels, 800/1200° C

Meas. Instr.: Capacitor strainmeters, for load and strain.
Time: intensity modulation of CR tube, 3 traces recorded on film.

[NB. Effect of specimen dimensions and texture on flow stress measured was studied experimentally.]

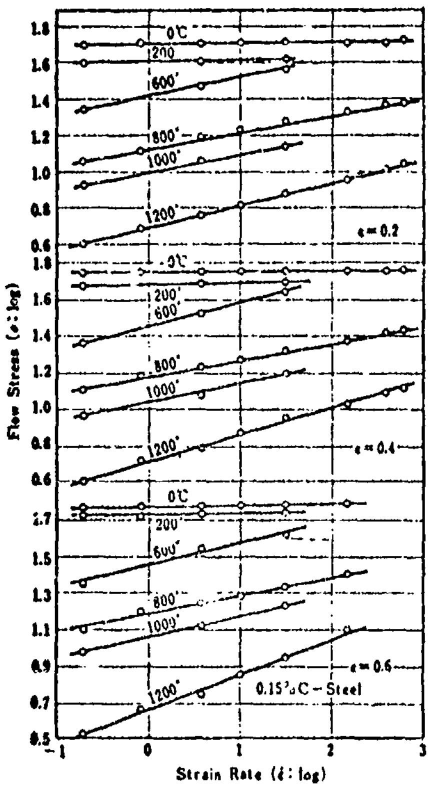


Fig. 3·7 Strain Rate Dependence of the Flow-Stress of 0.15% C-Steel.

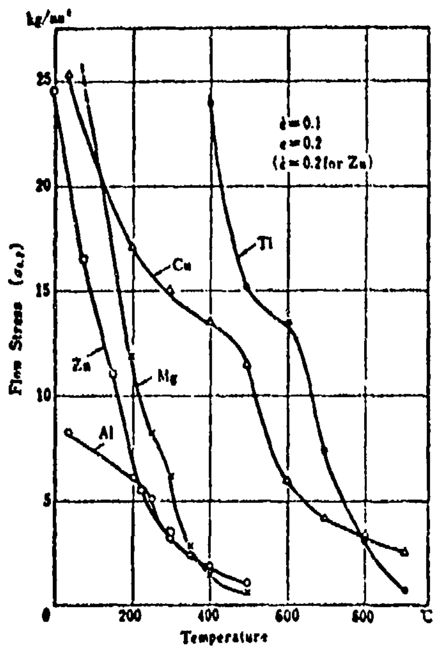


Fig. 3·1 Temperature Dependence of the Flow Stress of Commercial-Purity Metals.

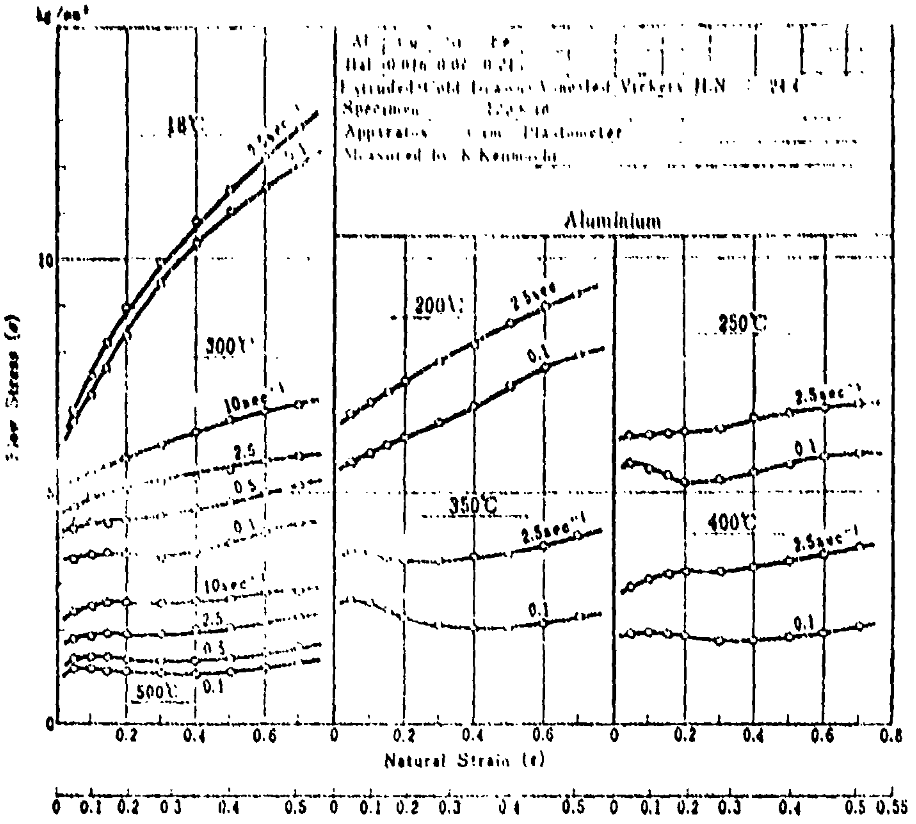


Fig. 4-8 Flow Stress-Strain Curves of Aluminium. Temperature Range: 18~500℃, Strain Rate Range: 0.1~10 sec⁻¹.

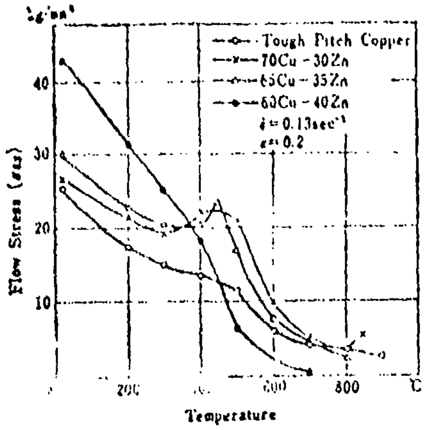


Fig. 2-8 Temperature Dependence of the Compression Stress of Copper and Copper-Zinc Alloys at ε = 0.2. Strain Rate: 0.13 sec⁻¹.

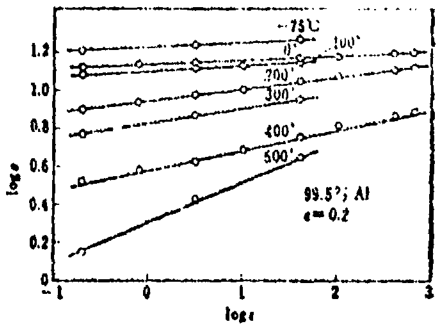


Fig. 2-10 Strain Rate Dependence of the Flow Stress of 99.5% Al at ε = 0.2.

Dynamic Compression	CAMPBELL and BRIGGS (1969), [9]	6

Apparatus: Universal rapid load testing machine, hydraulically operated.
Max. ε = 0.1; Mean $\dot{\varepsilon}$ = 6 x 10^{-3}/100 sec^{-1}

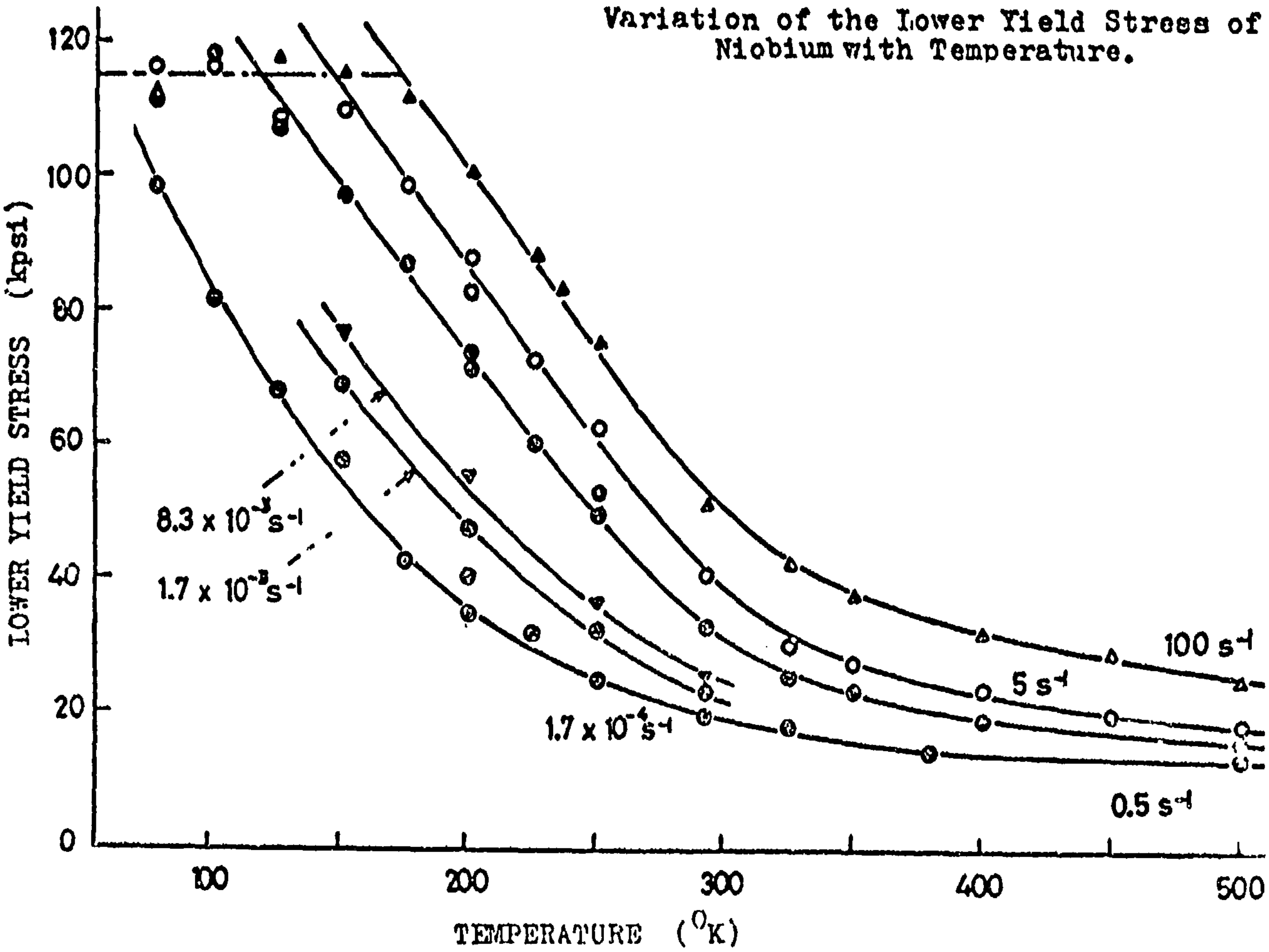
Mat.: Niobium (electron beam melted); sintered Molybdenum, 3 mm dia. Swaged and centreless ground rods.

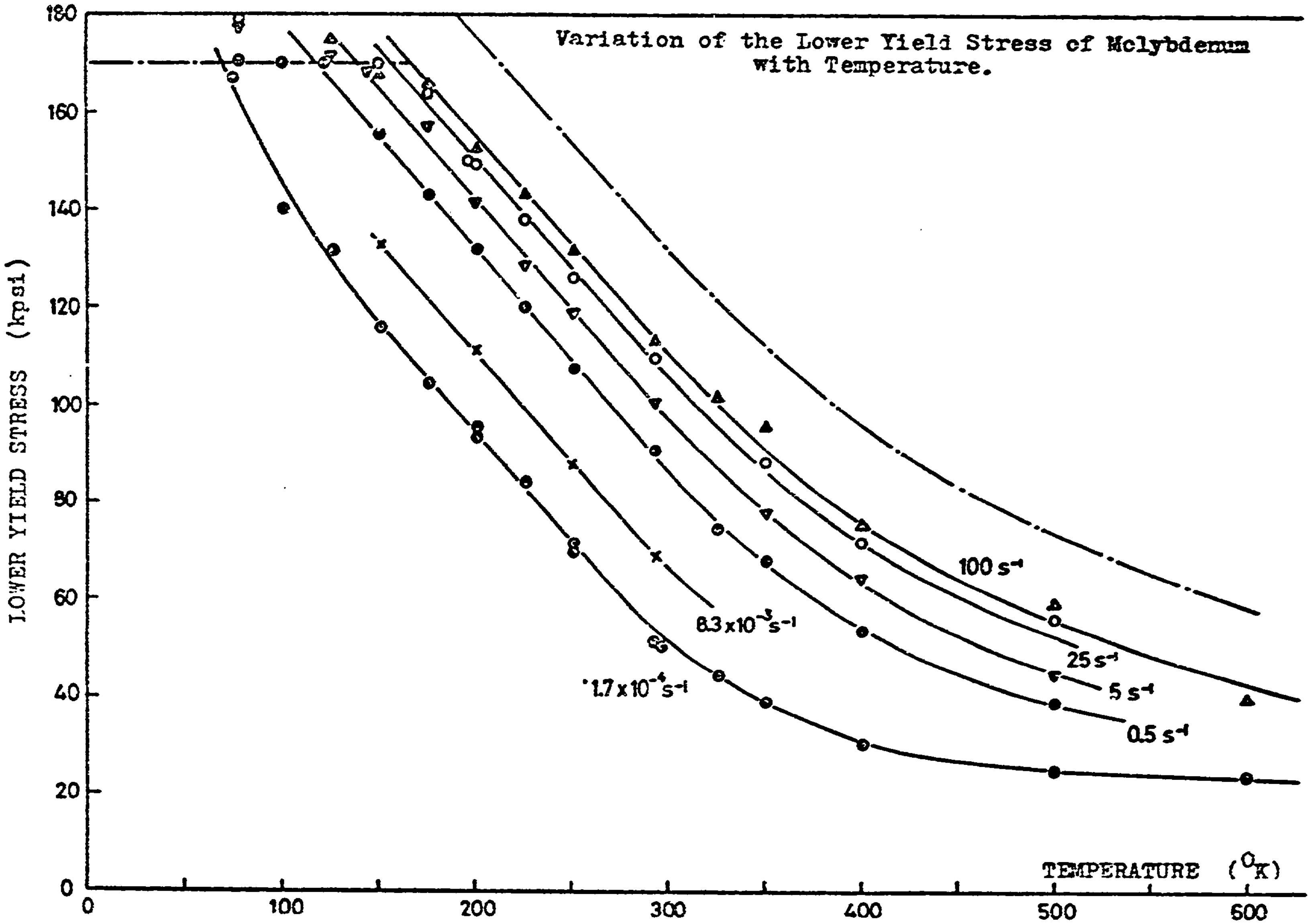
Spec.: Cylinders, parted off by spark machining, D = 3, L = 5 mm
Annealed: Niobium: 1020° C x 1 hr in vacuum, furnace cooled;
Molybdenum: 1200° C x 2 hrs in vacuum, furnace cooled.

Heat: Spec. enclosed within a small resistance furnace.
Testing Temp: 77, 292, 400, 500, 600° K

Meas. Instr.: - Load: strain gauge dynamometer
- Crosshead velocity: with an electromagnetic transducer. Outputs fed simultaneously into CRO & recorded on film.

Variation of the Lower Yield Stress of Niobium with Temperature.




Variation of the Lower Yield Stress of Mclybdenum
with Temperature.
LOWER YIELD STRESS (kpsi)
TEMPERATURE (°K)
0
20
40
60
80
100
120
140
160
180
0
100
200
300
400
500
600
100 s⁻¹
25 s⁻¹
5 s⁻¹
0.5 s⁻¹
8.3 x 10⁻³ s⁻¹
1.7 x 10⁻⁴ s⁻¹

Dynamic Compression	GREEN and BABCOCK (1966), [13]	7

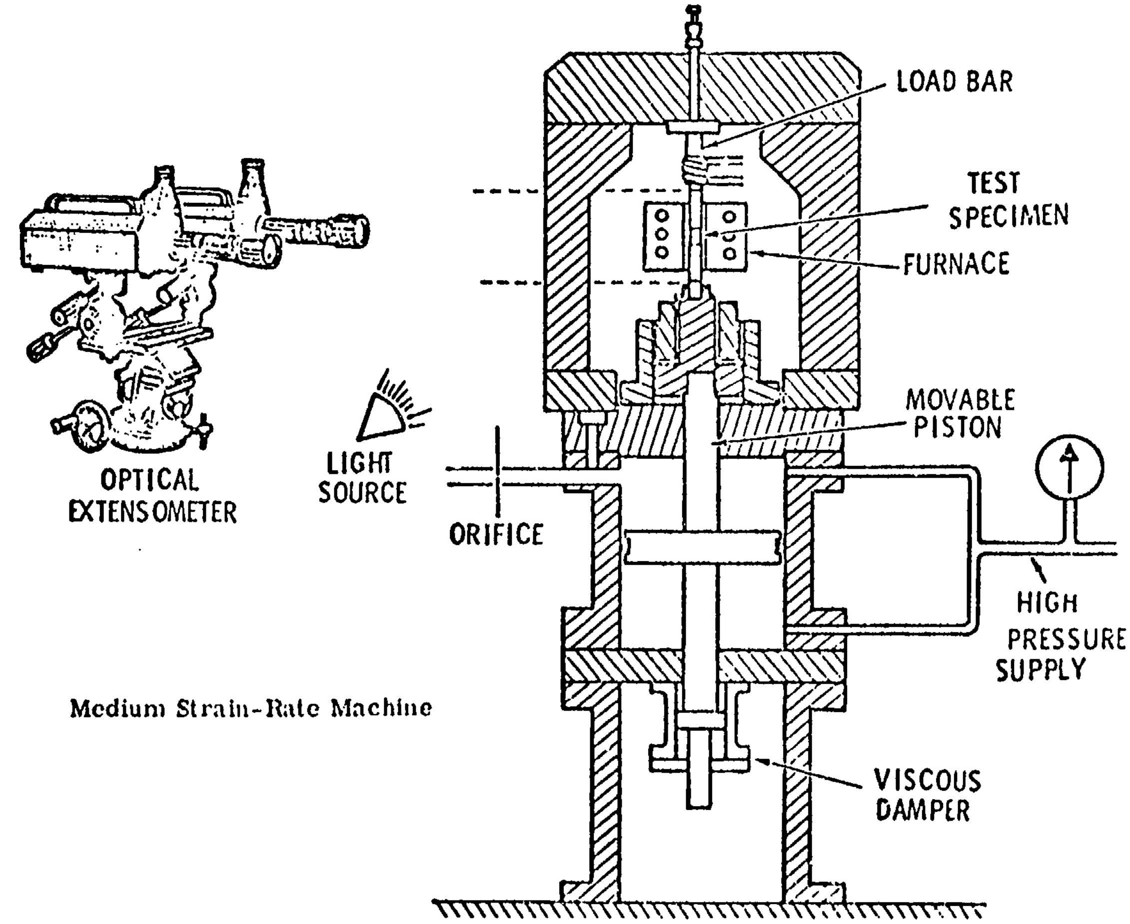
Apparatus: Gas operated device; desired constant strain rate is obtained by proper selection of gas (air, helium or nitrogen), pressure and orifice size. $\dot{\varepsilon}$: constant true $\dot{\varepsilon}$ = 0.001/100 sec^{-1}.

Mat.: 6061-T6 Alum. alloy; 7075-T6 Alum. alloy; 6Al-4V Titanium alloy; I-400 Beryllium.

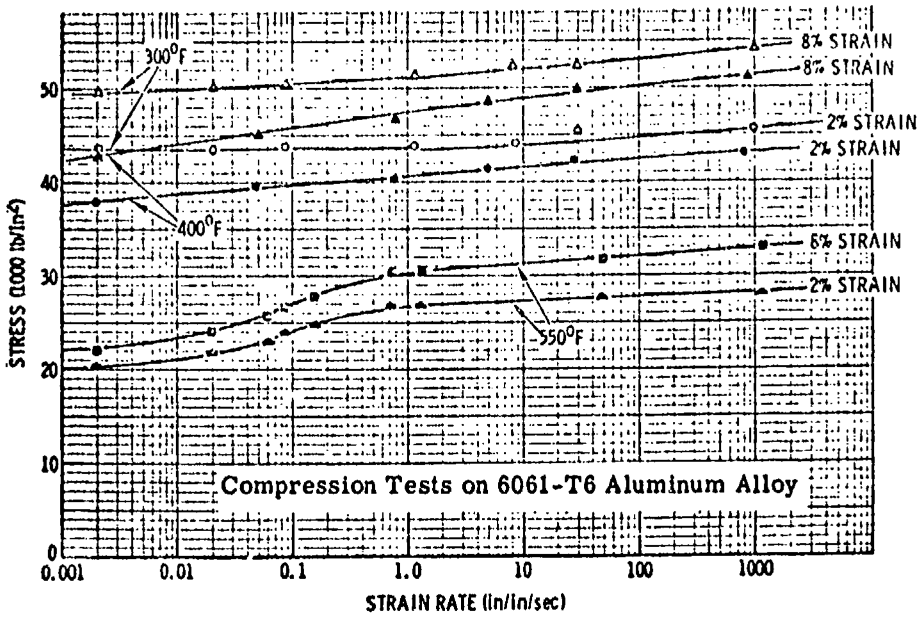
Spec.: Cylinders; Alum. alloys: D = 0.375 × L = 0.500 or D = 0.125" × L = 0.625"
Titanium and Beryllium: D = 0.250 × L = 0.500 or D = 0.125" × L = 0.625"

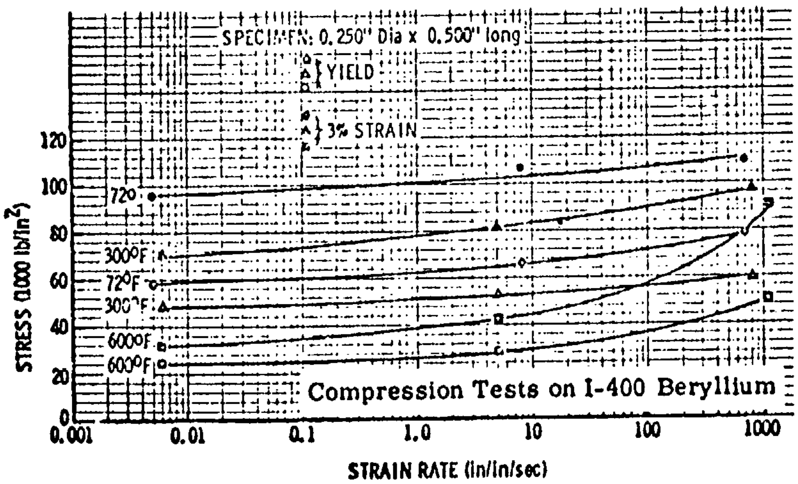
Heat: A radiant energy furnace with three independently controlled zones is used to heat the specimen and maintain uniform temp. along its length.
Test temp.: Alum., 72/550°F; Tit. alloy, 72/600; Beryllium, 72/600

Meas. Instr.: - Load: Measured by strain gages mounted on an elastic load bar directly above the specimen.
- Strain: by measuring piston displacement; by using strain gages mounted on specimen; by using an optical extensometer to look at marks placed on the specimen.

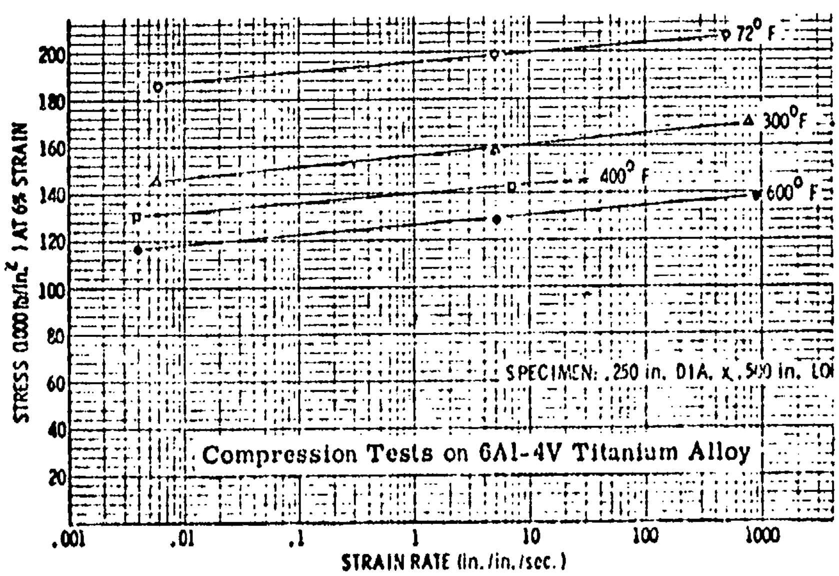


Medium Strain-Rate Machine





Flow Stress
vs
Log Strain Rate



Impact Compression	SUZUKI et al (1968), [41]	8

Apparatus: Experimental Drop Hammer.
$\dot{\varepsilon}$ = 100/650 sec^{-1}

Mat.: Aluminum, Duralumin, Zinc, Magnesium, Titanium, Copper and its alloys, Different kinds of steel.

Spec.: D = 12, L = 18 mm, and 8 × 12 mm.

[Lubr.: $\theta < 600$: Colloidal Graphite; $600 < \theta < 800$: Lead Glass $\theta > 1000°C$ = Pyrex glass. Degree of barrelling very small.]

Heat: Spec. in asbestos heated in Nichrome furnace for T < 600 or a silicon carbide furnace for T > 600, then compressed quickly in hammer.
Test temp.: Alum, 75/650; Duralumin, 200/500; Zinc; 75/300; Magnesium, 18/500; Titanium, 18/900; Steel, 800/1200°C

Meas. Instr.: Load: Capacitor Strainmeter.
- Strain: indirectly through hammer displacements by a photoelectric tube
Outputs fed into CRO and traces recorded on film.

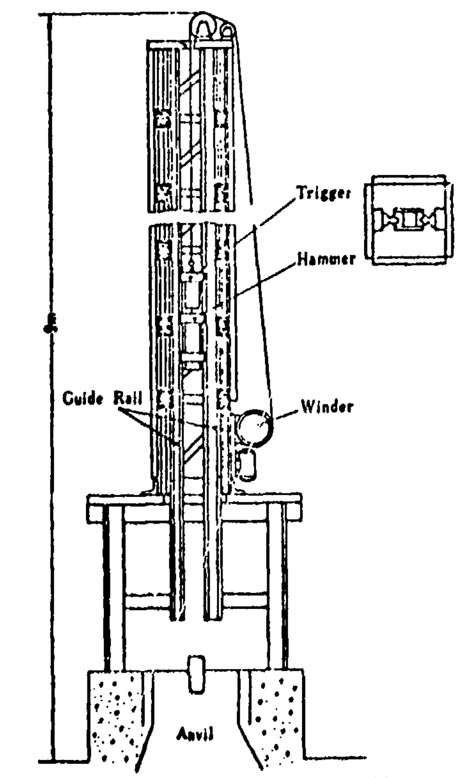


Fig. 1·3 Drop-Hammer Type of Testing Machine. Weight of Hammer 25, 50 kg, Maximum Strain rate 700 sec^{-1}.

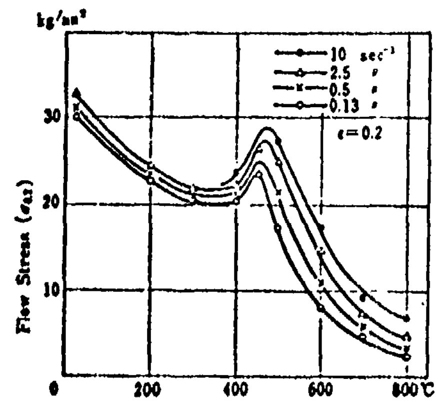
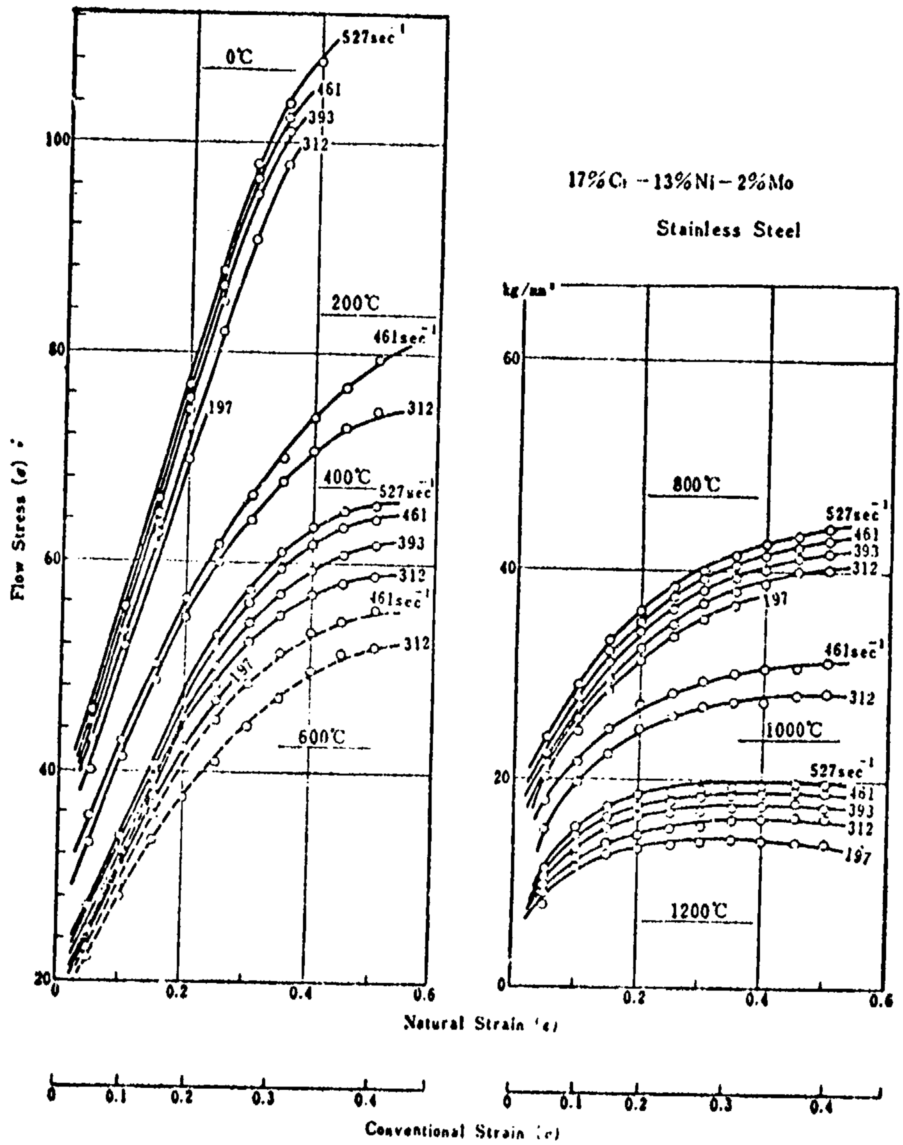


Fig. 2·6 Temperature Dependence of the Compression Stress of 65%Cu-35%Zn Alloys at ε=0.2.



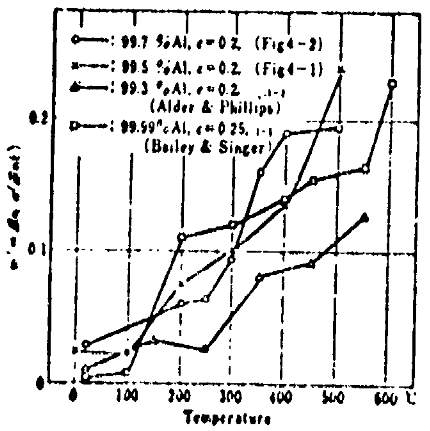


Fig. 3·13 "m"-Temperature Relation for Aluminium.

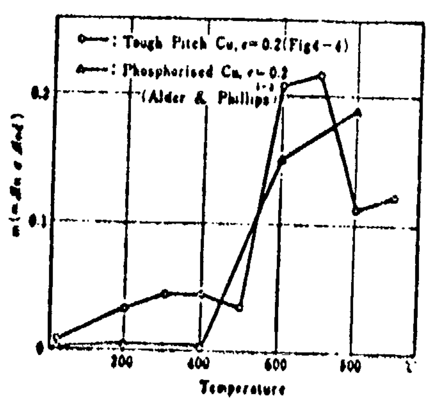


Fig. 3·12 "m"-Temperature Relation for Copper.

Impact Compression	SAMANTA (1968, 1969), [32, 33]	9

<u>Apparatus:</u> Experimental Drop Hammer.
Mean $\dot{\varepsilon}$ = for Alum: 110/260 sec^{-1}; Copper: 155/600 sec^{-1}

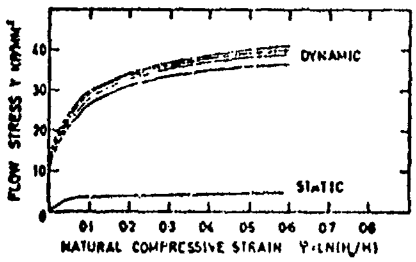
<u>Mat.:</u> Alum., commercially pure, 20 mm bars. [33]
Copper, 99 %, 20 mm bars. [33]
Steel, 5 different types. [32]

<u>Spec.:</u> Cylinders, Alum: D = 20, L = 20 mm, Annealed 325 × 1 hr
Copper: 20 × 10 mm, annealed: 650°C × 20 min, water quenched
Steel: 20 mm dia with different D/L ratios.

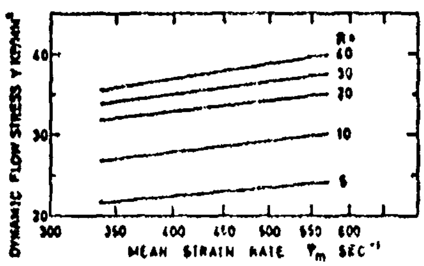
<u>Heat:</u> Spec. enclosed in a platinum cylindrical furnace, then transported through a highly polished shannel to platen and compressed.
Test Temp.: Alum, 250/550; Copper, 450/900; St., 20/1055°C

<u>Meas. Instr.:</u> - Position of tup: with capacitive gauge.
- Retardation of tup: with piezoelectric accelerometer.
Outputs fed into CRO and recorded on film, as displacement-time and force time relations for specimen (assuming wave effects in tup negligible.)

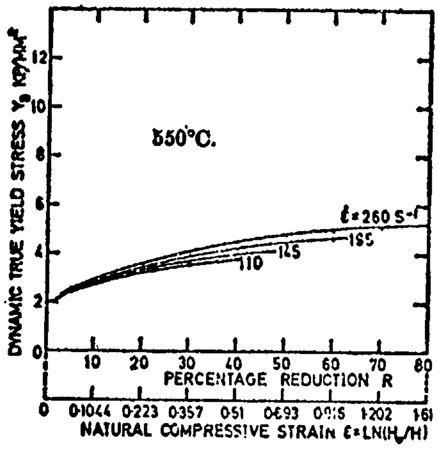
[$\dot{\varepsilon}$ = velocity/height at any instant, $\dot{\varepsilon}$-ε relation was plotted and mean integrated value taken as mean $\dot{\varepsilon}$]



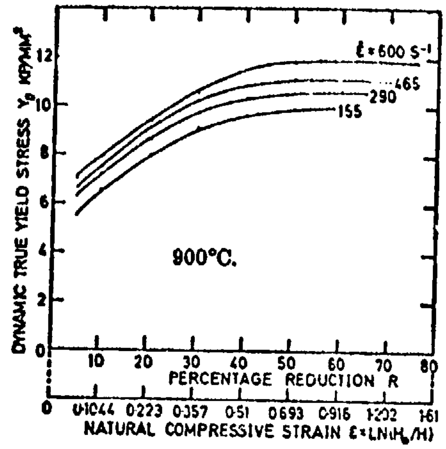
Relation between true compressive stress and natural compressive strain for high-speed steel (SIS 2722) at 1055°C



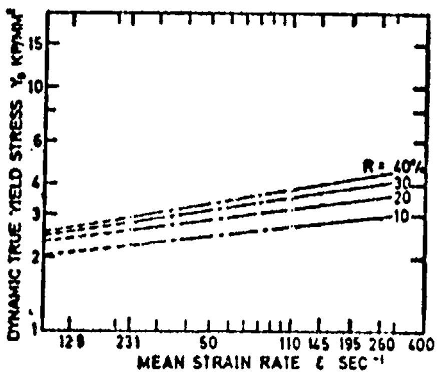
Relation between true dynamic compressive stress and mean strain-rate for high-speed steel (SIS 2722) at 1055°C.

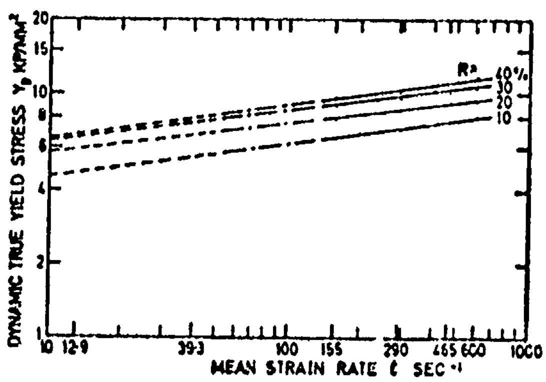


aluminium



copper





Relation between dynamic true yield stress and mean strain-rate for

aluminium at 550°C. copper at 900°C.

Impact Compression	MAHTAB, JOHNSON and SLATER (1965), [25]	10

Apparatus: Equipment for dynamic indentation, include horizontal air gun firing 0.5" dia cylindroconical projectiles
Impact vel.= 1000 - 2500 in/sec; $\dot{\varepsilon}_{mean} = 10^3/10^4 \text{ sec}^{-1}$

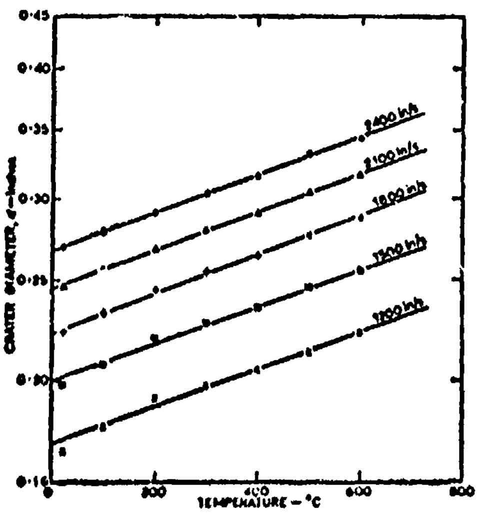
Mat.: Copper and Aluminum alloy.

Spec.: 1.5" square section bars used as targets
Annealed: Copper = 550 × 1 hr; Alum 450 × 1 hr

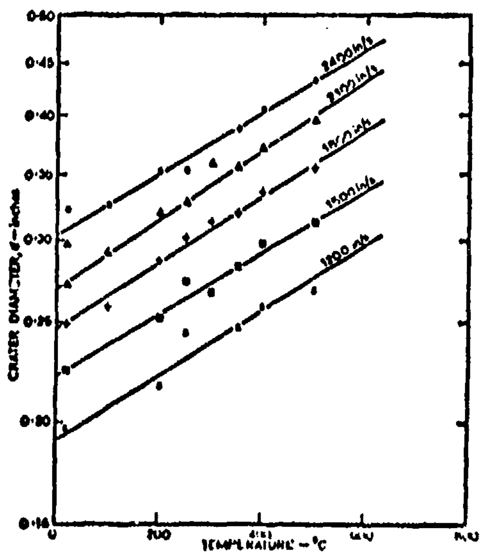
Heat: Spec. heated and tested in furnace
Test temp.: Copper, up to 600°C; Alum. up to 550°C

Meas. Instr.: - Impact velocity by measuring time between 2 signals from 2 phototransistors 2" apart.
- Diameter of crater on spec., after being cooled. (Correction for temp. effect on dia. done).

[Mean effective indentation pressure calculated using relation derived theoretically.
Mean $\dot{\varepsilon} = \bar{\varepsilon}/t = \bar{\varepsilon}v/y$; $\bar{\varepsilon} = 1$, v = mean indentation speed, y = indentation depth.]



a Annealed copper, B.S. 1433.



b Annealed aluminium alloy, B.S. 1476 HB 10.

Relation between the logarithm of the crater diameter and temperature for different impact velocities

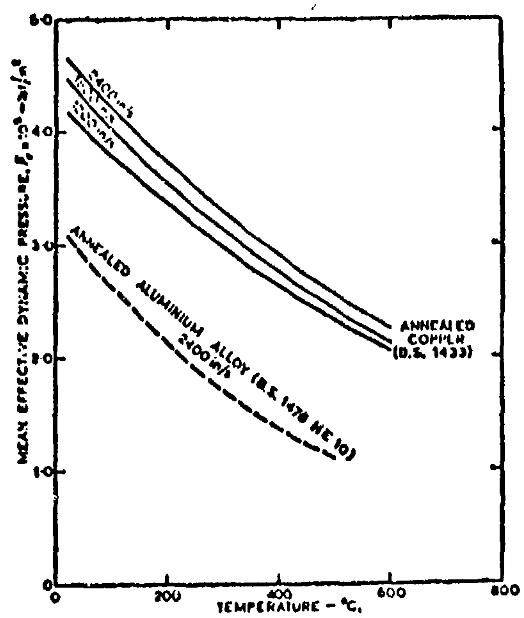


Fig. 12a. Relation between the mean effective dynamic indentation pressure $\bar{P}_d$ *and temperature*

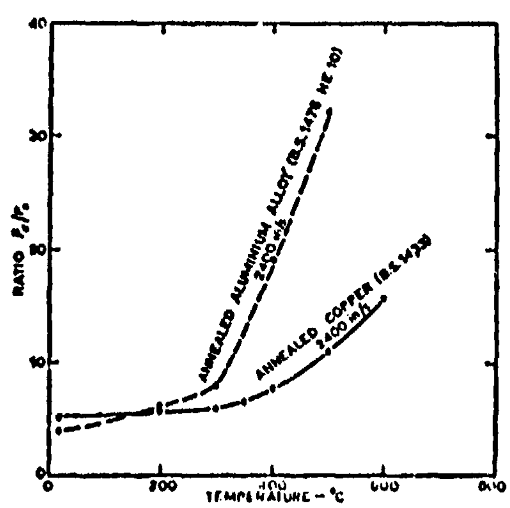


Fig. 12b. Relation between $\bar{P}_d/P_s$ *and temperature*

Impact Compression	BARAYA, JOHNSON and SLATER (1965), [8]	11

Apparatus: Experimental drop hammer.
Tup assembly mass = 15.7 lb; Dropping heights = 5, 7.5, 10, 15, 20 ft.
Max. $\dot{\varepsilon}$ = variable during test, max mean $\dot{\varepsilon}$ = 650 sec^{-1}

Mat.: Super Pure Alum.

Spec.: Cylinders, D = 1", L/D = 2, 1.5, 1, 0.5; annealed at 300°C × 1 hr.

Heat: Specimen in subpress heated in furnace to desired temp., then quickly transferred and compressed in hammer.
Max. temp. drop = 5°C
Test temp.: 20, 100, 200, 300, 400, 500°C

Meas. Instr.: Tup mass and dropping height are predetermined before test. Mean dyn. yield stress $\bar{Y}$ & mean strain rate $\dot{\varepsilon}$ are computed from:

$$E/V = \bar{Y} \left(\ln [1/(1-R)] + \frac{c}{6(H/D)} [R/(1-R)]\right); \quad \dot{\varepsilon} = 151.2c/HR$$

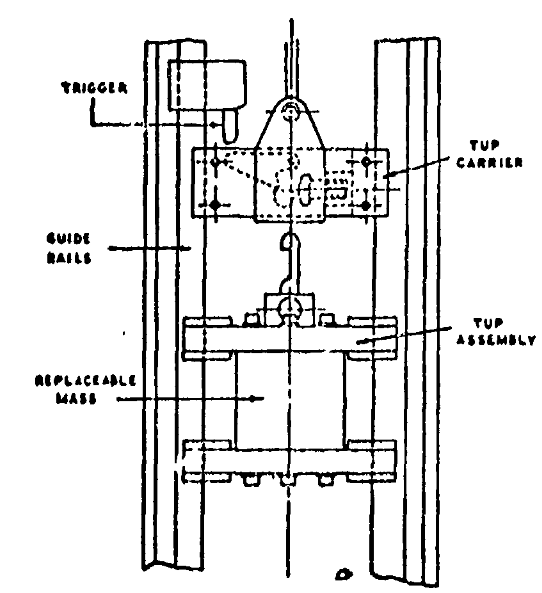


Fig. 1 Diagram of triggering mechanism and tup assembly.

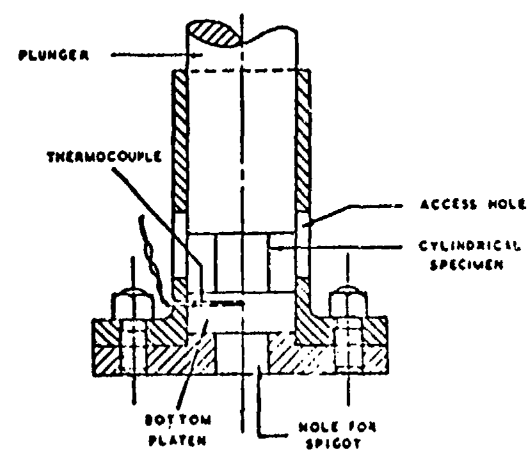
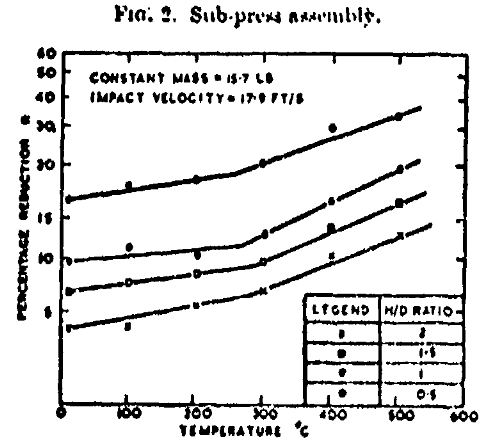
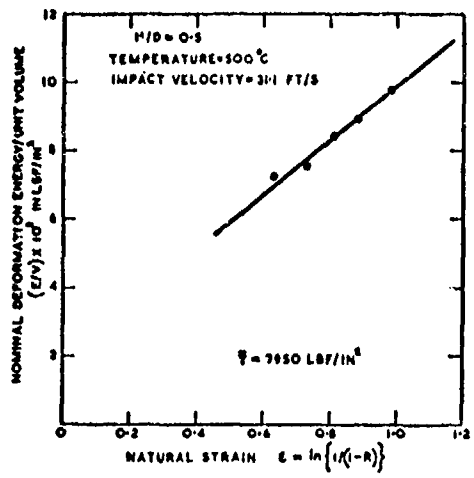


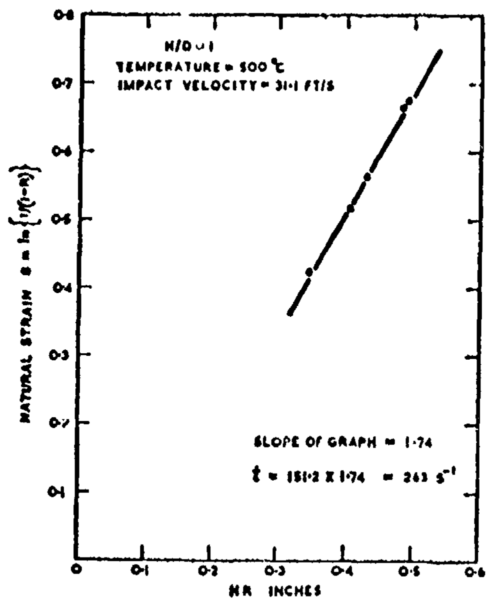
FIG. 2. Sub-press assembly.



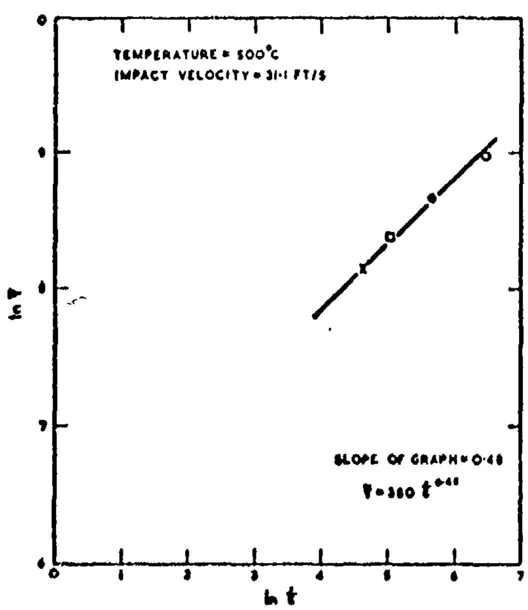
Relation between log R and temperature



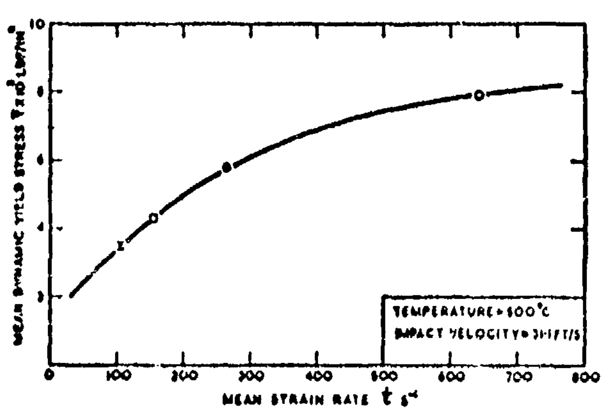
Relation between deformation energy/unit volume and natural strain



Relation between natural strain and the product HR,



Logarithmic relation between mean dynamic yield stress and mean strain rate for super-pure aluminium.



Relation between mean dynamic yield stress and mean strain rate for super-pure aluminium

Impact Compression	HAWKYARD, EATON and JOHNSON (1968), [14]	12

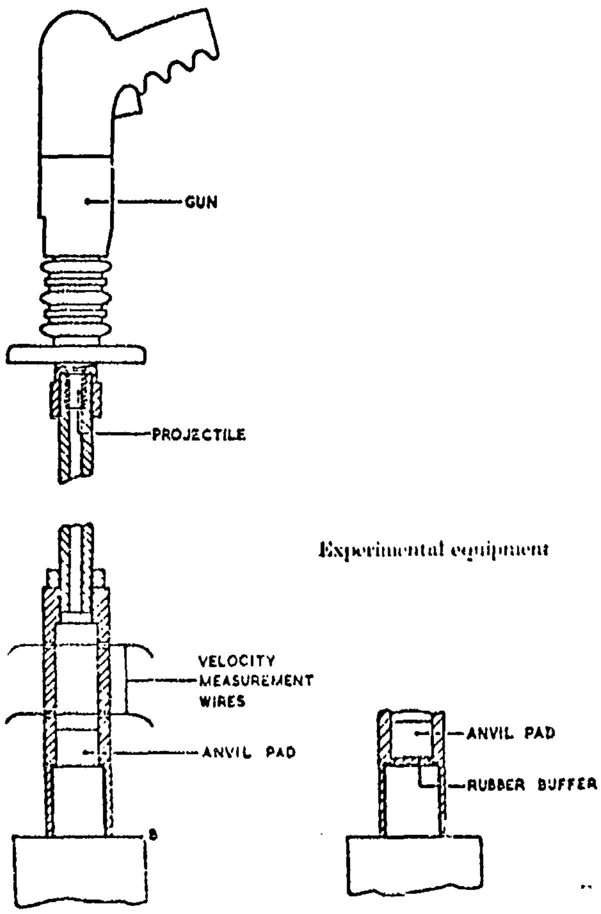
Apparatus: Commercial stud-driven gun for firing flat ended cylindrical projectiles (specimens) on a hardened steel anvil.
Impact vel. ∿ 600 ft/sec ; $\dot{\varepsilon}$: mean rate ∿ 5×10^3 sec^{-1}

Mat.: High conductivity Copper, B.S. 1432
Annealed Steel to B.S. 970 En 2
Bright drawn Mild Steel to B.S. 970 En 1a

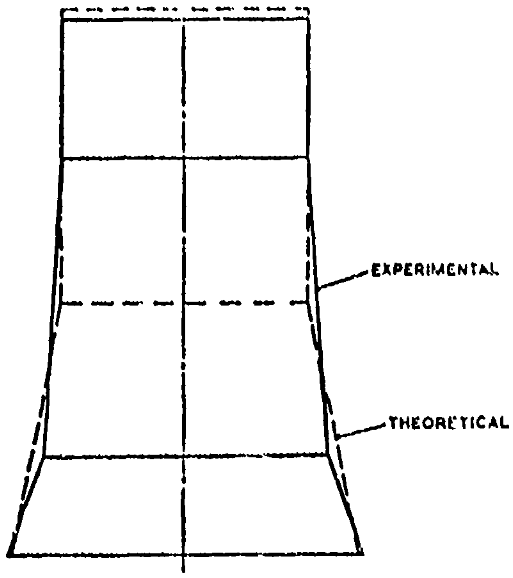
Spec.: Cylinders, 0.370" dia × 1" long

Heat: Spec. preheated in an electric furnace to a greater temp. than required, transferred quickly within a steel jacket into position and fired after a predetermined interval when it is expected to reach desired temp.
Test temp.: 20, 400, 600, 700°C.

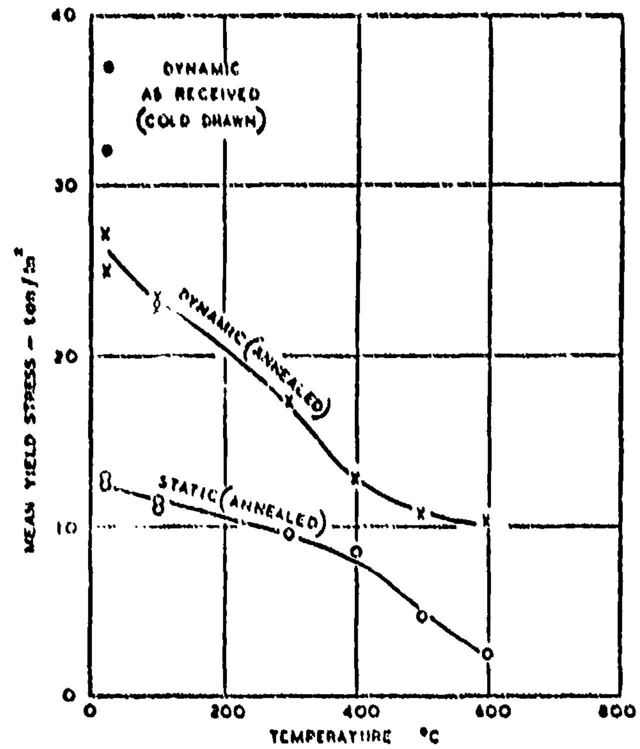
Meas. Instr.: - Impact vel. before impact: by measuring time interval between fracture of 2 fine wires in the path of the projectile (wires connected to microsecond timer).
- Deformed specimen profile obtained using a Shadowgraph..
[Equating K.E., from impact velocity measurement, to mean plastic strain energy, from spec. profile, gives mean eff. yield stress]



Experimental equipment



Comparison between a typical experimental profile and a theoretical profile based on Taylor's analysis.



Showing variation of mean dynamic yield stress σ_D and mean static yield stress σ_S with temperature for copper.

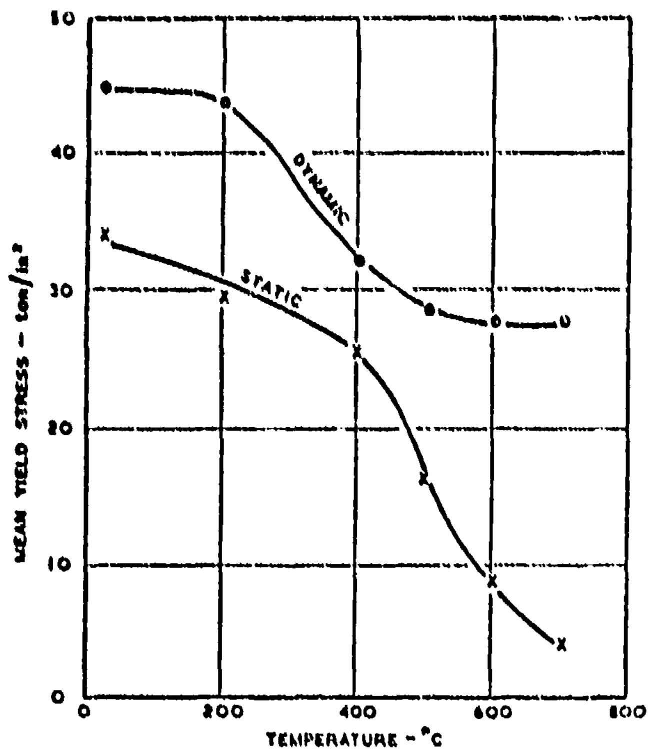


FIG. 15. Showing variation of mean dynamic yield stress σ_D and mean static yield stress σ_S with temperature for annealed mild steel En 2.

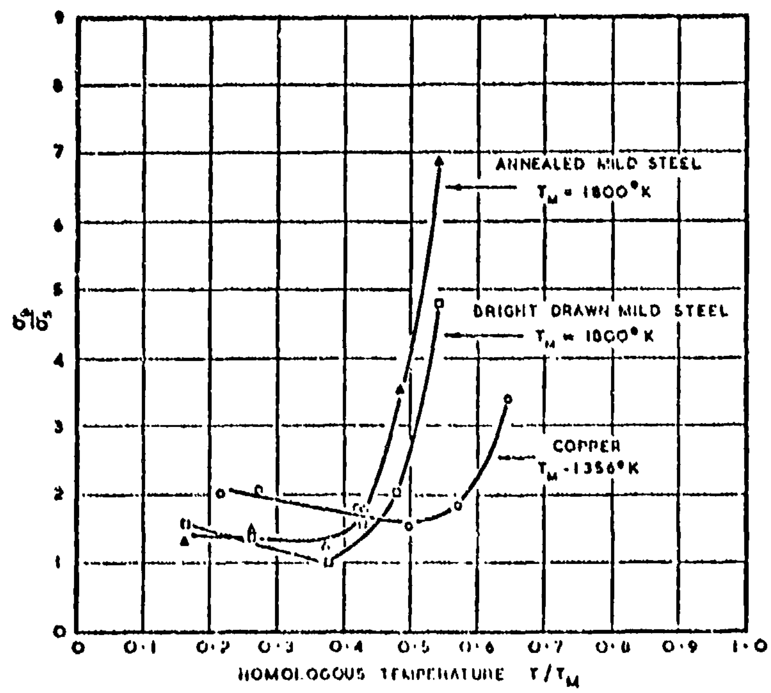


FIG. 16. Showing variation of dynamic/static mean yield stress ratios with homologous temperature (T/T_M).

Impact Compression	CHIDDISTER and MALVERN (1963), [11]	13

<u>Apparatus</u>: Split Hopkinson pressure bar

Loading: Hyge shock tester and striker bar.

$\dot{\varepsilon}$ = 300/2000 sec^{-1} nearly constant during test.

Max. ε = 0.05 for lowest $\dot{\varepsilon}$, and 0.25 for highest $\dot{\varepsilon}$

<u>Mat.</u>: Aluminum 1100 F, extruded

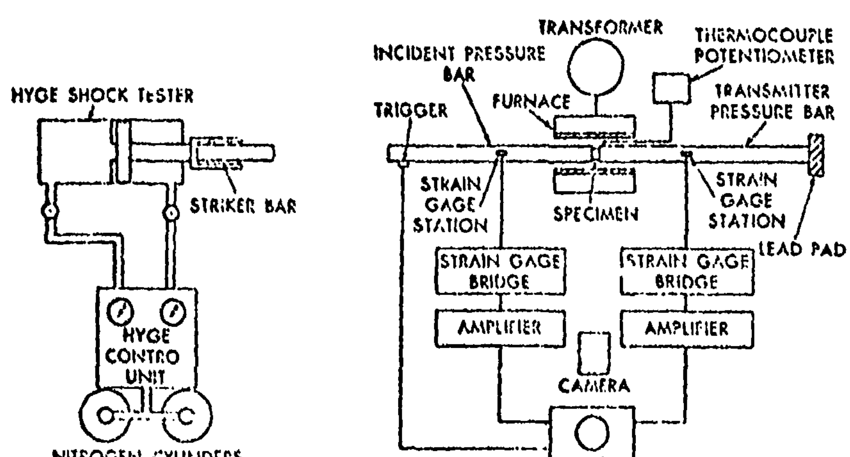
<u>Spec.</u>: D = <$\frac{3}{4}$" (bars dia.) × L = $\frac{1}{4}$" ; Annealed: 400°C × 1 hr

[<u>Lubr.</u>: Powder Graphite: 250°C , Powder glass + alcohol: 550°C
Molykote (commercial Molybdenum disulfide: at other temps.
No barrelling at room temp; slight, at higher temp.]

<u>Heat</u>: Electric combustion tube furnace, 12" long heating elements,
TC welded to transmitter bar $\frac{3}{4}$" from specimen
Temp. distribution by TC (chromel alumel) 2 inches apart.
Test temp.:30,150, 250, 350, 450°C

<u>Meas. Instr.</u>: 2 opposite foil strain gauges at each station (θ = room temp).
Output fed to CRO, signal recorded on film as ε_I, ε_R, ε_T.

$$[\varepsilon_s = \frac{2\,C_\alpha}{L_o}\int_0^k (\varepsilon_{I\alpha} - \varepsilon_{TB} - \varepsilon'_\alpha)\,dt \;;\; \sigma_s = E_B(\varepsilon_{TB} - \varepsilon''_B)]$$



Experimental test setup

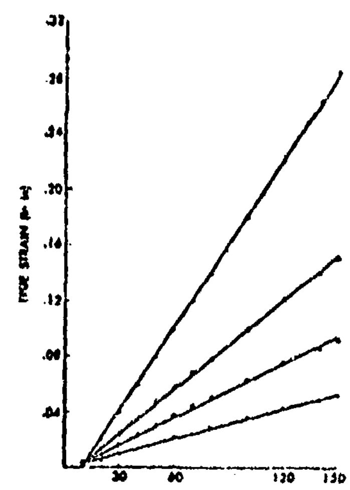
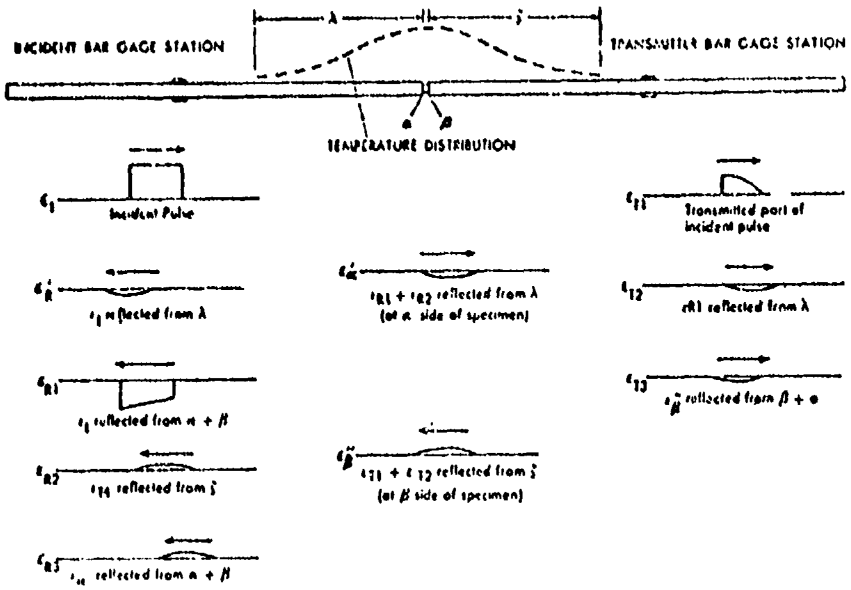
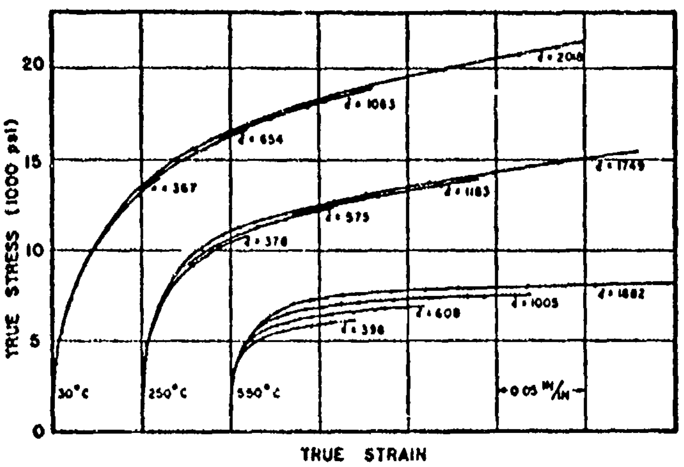


Fig. 7—Strain-tim curves at 30°C



Reflected and transmitted strain pulses



STRESS-STRAIN CURVES AT VARIOUS TEST TEMPERATURES.

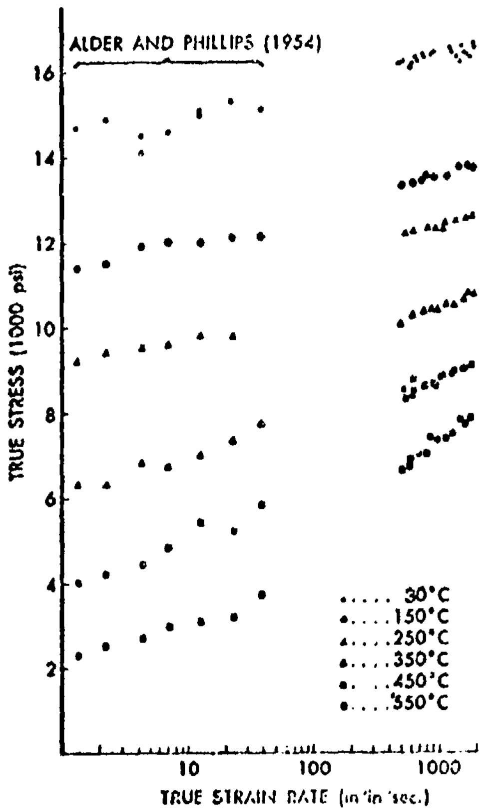


Fig. 13--Semilogarithmic plot of stress vs. strain rate at 10.54 percent true strain

Impact Compression	WATSON and RIPPERGER (1969), [43]	14

Apparatus: Variation of split Hopkinson pressure bar
Loading: Air gun and projectile.
Max $\dot{\varepsilon} = 10^3$ sec^{-1}; variable during test
Max $\varepsilon = 0.6\%$

Mat.: High purity Copper, Iron

Spec.: $D = \frac{1''}{2}$, $L = 1''$; ends lapped; lateral sides grit blasted

Heat: in furnace with 11" long quartz lamps.
Temp. Control: T.Couple → temp. controler → power controller → furnace
Test Temp.: Copper and Iron: 78, 400, 600, 800, 1000°F.

Meas. Instr.: Thin quartz crystal, for mean stress over cross section
High temp. strain gage welded to specimen, for mean strain
Output fed in CRO, signal recorded on film.

[N.B. Since $\dot{\varepsilon}$ could not be maintained constant during the course of a single test, the values of stress and strain at each strain rate deduced from several different tests, and therefore from several different specimens of the same material]

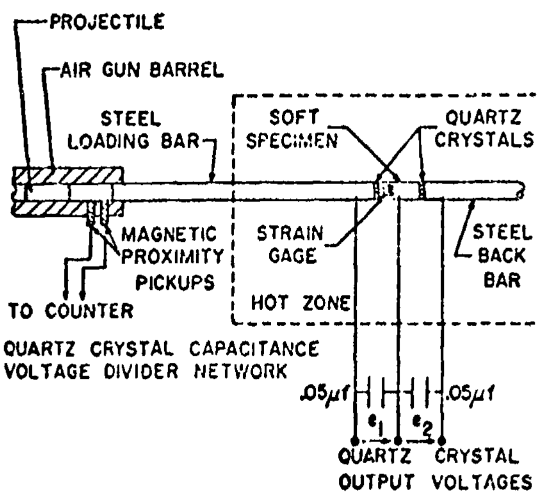


Fig. 1—Schematic of short-specimen impact setup

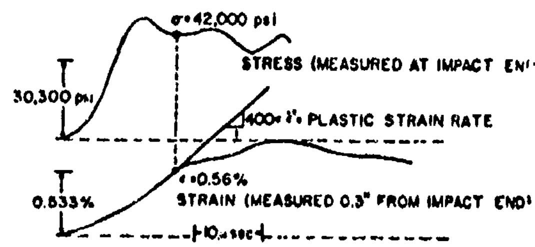


Fig. 6—Typical short-specimen dynamic-test results for copper at 600° F

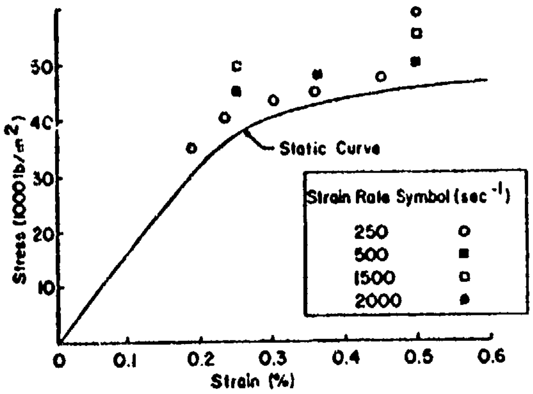


Fig. 7—Copper stress-strain-strain rate at 78° F

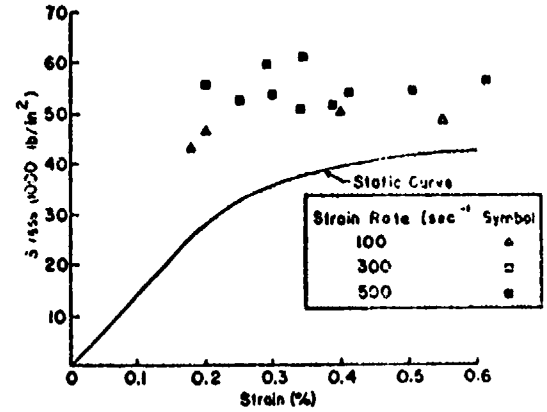


Fig. 8—Copper stress-strain-strain rate at 400° F

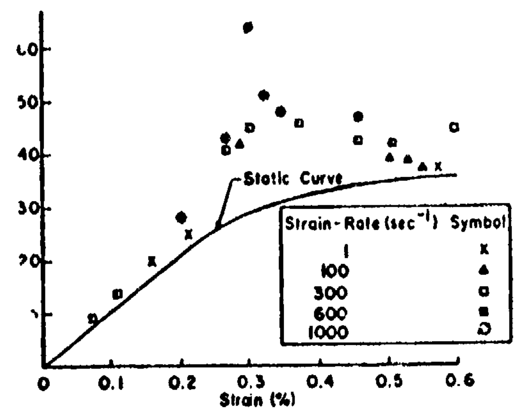


Fig. 9—Copper stress-strain-strain rate at 600° F

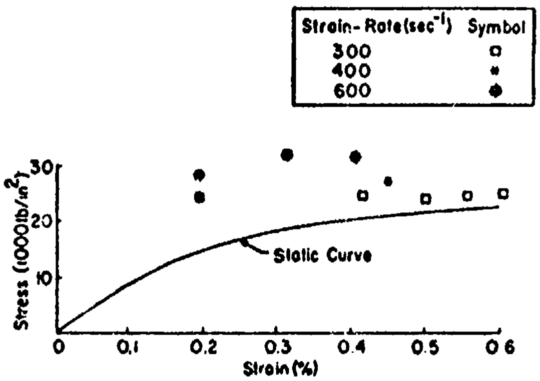


Fig. 10—Copper stress-strain-strain rate at 800° F

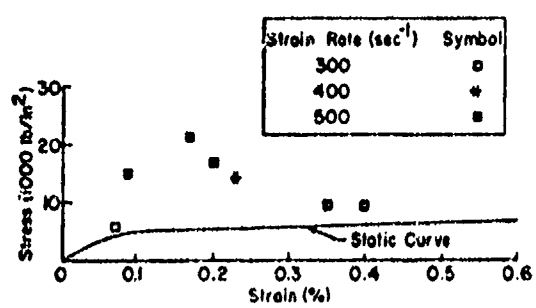


Fig. 11—Copper stress-strain-strain rate at 1000° F

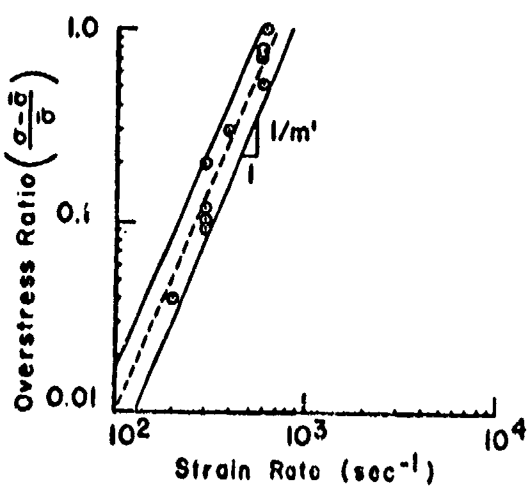


Fig. 12—Copper dynamic overstress ratio vs. strain rate at 800° F

Impact Compression	GREEN and BABCOCK (1966), [13]	15

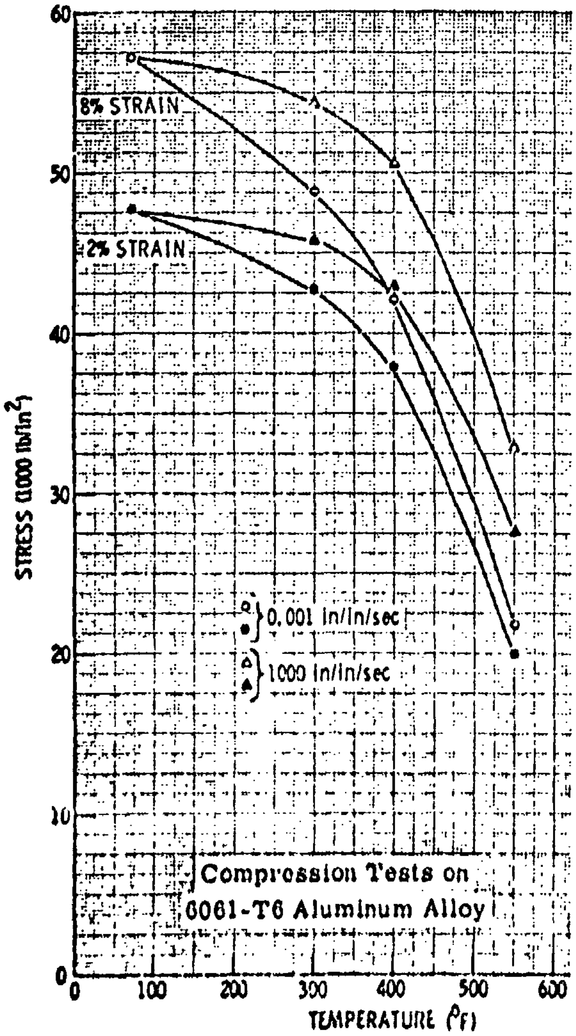
Apparatus: Split Hopkinson pressure bar
Loading: Launch tube and driver bar
$\dot{\epsilon} = 50/10^4 \text{ sec}^{-1}$, variable during test.
$\epsilon = > 0.5$

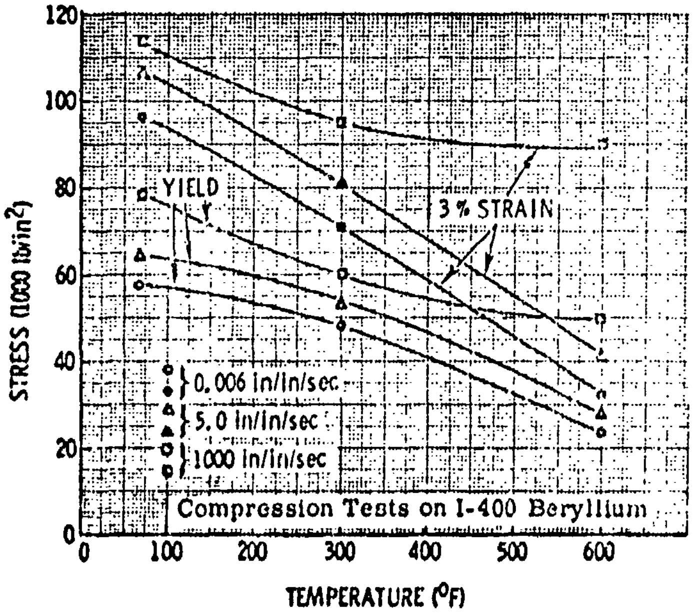
Mat.: Two Alum. alloys, Titanium, Beryllium

Spec.: Cylinders of different D/L ratios.

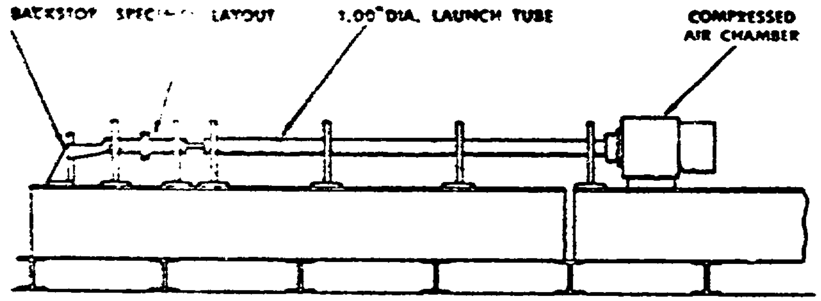
Heat: Specimen alone heated in a single zone resistance wire furnace. At testing temp., furnace is opened and pressure bars moved in quickly to compress the specimen. Insignificant heat conduction losses.
Test temp.: for all metals, 72, 300, 600°F.

Meas. Instr.: 3 strain gages in series at each gage station, output fed to oscilloscope and recorded on film.

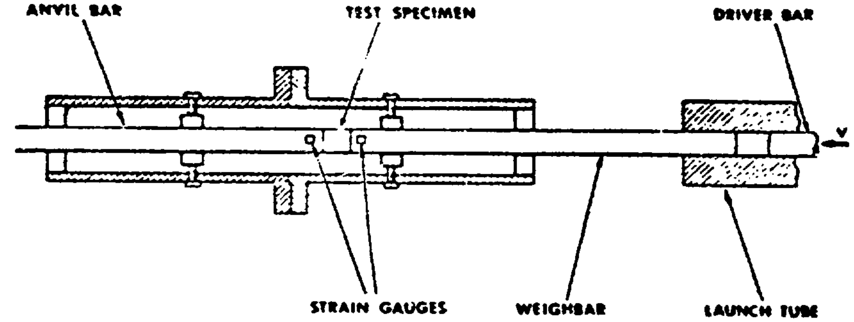




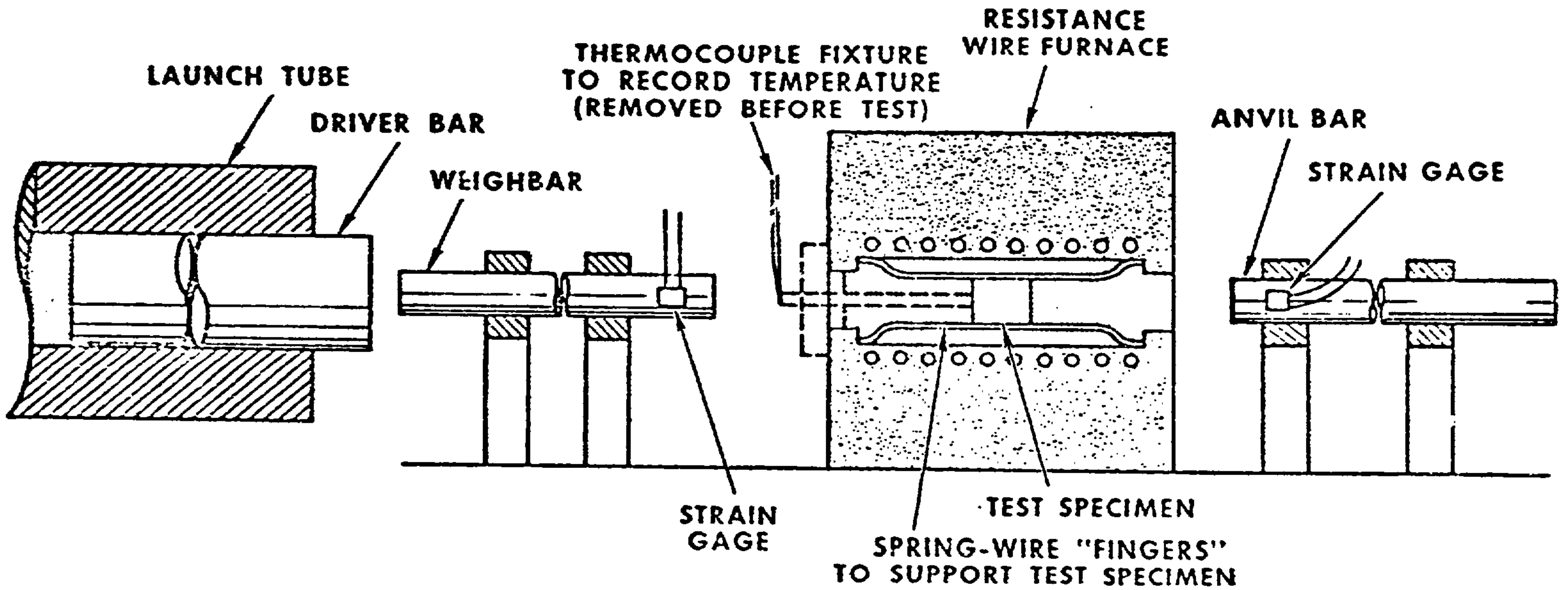
Flow Stress vs Temperature



Schematic of Modified Hopkinson Bar



Specimen Layout



BARS ARE SHOWN IN POSITION FOR HEATING SPECIMEN. THEY ARE MOVED TO TOUCH SPECIMEN BEFORE TEST IS CONDUCTED

Impact Compression	LINDHOLM and YEAKLEY (1968), [22] LINDHOLM (1968), [21]	16

Apparatus: Split Hopkinson pressure bar

Loading: striker bar producing pulse of constant amplitude

$\dot{\varepsilon}$ = up to 1000 sec^{-1}

Mat.: 1100 O Aluminum

Spec.: Cylindrical D = < pressure bar dia.

Heat: By a cyl. furnace surrounding the specimen, and producing symmetrical heat gradients along the bars.

Test temp.: 27, 127, 262, 402°C

Meas. Instr.: Strain gauges at 2 stations, output fed to CRO

ε_I, ε_R and ε_T recorded on film.

[N.B. Recorded strains are corrected using a correction factor

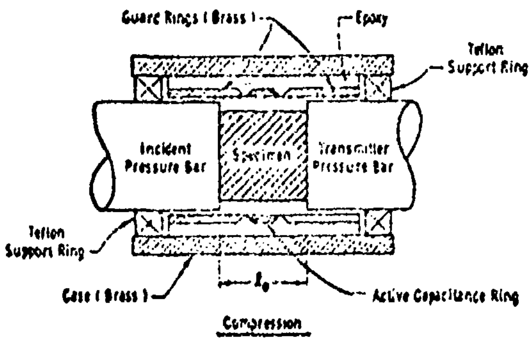
$\varepsilon_o/\varepsilon_T = (1 + c_a^{3/4})$, $C_a = a_2(T-T_o)/a$.

based on assumptions of:

- exponential temp. gradient $T - T_o = T_s e^{-kx}$; $T \geq T_o$
- linear dependence of modulus $E = a_1 + a_2(T - T_o)$.

Usual analysis for computing σ_s & ε_s is used.

Correction factor is checked experimentally].



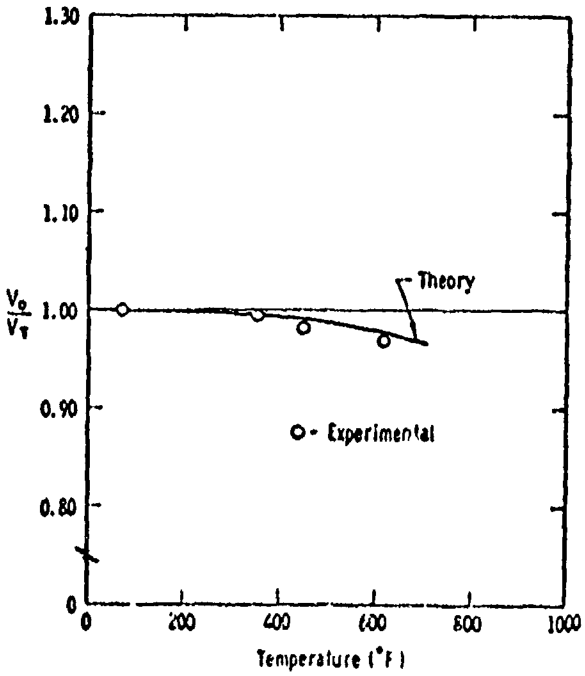


Fig. 7--Ratio of particle velocity at st... ...tion to particle velocity at heated end; comparison of theory with experiment

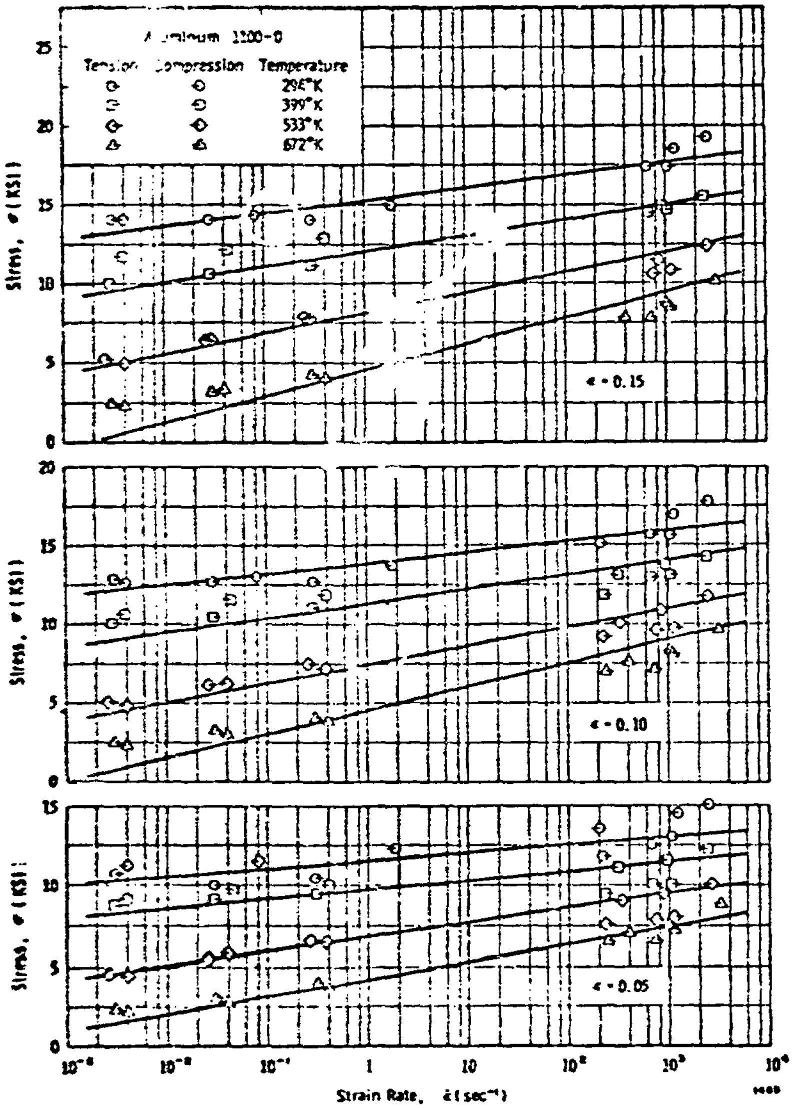


Fig. 5. Stress vs. strain-rate at constant temperature and strain.

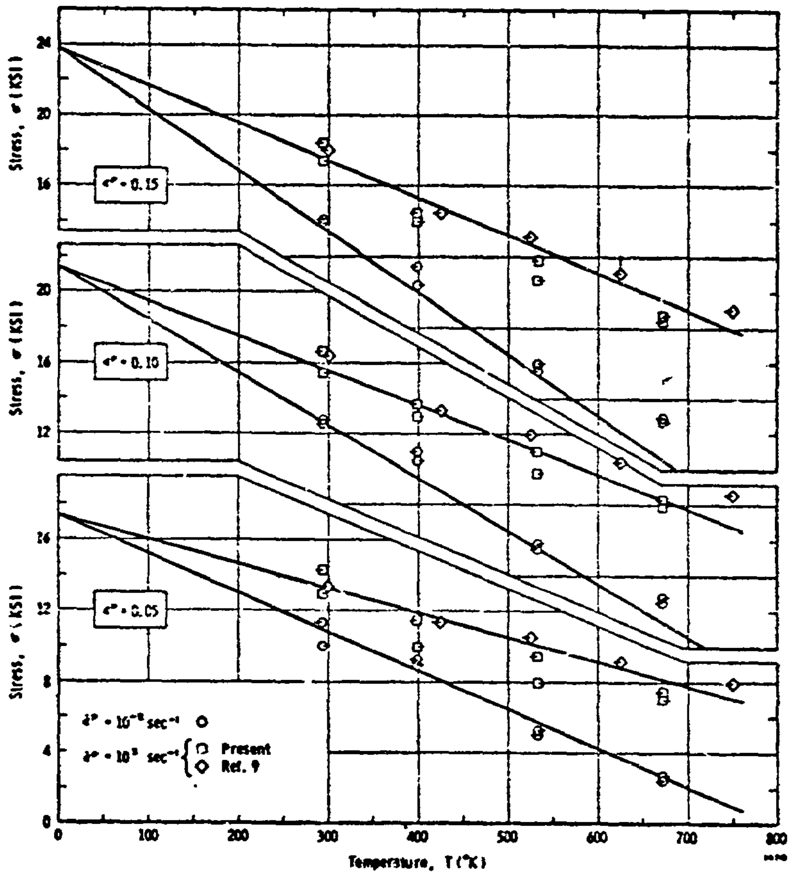


Fig. 6. Stress vs. temperature at constant strain-rate and strain.

Impact Compression	NAGATA, YOSHIDA and SEKINO (1969), [23]	17

Apparatus: Split Hopkinson pressure bar

$\dot{\varepsilon}$ = up to 4×10^3 sec^{-1}

Mat.: Polycrystalline iron containing 0.002, 0.01 and 0.05 wt % C. Ingots were forged, hot-rolled to bars and cold swaged.

Spec.: Cylindrical: D = 9 - 10 mm. , L = 5 and 10 mm. Annealed in vacuum at 570° - 880°C × 1-2 hr; furnace-cooled

Heat: Details not included in paper. Test Temp.: 77, 126, 196, 242, 293, 373, 473, 573°K.

Meas. Instr.: Strain gauges at 2 stations, output fed to CRO

ε_I, ε_R and ε_T recorded on film.

[N.B. Nothing is mentioned in the paper about the method used to bring the specimen to the required testing temp; for method of stress analysis, authors refer to their previous work on aluminum at room temp.; apparently, same analysis has been followed at other temperatures.]

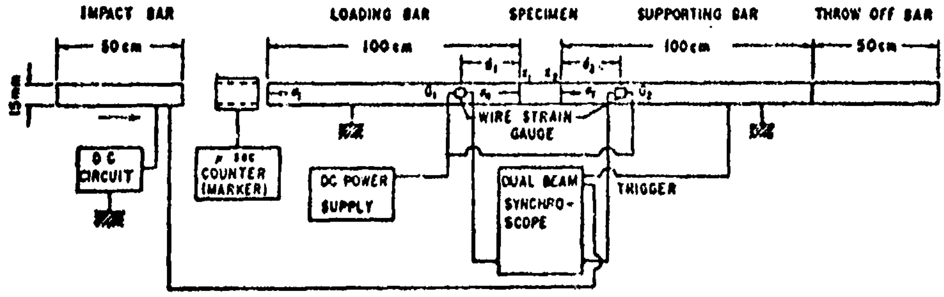
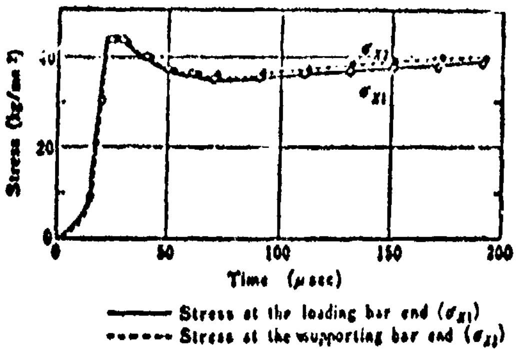


Fig.1 Schematic diagram of the apparatus.



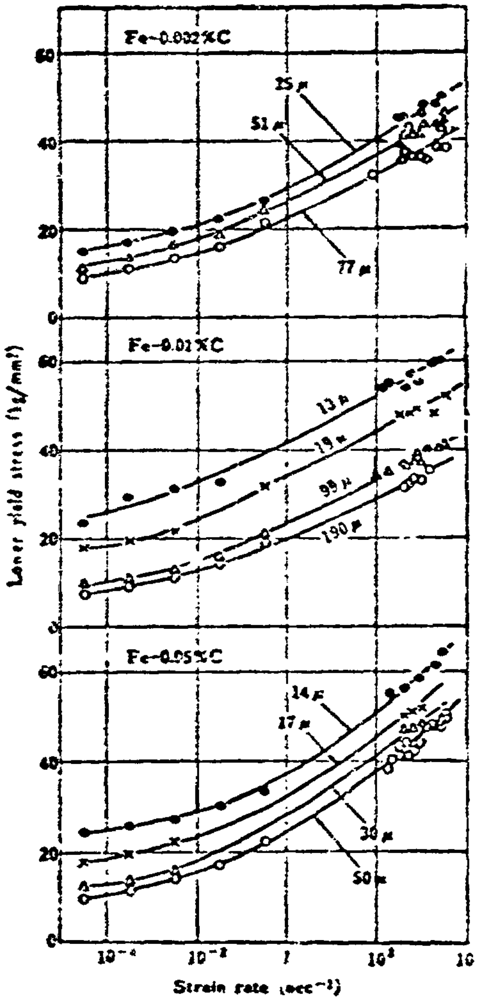


Fig. 4. Relation between the lower yield stress and the logarithm of the strain rate at room temperature for polycrystalline

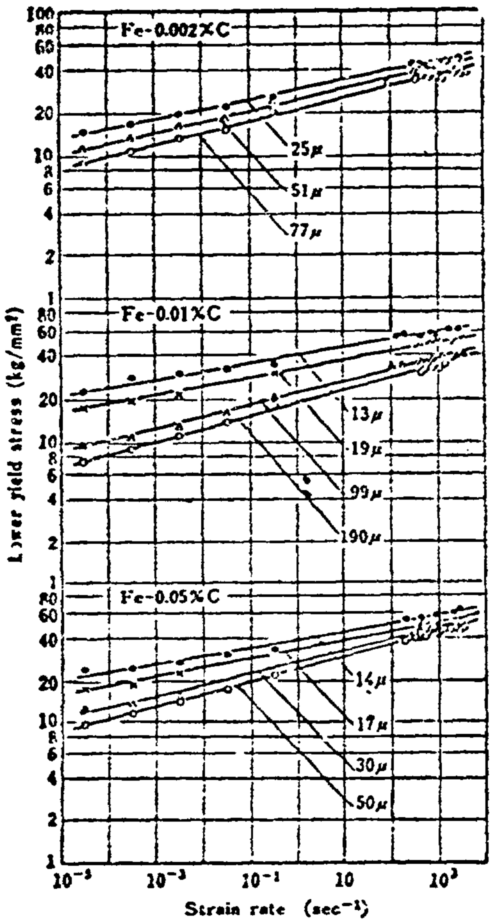


Fig. 10. Relation between the logarithm of the lower yield stress and that of the strain rate at constant grain diameters replotted from Fig. 4.

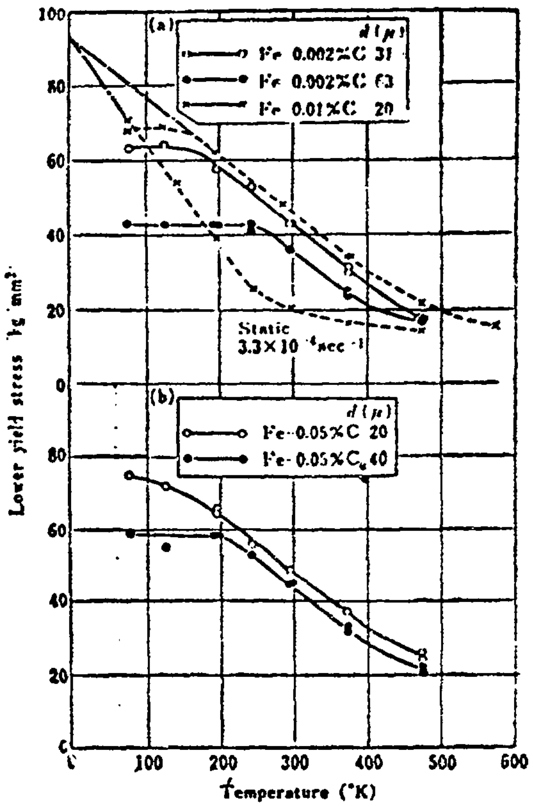


Fig. 7. Relation between the dynamic lower yield stress and temperature for specimens of Fe–0.002%C, Fe–0.01%C (a), and Fe–0.05%C (b)

Impact Compression	MULLER (1971), [26]	18

<u>Apparatus</u>: Split Hopkinson pressure bar
$\dot{\varepsilon}$ = 500/10^4 sec^{-1}
Max ε = 10% natural strain.

<u>Mat.</u>: Ferrovac - E Iron; vacuum melted with 99.95% purity
Nickel - S; vacuum melted with 99.95% purity

<u>Spec.</u>: Cylinders: D = 10 mm, L = from 5 to 20 mm.
Annealed in vacuum for 2 hrs : Iron at 750°C,
Nickel at 800°C
Mean grain diameter after annealing : Iron : 90 μm
Nickel 70 μm

<u>Heat</u>: By a furnace surrounding the specimen and portions of the pressure bars.
Test Temp. : RT, 100, 200, 300, 400, 500°C

<u>Meas. Instr.</u>: Capacitance gauges directly coupled to emitter-followers, with a very high imput impedance. Output fed into oscilloscope

[Recorded pulses are not corrected for the thermal gradient along the pressure bars. Maximum error in computed stress and strain estimated to be 0.2 and 0.4% respectively, for every 100°C increase in test temperature.]

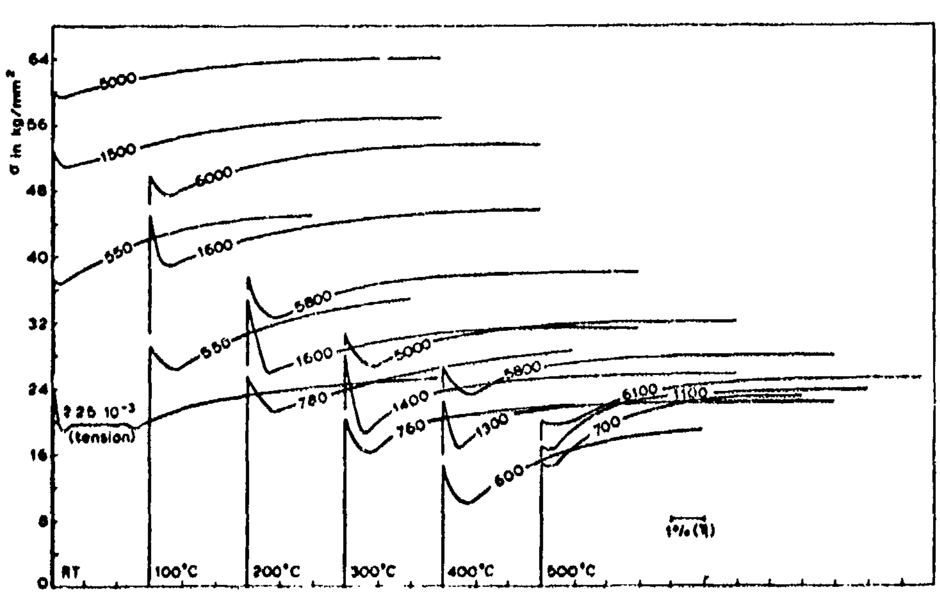


Fig. 1. Iron. True stress-true strain curves. The average true strain rate $\bar{\eta}$ is indicated on each curve.

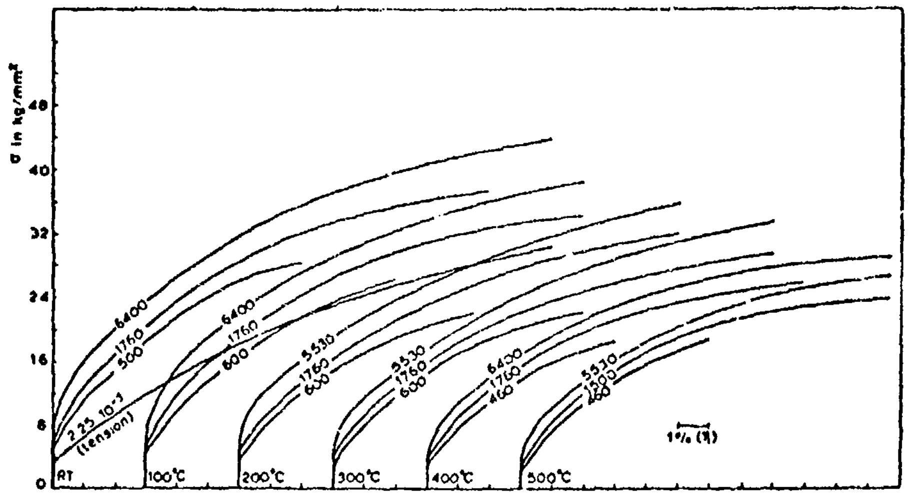
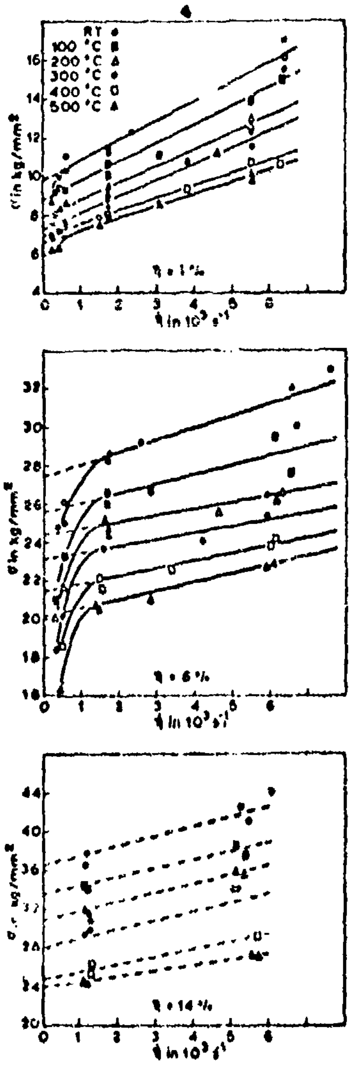
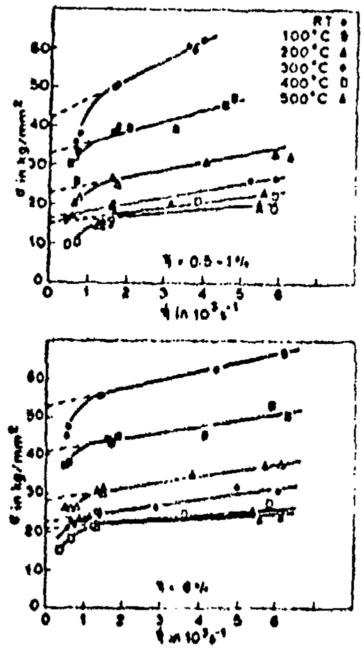


FIG. 2. Nickel. True stress–true strain curves. The average true strain rate $\bar{\dot{\eta}}$ is indicated on each curve.



Nickel.



Iron.

Linear plot of true stress against true strain rate at various strains and temperatures.

Dynamic Plane Comp.	BAILEY and SINGER (1963), [6, 7]	10

Apparatus: Plane Strain Cam Plastometer
Cam of log. profile, to compress strip $\frac{1}{H}$" thick × 1" wide to 90%
Indenting dies: die face 4" wide × 1.5" long
Max plane ϵ = 0.9 ; Plane $\dot{\epsilon}$: constant = 0.3/311 sec^{-1}

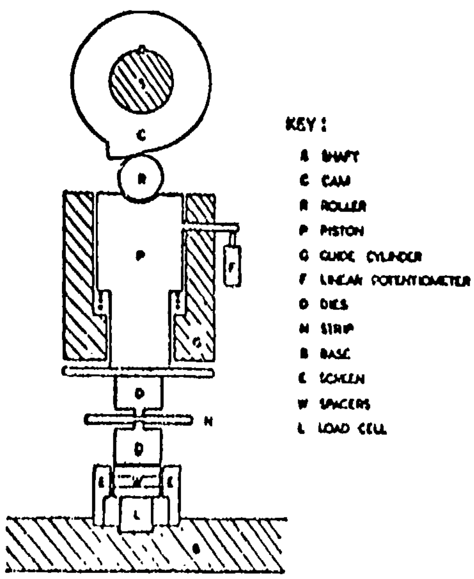
Mat.: Super pure Alum.; Lead; 2 Alum. alloys, in cold rolled sheets , 0.125" thick.

Spec.: Strip 4" long × 1" wide × 1/4" thick; annealed:
Lead 300°C × 1/2 hr, Alum 600 × 1/2 hr, air cooled
Duralumin: 400°C × 4 hr, furnace cooled.

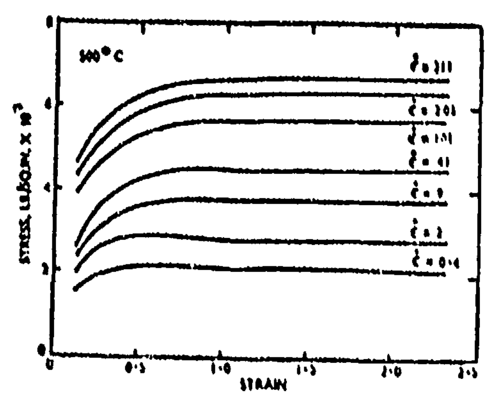
[Lubr.: Graphite & cadmium oxide suspended in alcohol.]

Heat: Compression dies heated in air circulation furnace for <2 hr. Specimen preheated for 20 min, transferred to plastometer, compressed, removed & water quenched.
Test temp.: up to 0.95 of melting temp.

Meas. Instr.: - Load: Resistance strain gauge dynamometer
- Displ.: linear potentiometer, outputs fed to CRO



Diagrammatic representation of the cam plastometer in section.



Effect of strain rate on the resistance to deformation of super-purity aluminium at 500° C. $\dot{\epsilon}$ = strain rate/sec.

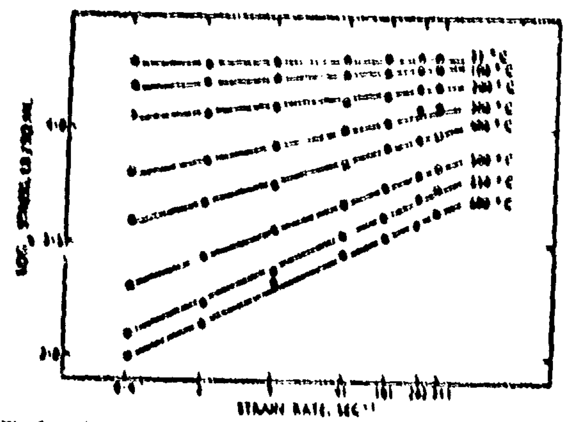


Fig. 2 Effect of strain rate on the stress required to produce a strain of 2·3 in aluminium.

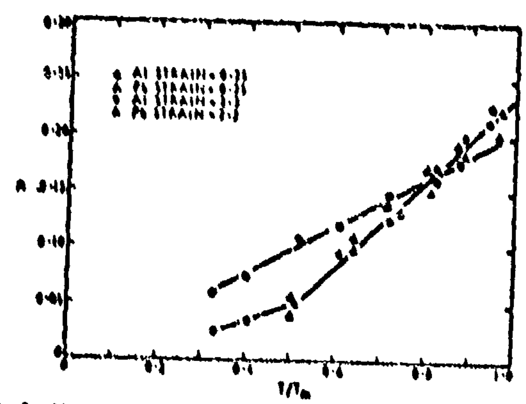


Fig. 3 Variation of n with the ratio of the absolute testing temperature (T) to the absolute melting point (T_m) for aluminium and lead.

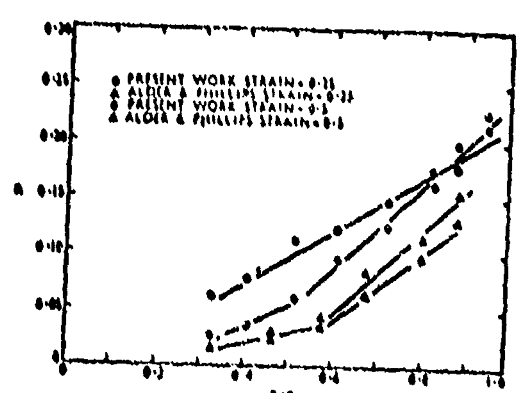


Fig. 4 Variation of n with the ratio of the absolute testing temperature (T) to the absolute melting point (T_m) for aluminium. Comparison with the work of Alder and Phillips (ref. 1).

Dynamic Plane Comp.	BAILEY (1967), [5]	20

Apparatus: Constant speed hydraulic press and a subpress
Indenting dies: die face 4" wide × 1.5" long
Speeds: 2, 5, 10, 30, 60 in/min.
$\dot{\varepsilon}$: variable, initial $\dot{\varepsilon}$ = 0.65, 1.3, 4, 8 sec.$^{-1}$

Mat.: Pure Aluminum; Alum 4.2% Cu alloy, in cold rolled sheets 0.125" thick.

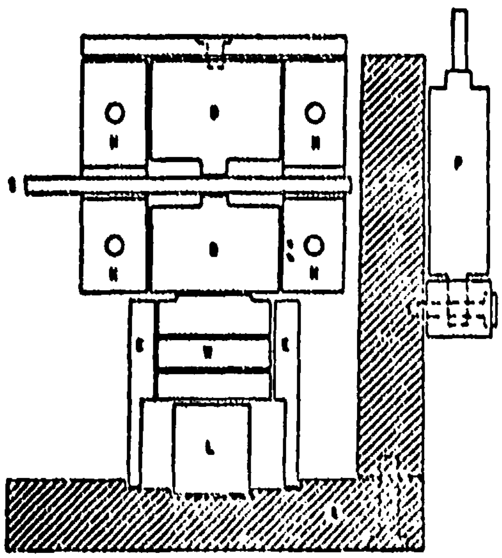
Spec.: Strip 4" long × 1" wide; annealed.
Alum: 600°C × 1/2 hr, AlCu alloy; 400°C × 4 hr.

[Lubr.: Alcoholic suspension of graphite and cadmium oxide.]

Heat: Dies and strip spec. preheated in an air circulated furnace, transferred quickly to subpress and compressed.
Test temp.: Pure Alum. 22-600°C; Alum Alloy 300-500°C

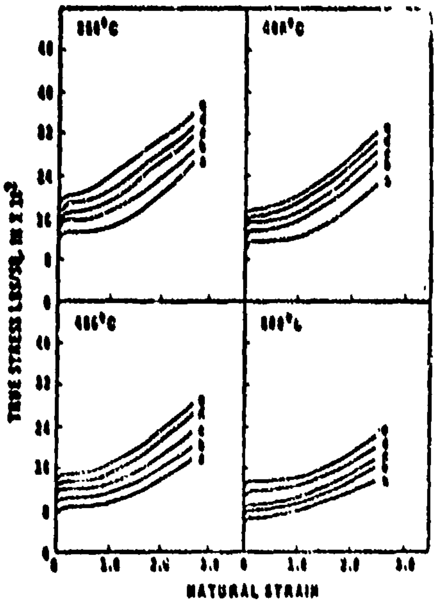
Meas. Instr.: - Load: Resistance strain gauge dynamometer
- Displ: Linear potentiometer,
Outputs fed in a CRO and recorded on film.

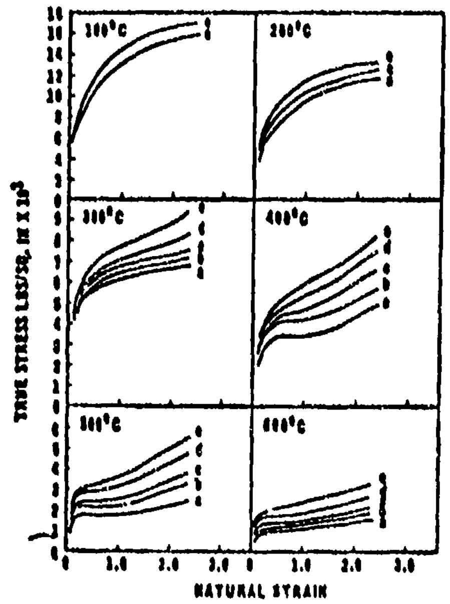
[Correction made for the increase in strain rate produced in a constant velocity test]

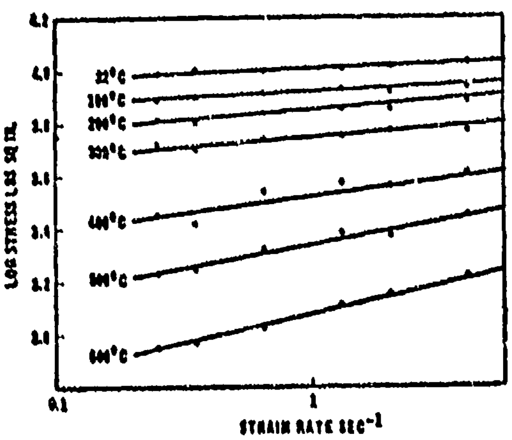


LEGEND
B SUB PRESS
D DIE
E SCREEN
H DIE HOLDER
L LOAD CELL
P LINEAR POTENTIOMETER
S STRIP SPECIMEN
W SPACERS

Fig. 1 Subpress and die assembly

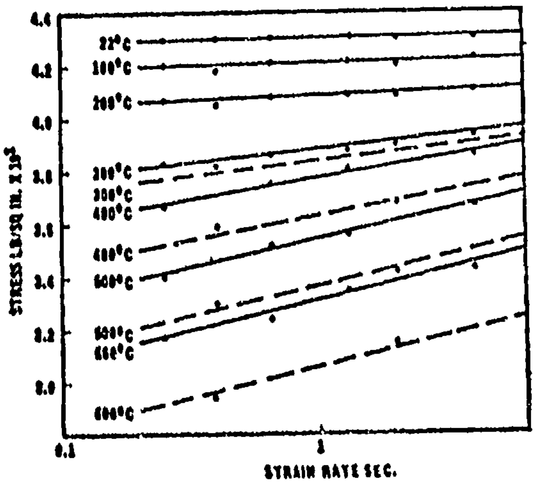






- Initial strain rate in constant-velocity tests
- o Constant-strain-rate tests (8)

Effect of strain rate on stress required to produce a strain of 0.25 in pure aluminum



- Initial strain rate in constant-velocity tests.
- o Constant-strain-rate tests (8)

Effect of strain rate on stress required to produce a strain of 2.3 in pure aluminum

Dynamic Tension	MacDONALD, CARLSON and LANKFORD (1956), [24]	21

Apparatus: High speed hydraulic press and a special subpress. $\dot{\varepsilon}$ = 0.002/0.8 sec^{-1}

Mat.: Low carbon sheet steel (fully aluminum killed, temper rolled sheet of thickness 0.038")

Spec.: Standard sheet specimen, of 4" gage section

Heat: Specimen submerged in heated oil contained in a special insulated tank attached to lower movable head
Test temp.: 75, 150, 225, 300°F

Meas. Instr.: - Load: calibrated wire strain gauge dynamometer bar combined with an analyser and oscillograph.
- Strain: a calibrated semi-circular clip gage equipped with wire strain gages connected to recorder. Thus load time and displacement time traces are recorded simultaneously.

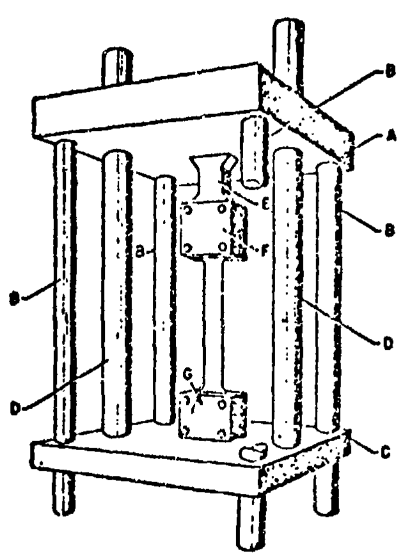


FIG. 1.—Subpress for High-Speed Tension Tests.

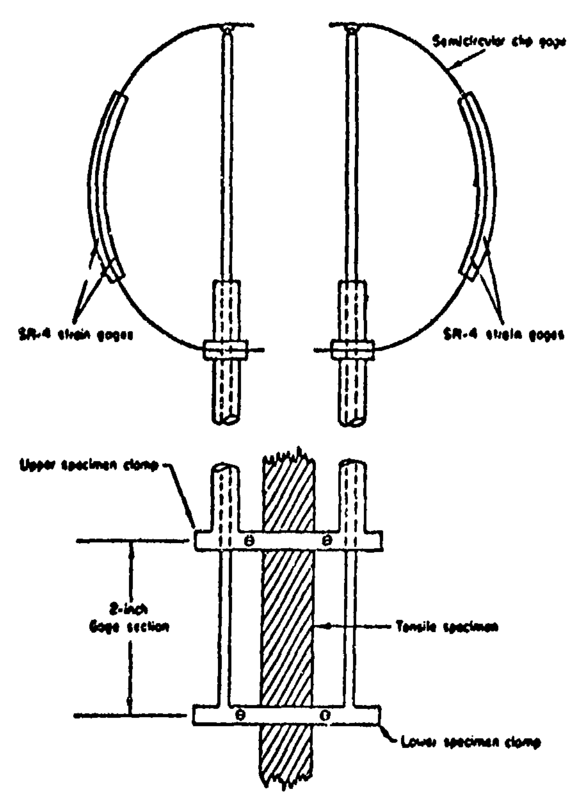


FIG. 4. BASIC DESIGN OF CLIP-GAGE EXTENSOMETER.

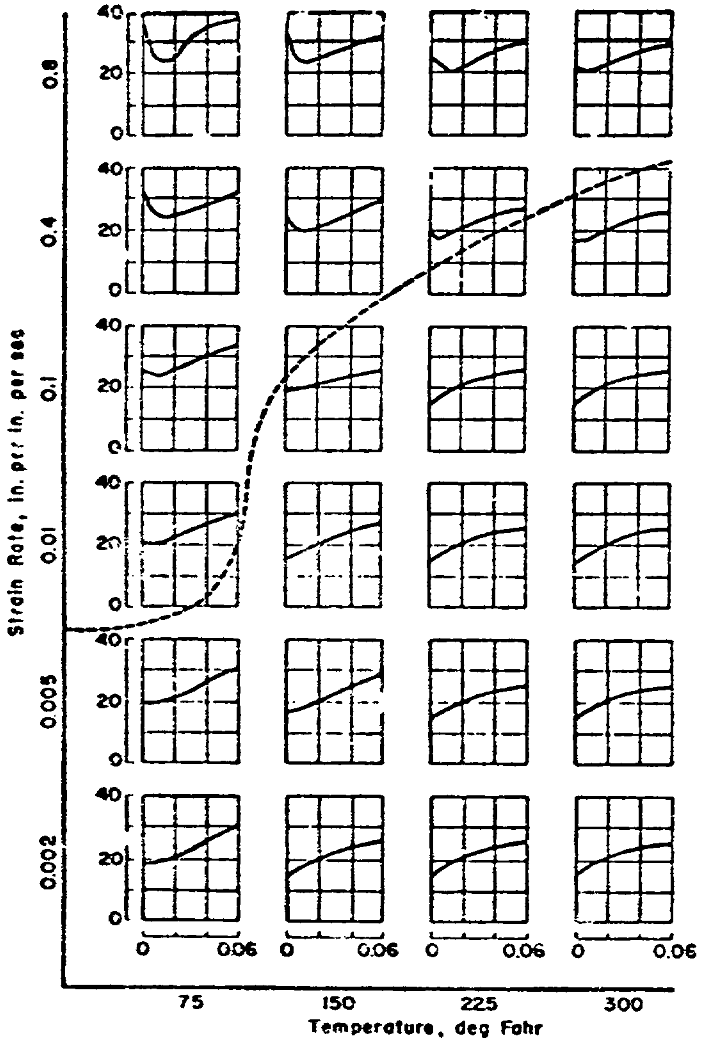


FIG. 3.—Nominal Stress-Strain Curves for Special-Killed, Temper-Rolled Steel as Affected by Strain Rate and Temperature.

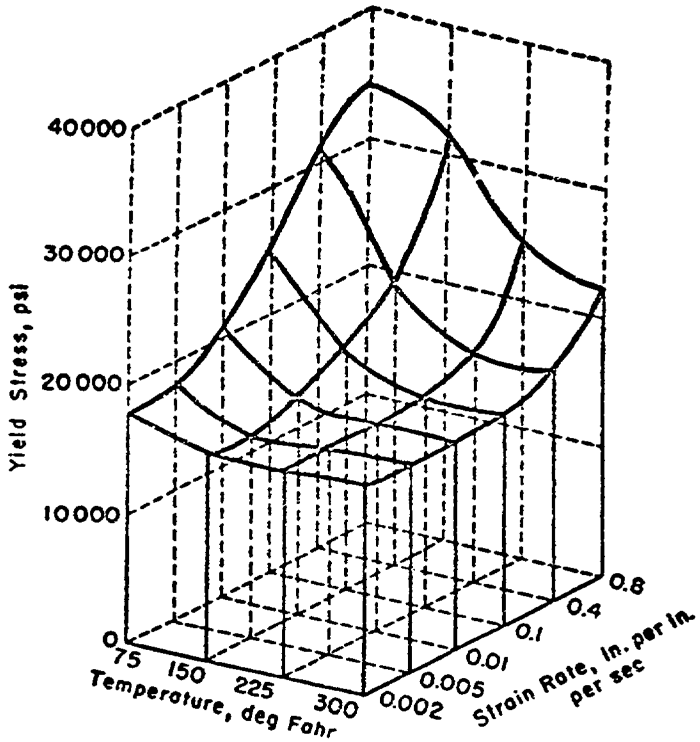


FIG. 4.—The Effect of Strain Rate and Temperature on the Upper Yield Stress of Fully Aluminum-Killed, Temper-Rolled Steel.

Dynamic Tension	PUGH, CHANG and HOPKINS (1961), [31]	22

<u>Apparatus:</u> Constant strain rate screw straining apparatus

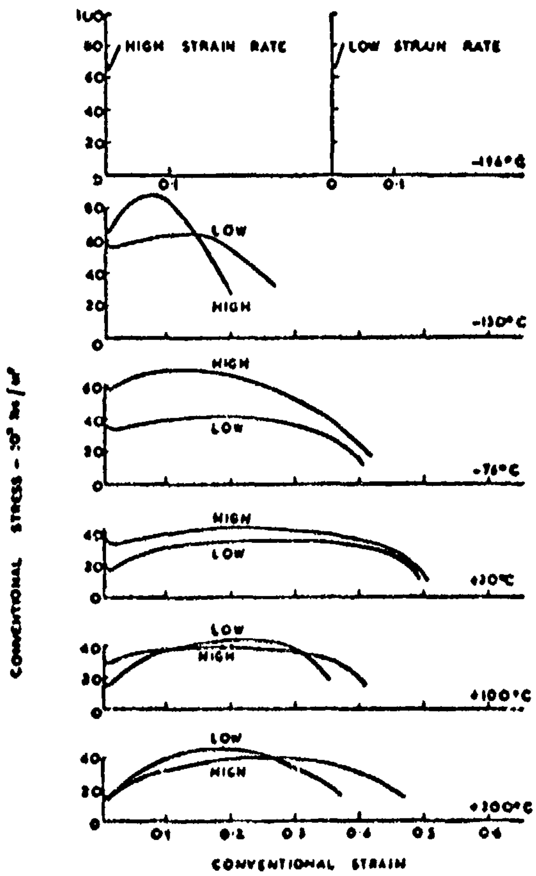
$\dot{\varepsilon}$: Constant, $10^{-4}/0.37\ sec^{-1}$

<u>Mat.:</u> Polycrystalline high purity iron, hot rolled $\frac{5}{8}''$ dia., normalized at 950°C before machining specimens.

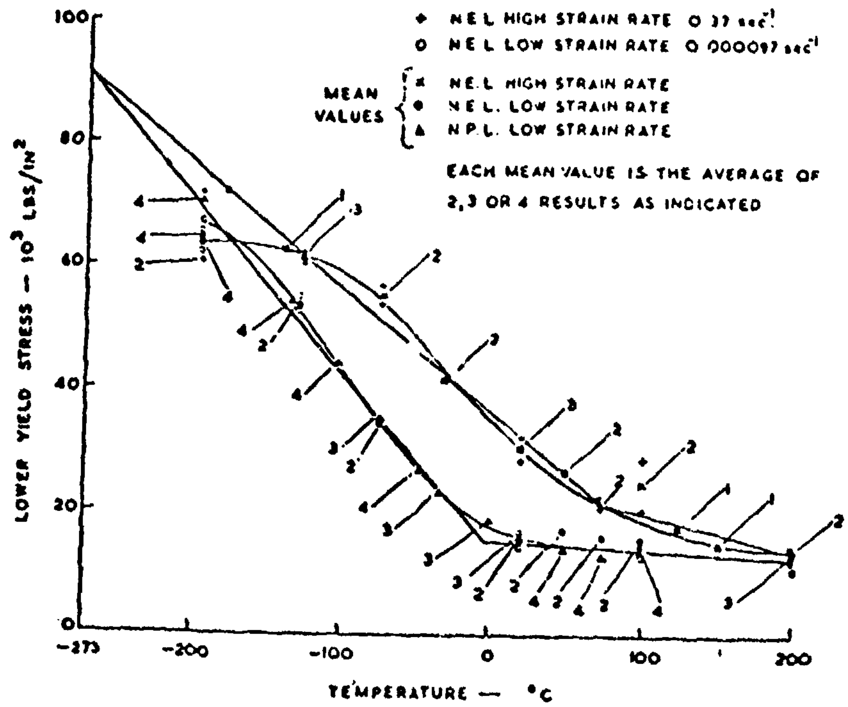
<u>Spec.:</u> Gauge length $1\frac{1}{4}''$ long × 0.282"ϕ, threaded ends

<u>Heat:</u> Specimen surrounded with insulated temp. chamber.
Test temp.: - 196°/200°C

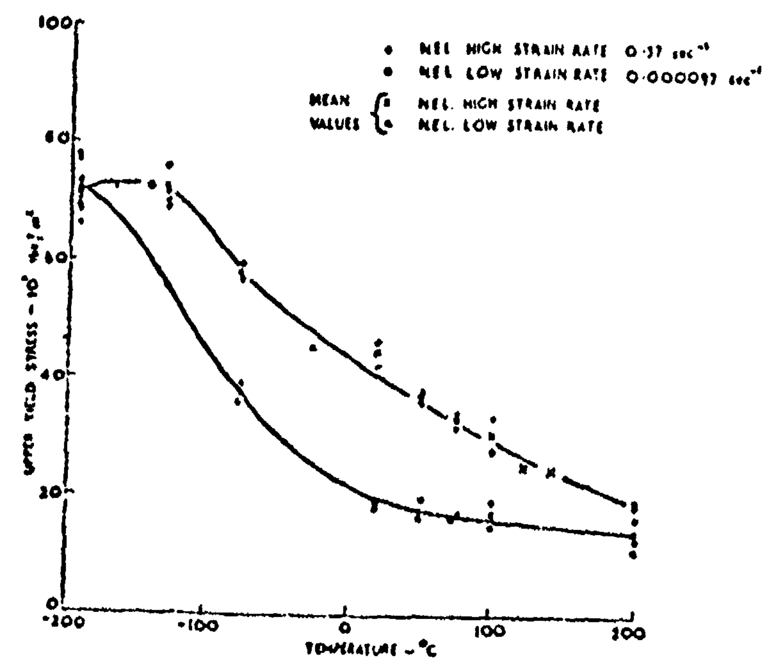
<u>Meas. Instr.:</u> - Load: by 8 electrical strain gauges on load bar.
- Elongation: indirectly using a counter.
Output fed to CRO; signal recorded on film.



Typical conventional stress strain curves.



Effect of temperature on the lower yield stress at two strain rates.



Effect of temperature on the upper yield stress at two strain rates.

Dynamic Tension	GREEN and BABCOCK (1966), [13]	23

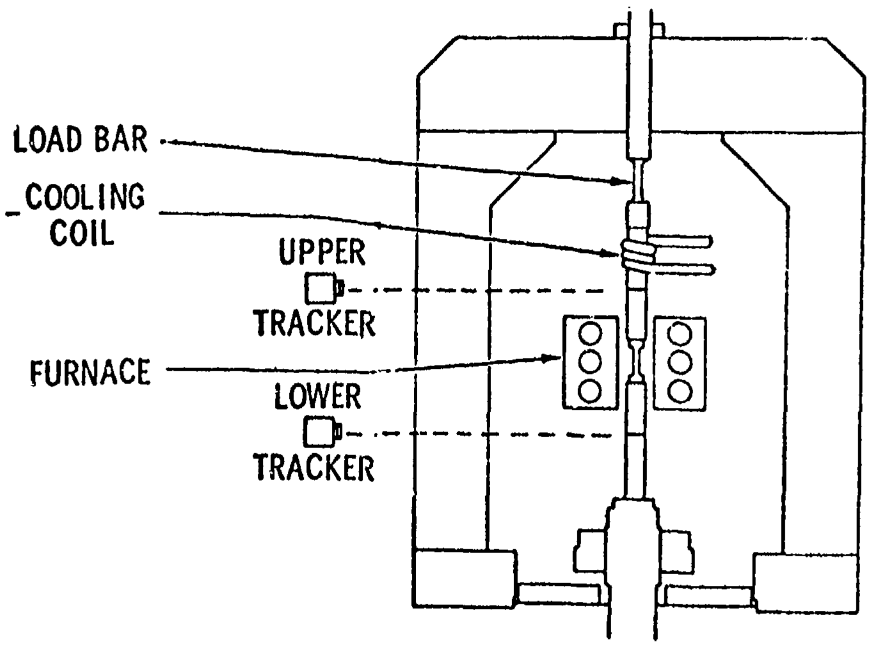
Apparatus: Gas operated device; desired constant strain rate is obtained by proper selection of gas (air, helium or nitrogen), pressure and orifice size. $\dot{\varepsilon}$: constant true $\dot{\varepsilon}$ = 0.001/100 sec^{-1}

Mat.: 6061-T6 Alum. alloy; 7075-T6 Alum. alloy; 6Al-4V Titanium alloy; I-400 Beryllium

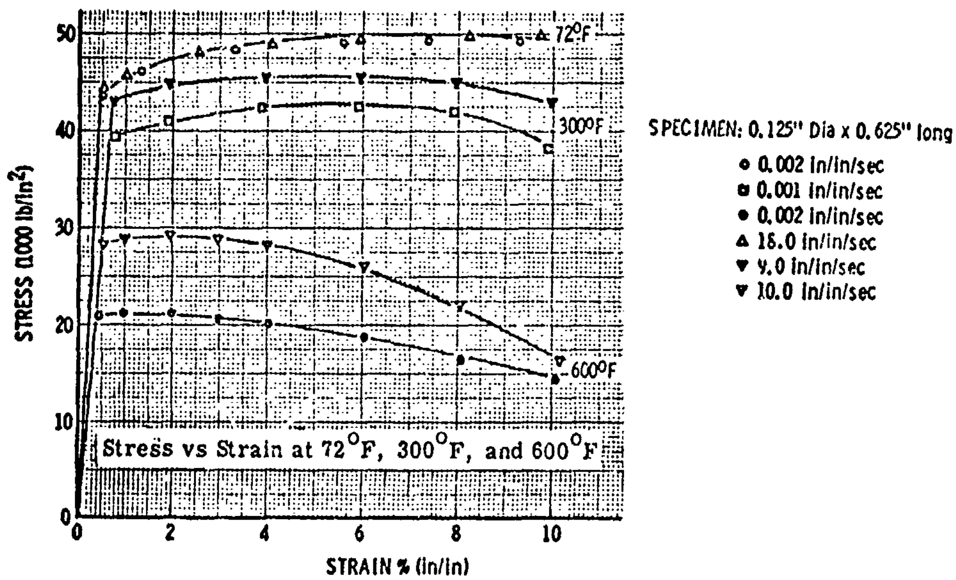
Spec.: Cylinders: D = 0.125" x L = 0.625"

Heat: A radiant energy furnace with three independently controlled zones is used to heat the specimen and maintain uniform temp. along its length. Test temp.: 72/600° F

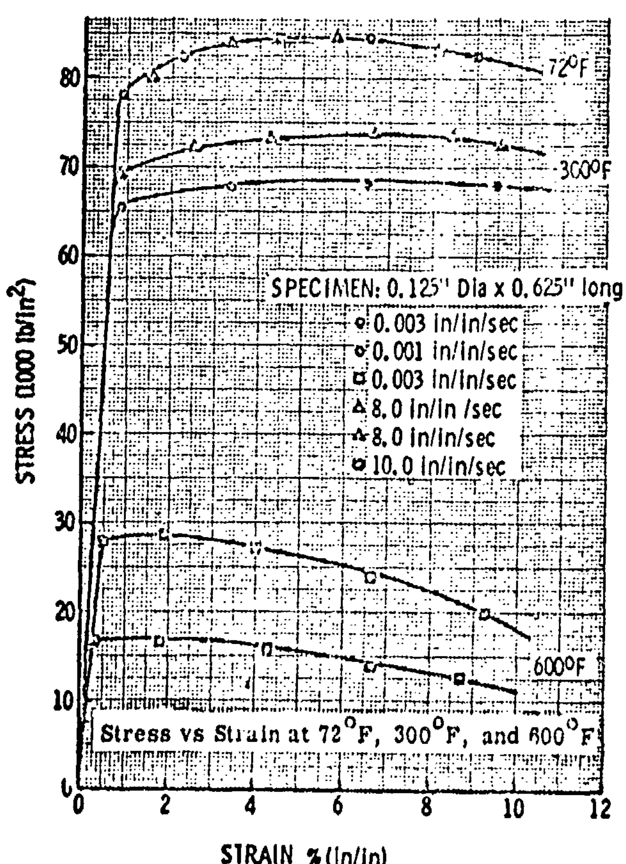
Meas. Instr.: - Load: Measured by strain gages mounted on an elastic load bar directly above the specimen.
- Strain: by measuring piston displacement; by using strain gages mounted on specimen; or by using an optical extensometer to look at marks placed on the specimen.



TENSION HEAD



Tension Tests on 6061-T6 Aluminum Alloy



Tension Tests on 7075-T6 Aluminum Alloy

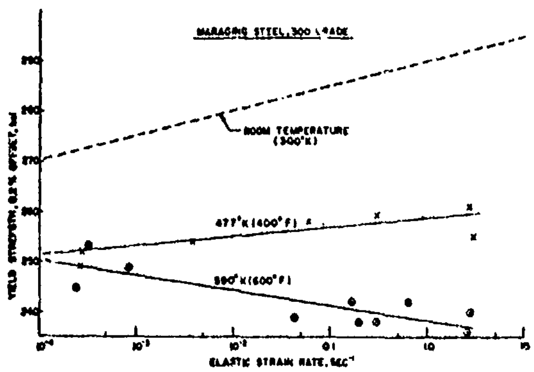


Fig. 10 Yield stress versus elastic strain rate f(maraging 300 steel

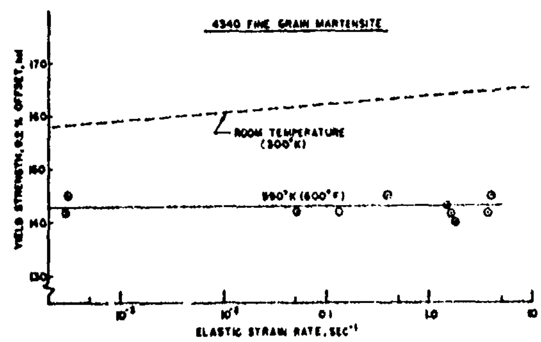


Fig. 2 Yield stress versus elastic strain rate for 4340 fine grain martensite

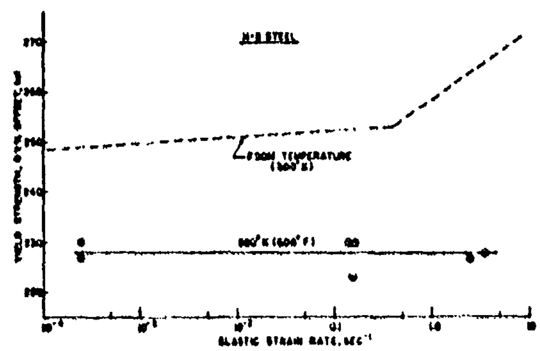


Fig. 3 Yield stress versus elastic strain rate for type H-11 steel

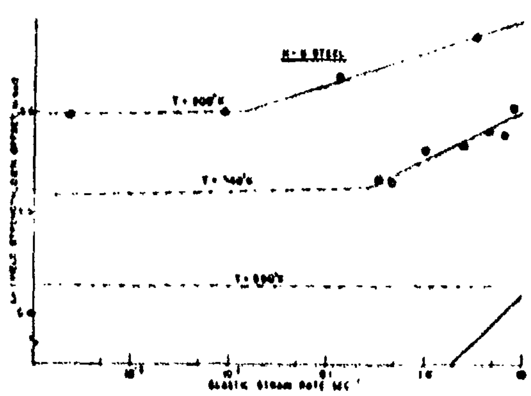


Fig. 9 Logarithm of yield stress versus elastic strain rate for type H-11 steel

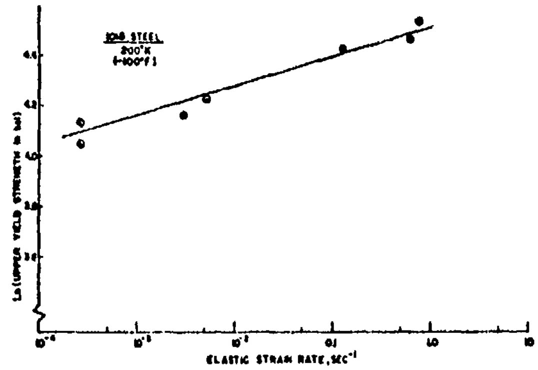


Fig. 4 Logarithm of upper yield stress versus elastic strain rate for 1018 steel at 200 deg K

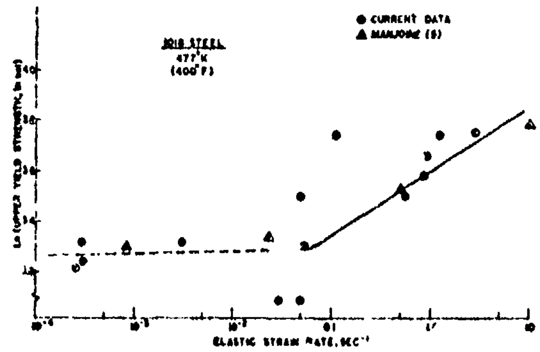


Fig. 7 Logarithm of upper yield stress versus elastic strain rate for 1018 steel at 477 deg K

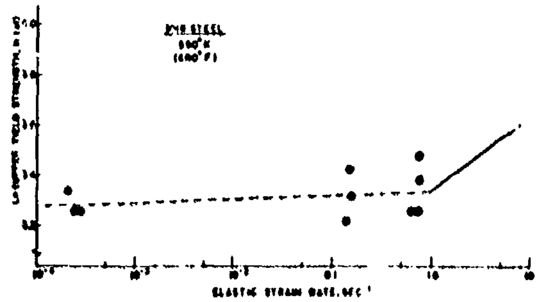


Fig. 8 Logarithm of upper yield stress versus elastic strain rate for 1018 steel at 590 deg K

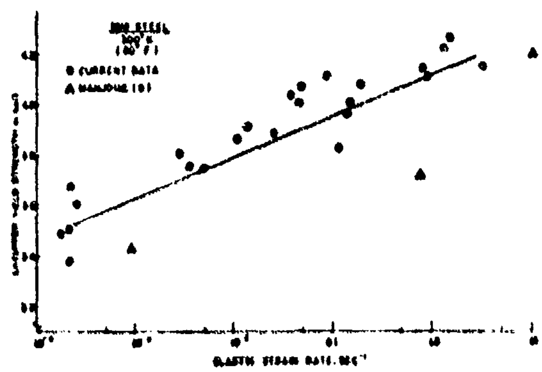


Fig. 5 Logarithm of upper yield stress versus elastic strain rate for 1018 steel at 300 deg K

Dynamic Tension	KENDALL (1970), [19]	24

Apparatus: Special high rate tensile testing system.
(fluid transfer from a high pressure accumulator to a hydraulic cylinder rapidly loads a standard tensile specimen)
$\varepsilon = 10^{-4}/10\ sec^{-1}$ (elastic strain rates).

Mat.: Mild steel: commercial grade 1018; cold rolled 1" dia.
Alloy steel: 4340, tool st. and grade 300; heat treated, tempered at 1025° F

Spec.: Standard ASTM round tensile specimens, 0.505" ϕ , threaded ends.

Heat: Split tubular electrical resistance furnace, heating zone:
3" ϕ x 5" L, surrounds the specimen; heating rate: 15° F/min.
Time in temp: 5 min. before testing. Temp. gradient along specimen is neglected.
Test temp.: up to 600° F

Meas. Instr.: - Load: with a load cell and high temp. res. strain gauges
- Displacement: with a variable impedance transducer. (not reliable for strain measurement at high temp.)
Output fed into CRO.

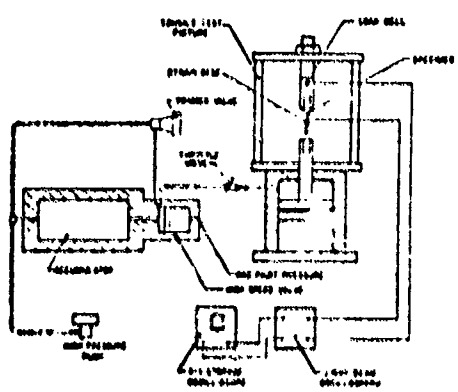


Fig. 4 Schematic diagram of high strain-rate testing system

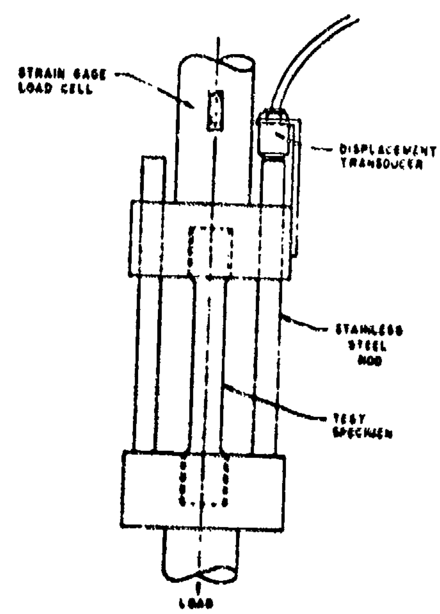


Fig. 1 Load and displacement measuring system

Impact Tension	NADAI and MANJOINE (1941), [27, 28]	25

Apparatus: High speed rotary impact machine.
$\dot{\varepsilon}$ = from 100 up to 1000 sec^{-1}

Mat.: Copper, Alum., Pure Iron and Mild Steel

Spec.: D = 0.2", G. L. = 1"

Heat: With an induction furnace surrounding the spec.
Test temp.: Copper, 25/1000° C;
Alum., 25/600° C; Pure Iron, 25/1200° C; Mild Steel, 25/1200° C

Meas. Instr.: Two Photoelectric cells which depict:
- Load, through the elastic extension of a load bar
- Strain, through motion of the lower head.

Output of photo cells fed into CRO and recorded.

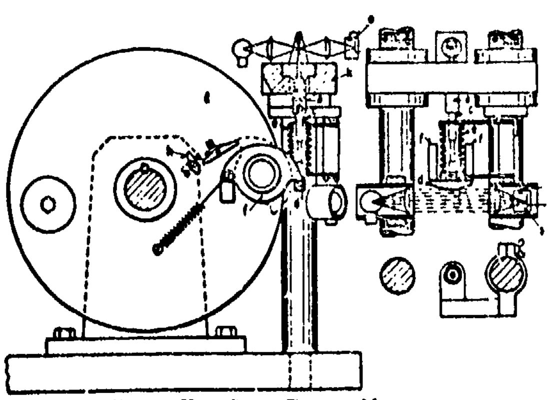


Fig. 1 High-Speed Tensile Machine

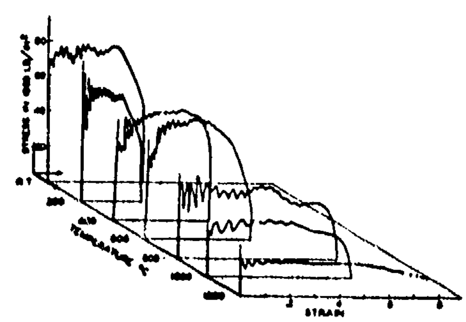


Fig. 5 Stress-Strain Curves for Mild Steel at Elevated Temperatures and High Speeds

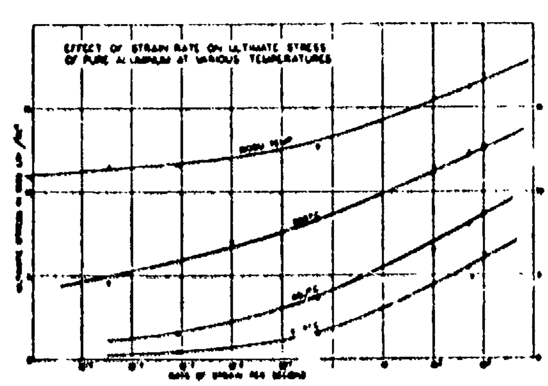


Fig. 11 Effect of Strain Rate on Ultimate Stress of Pure Aluminum at Various Temperatures

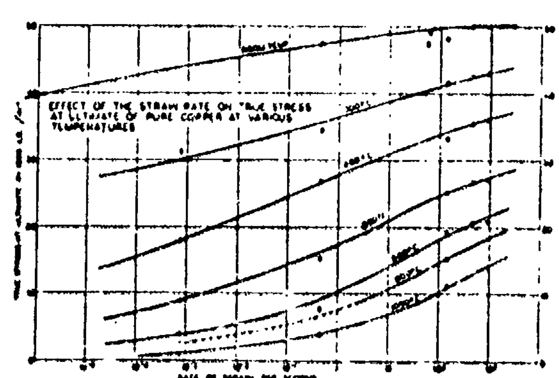


Fig. 10 Effect of Strain Rate on True Stress at Ultimate of Pure Copper at Various Temperatures

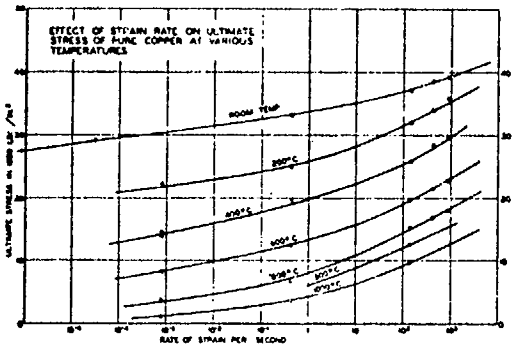
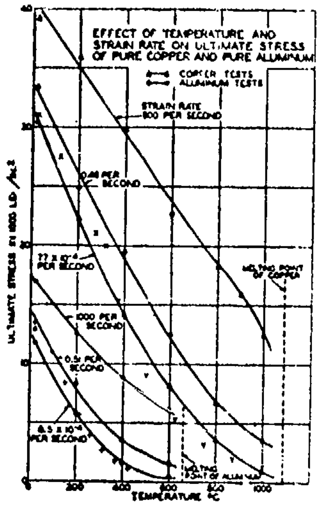


Fig. 9 Effect of Strain Rate on Ultimate Stress of Pure Copper at Various Temperatures



Effect of Temperature and Strain Rate on Ultimate Stress of Pure Copper and Pure Aluminum

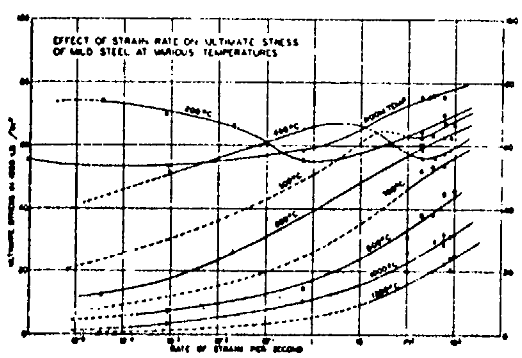


Fig. 13 Effect of Strain Rate on Ultimate Stress of Mild Steel at Various Temperatures

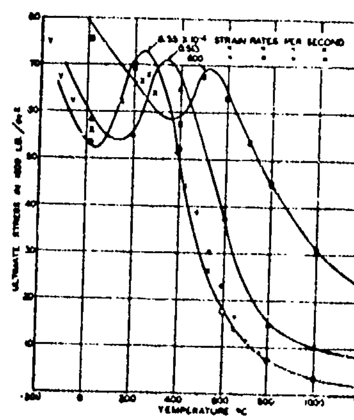


Fig. 14 Tension Tests of Mild Steel at Various Temperatures and Rates of Strain

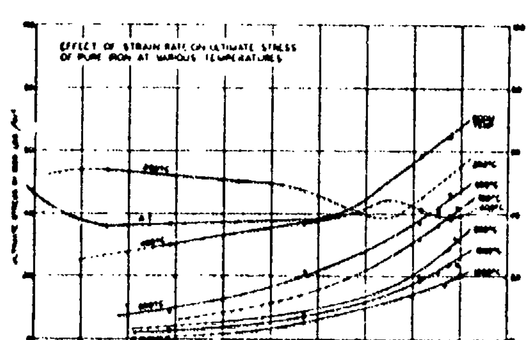
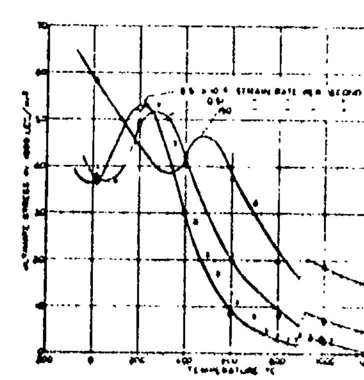


Fig. 15 Effect of Strain Rate on Ultimate Stress of Pure Iron at Various Temperatures



Tension Tests of Pure Iron at Various Temperatures and Rates of Strain

Impact Tension	LINDHOLM and YEAKLEY (1971), [23]	26

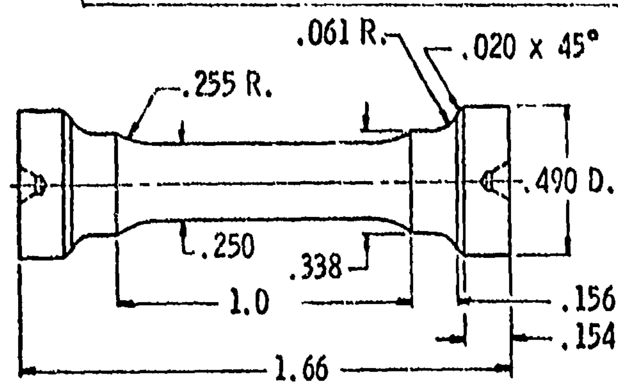
Apparatus: - High-speed servo-controlled hydraulic testing machine; $\dot{\epsilon} = 10^{-3}/10\ sec^{-1}$
- Split Hopkinson bar in tension; $\dot{\epsilon} = 10^{3}\ sec^{-1}$

Mat.: Titanium: 6Al-4V alloy; Beryllium S-200E

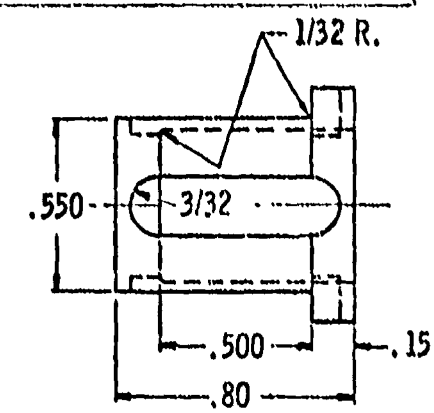
Spec.: Three different specimen geometries, depending upon the type of loading
- a button-head end type, for uniaxial tension testing on hydraulic machine
- a tubular biaxial specimen, for biaxial testing on hydraulic machine
- a Hopkinson bar tensile specimen, for uniaxial tension at $10^{3}\ sec^{-1}$

Heat: Specimens were heated by a coaxial, three-zone quartz lamp oven. Temp. gradient within the central 1/2-inch of the specimen gage section was symmetric and small.
Test temp.: 300, 600, 1000° F

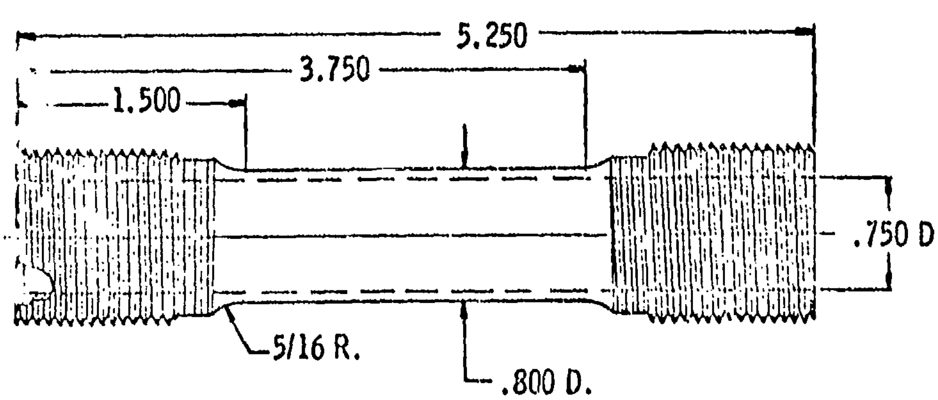
Meas. Instr.: - Load and pressure: using load and pressure cells
- Strain: using specially designed electro-mechanical strain extensometers, for the uniaxial loading, the biaxial linear-torsional loading and for the biaxial linear-internal pressure loading.



Button Head End Tensile Specimen



Hopkinson Bar Tensile Specimen



Biaxial Tube Specimen

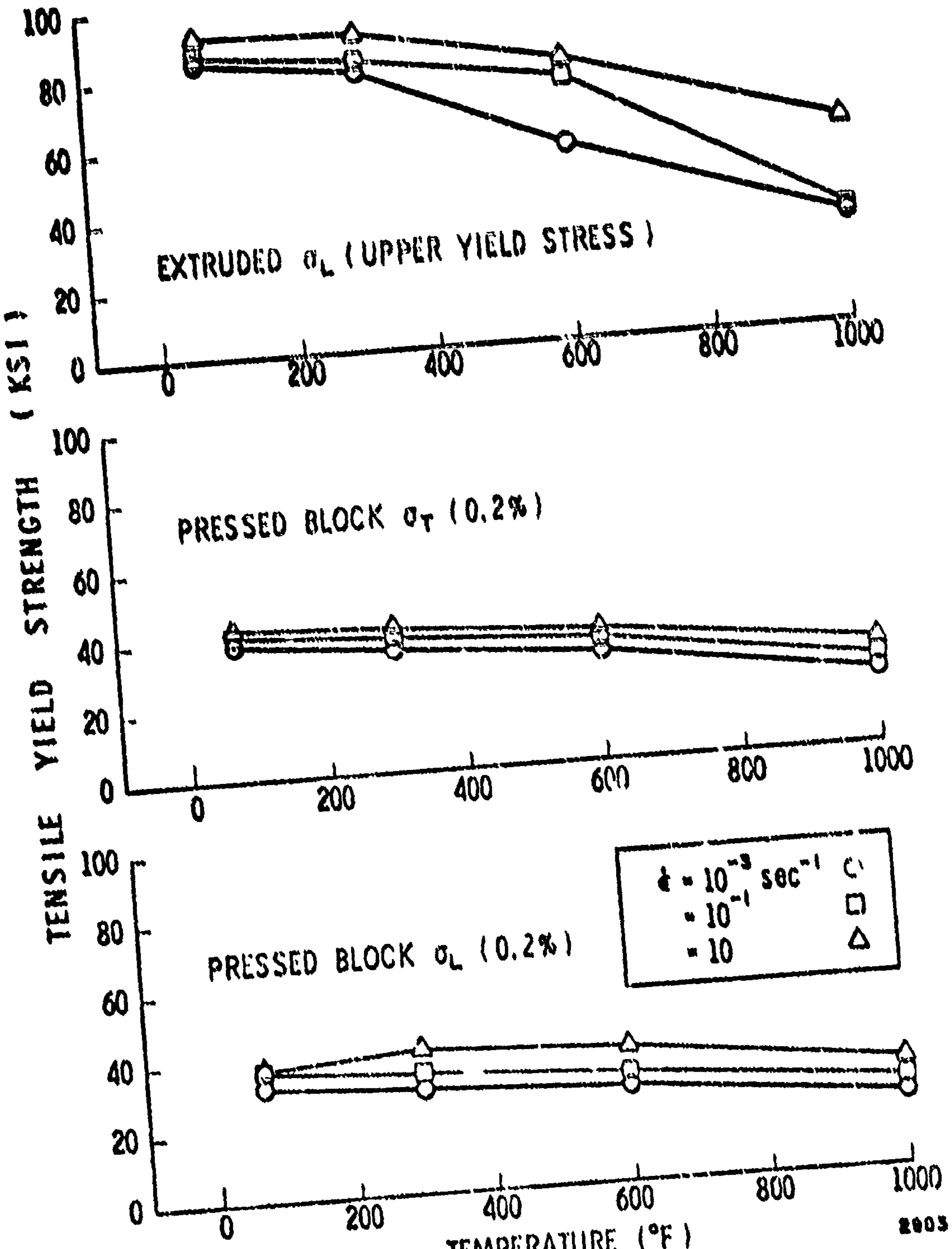


FIGURE 13. EFFECT OF TEMPERATURE AND STRAIN RATE ON THE TENSILE YIELD STRENGTH OF S-200E BERYLLIUM

Impact Tension	THIRUVENGADAN and CONN (1971), [42]	37

Apparatus: Modified Hopkinson pressure bar
Loading: Compressed nitrogen gun accelerating an impact projectile which strikes the incident pressure bar.
$\dot{\epsilon} = \sim 10^3\ sec^{-1}$

Mat.: 310 Stainless Steel and a Titanium alloy

Spec.: Tensile specimens, of the type developed by Lindholm and Yeakley (hat shaped, fitting between a hollow thick-walled tube input bar (Involoy 825) and a solid cylindrical output bar. (Inconel X 750)).

Heat: A furnace was made to entirely encase both pressure bars. (Therefore no thermal gradients were encountered by the stress waves in these bars, which simplified data reduction)

[NB No numerical data is given about the uniformity of temp. inside the furnace and along the two long pressure bars, 30" each]
Test temp.: St. Steel, Room & 1300° F; Tit. alloy, Room & 900° F

Meas. Instr.: High temp. strain gauges (Microdot weldable type, MG 120) were used at two stations. Output fed to CRO; ϵ_I, ϵ_R and ϵ_T recorded on film.

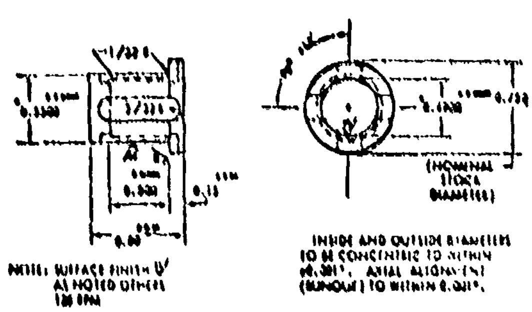


Fig. 1—High-strain-rate tensile specimen

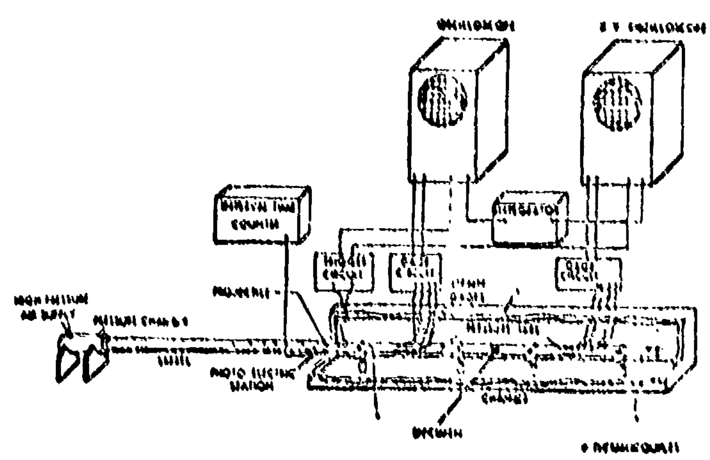


Fig. 2—Schematic of split-Hopkinson-pressure-bar test facility

TABLE 1—STATIC AND DYNAMIC TENSILE PROPERTIES OF ANNEALED 316 STAINLESS STEEL

Property	Room Temperature			1300° F		
	Static[a]	Dynamic[g]	Ratio[d]	Static[a]	Dynamic[g]	Ratio[d]
Ultimate Tensile Strength, σ_u, ksi	81.2	138[b]	1.63	46.0	109.2[b]	2.37
Reduction of Area, RA, %	76.9	52.3[b]	0.68	50.0	59.3[b]	1.19
Elongation, %	55.0	37.3[b]	0.68	35.0	31.8[b]	0.91
Logarithmic Ductility[e], D	1.4653	0.7391	0.50	0.6932	0.8989	1.30
True Fracture Strength[f], σ_f, ksi	200.2	240.0	1.20	76.3	207.4	2.72
Elastic Modulus, E, 10^6 psi	28.4	28.8[c]	1.01	20.5	19.8[c]	0.97

[a] Values from Ref. 29
[b] Split-Hopkinson pressure-bar experiments
[c] High-frequency-fatigue experiments
[d] Ratio of dynamic to static value
[e] $D = \ln\left(\frac{1}{1 - RA}\right)$, Refs. 7 and 8
[f] $\sigma_f = \sigma_u(1 + D)$, Refs. 7 and 8
[g] Strain rate ~ 10^3 in./in./sec

TABLE 2—STATIC AND DYNAMIC TENSILE PROPERTIES OF TITANIUM ALLOY Ti-6-2-4-2

Property	Room Temperature			900° F		
	Static[a]	Dynamic[h]	Ratio[e]	Static[a]	Dynamic[h]	Ratio[e]
Ultimate Tensile Strength, σ_u, ksi	152.0	229.5[c]	1.51	106.0	166.8[c]	1.57
Reduction of Area, RA, %	44.0	40.3[c]	0.92	60.3	57.2[c]	0.95
Elongation, %	17.0	15.1[c]	0.89	21.0	20.7[c]	0.99
Logarithmic Ductility[f], D	0.5805	0.5158	0.89	0.9239	0.8484	0.92
True Fracture Strength[g], σ_f, ksi	240.2	347.4	1.45	203.9	308.3	1.51
Elastic Modulus, E, 10^6 psi	16.0	16.7[d]	1.04	11.6[b]	12.0[d]	1.03

[a] Test value from manufacturer Titanium Metals Corp. of America
[b] Value from Reference 35
[c] Split-Hopkinson-pressure-bar experiments
[d] High-frequency-fatigue experiments
[e] Ratio of dynamic to static value
[f] $D = \ln\left(\frac{1}{1 - RA}\right)$, Refs. 7 and 8
[g] $\sigma_f = \sigma_u(1 + D)$, Refs. 7 and 8
[h] Strain Rate ~ 10^3 in./in./sec

Impact Tension	SCHULTZ (1969), [34]	28

<u>Apparatus</u>: Transverse impact on long thin wire specimen.
Loading: Nylon projectile transversely impacting specimen at its mid-span.
$\dot{\epsilon}$: variable during test, $\dot{\epsilon}$ average = 10^2 - 10^3 sec^{-1}

<u>Mat.</u>: Alum. 1100, annealed 800 F × 3 min; Alum. 2024, annealed 600 × 3 min; Steel C 1010, annealed.

<u>Spec.</u>: Long thin wire, D = 0.04", L = 32 ft. annealed in place, and pre-tensioned.

<u>Heat</u>: By passing an electric current through the wire. Temp. controlled through resistivity measurement. Temp. distribution checked with temp. sensitive paint. Test temp.: 1100 Alum., 200, 350, 550, 800°F; 2024 Alum., 200, 450, 600°F; Steel, 430, 700, 1050, 1400°F

<u>Meas. Instr.</u>: - Transverse impact: observed by still photography with stroboscope of known flash rate, over a period of 1.5 msec. after impact.

[<u>NB</u>. From theoretical analysis, only measurements needed are: static prestrain, impact velocity (from distance travelled by projectile between flashes) and deformation angle behind transverse wave front].

- Strain: Observed optically.

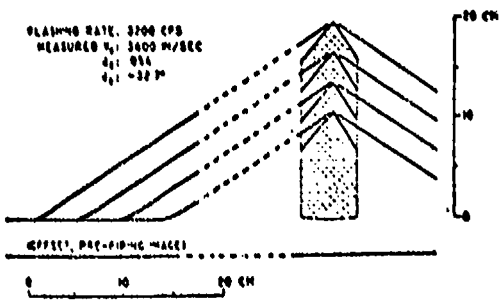
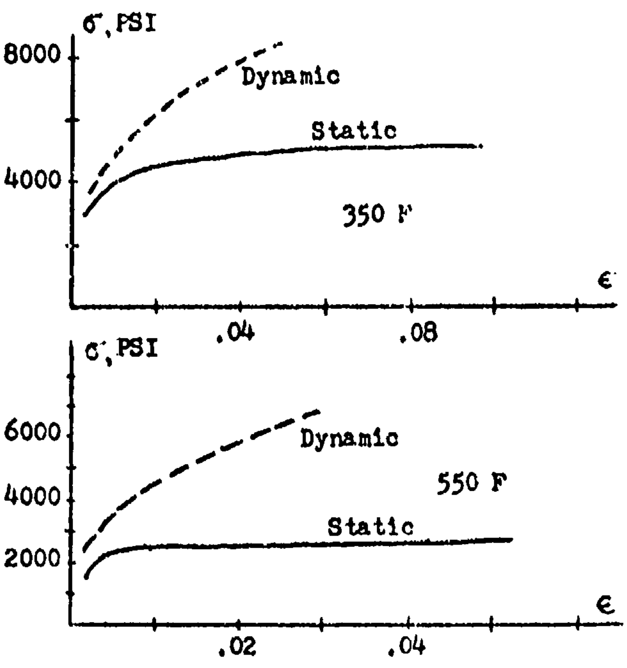


Fig. 1 Schematic diagram of deforming wire, banded for measurement of strain; 740 psi prestress series



Stress-Strain Data, 1100 Alum.

MATERIAL	ULTIMATE STRAIN STATIC	ULTIMATE STRAIN DYN.	ULTIMATE STRAIN DYN./STATIC	ULTIMATE STRESS, 10^3 PSI STATIC	ULTIMATE STRESS, 10^3 PSI DYN.	ULTIMATE STRESS, 10^3 PSI DYN./STATIC
1100 ALUMINUM						
200° F	.20	.075	.38	9.4	10.8	1.15
350° F	.09	.044	.49	4.5	7.8	1.7
550° F	.05	.03	.60	2.7	6.7	2.5
800° F	.02	.064	3.2	1.8	4.8	2.7
2024 ALUMINUM						
200° F	.077	.05	.65	28.0	20	.71
450° F	.04	.033	.82	14.5	20.5	1.4
600° F	.03	.025	.83	6.0	20.8	3.5
C1010 STEEL						
430° F	.11	.03	.28	45 (FLOW)	48	1.07
700° F	.07	.07	1.0	52	42	.81
1050° F	.04	.12	3.0	24	57	2.4
1400° F	.02	.044	2.2	6.5	39	6.0

Impact Tension	LEECH, GREGORY and EBORALL (1954), [20]	29

Apparatus: Standard Izod impact machine fitted with a simple attachment to perform a tension test; $\dot{\varepsilon}$ max = ∿ 250 sec^{-1}

Mat.: Copper base alloys (including brasses, bronzes, and coppers with various amounts of bismuth.

Spec.: Of suitable form; G. L. = 1/2" and cross section 3/8 x 1/4"

Heat: Furnace placed close to the anvil; transfer into position for test takes only two sec. Cooling rate ∿ 10°C/sec at 700° C
Test temp: Bismuth Bearing Coppers, 350, 450, 550, 650, 750° C;
Brasses, bronzes and alum. bronzes, Room temp. up to 900° C

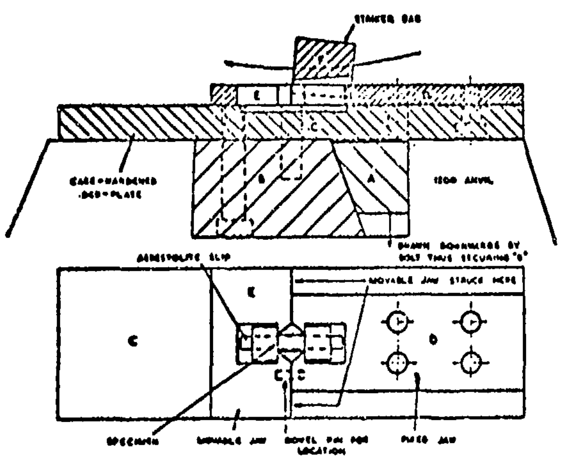


FIG. 1.—Impact Tensile Tester.

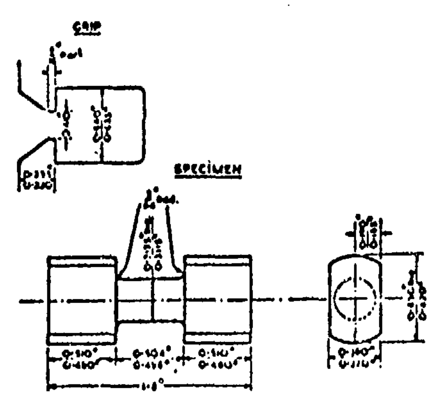


FIG. 2.—Impact Tensile Specimen and Detail of Grip.

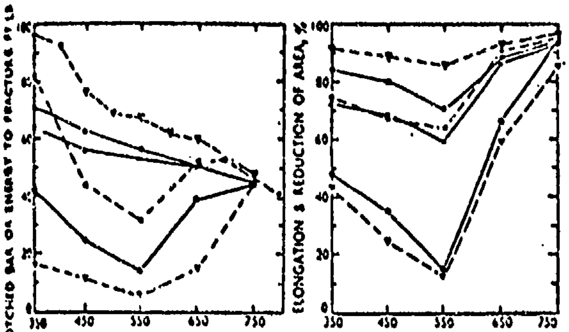


Fig. 3.—Impact Tensile and Notched-Bar Tests on Bismuth-Containing Coppers.

●—● 0·0005% Bi; ×—× 0·0011% Bi; o—o 0·0051% Bi: Impact Tensile Test: Energy to Fracture and Elongation.

▽—▽ 0·0005% Bi; ⊠—⊠ 0·0011% Bi; ▼—▼ 0·0051% Bi: Notched-Bar Impact Test Result, and Reduction of Area in Impact Tensile Test.

Table II.—*Analyses of Commercial Copper Alloys Tested.*

	Cu, %	Bi, %	Pb, %
Brasses	62·1 63·3 65·3 80·1	0·0001 0·0002 0·0002 0·0001	<0·001 <0·001 <0·001 <0·001
Aluminium Bronzes	93·4 90·4	0·0002 0·0004	<0·001 <0·001
Tin Bronzes : Nom. 5% Sn, 0·1% P „ 8% Sn, 0·1% P		 0·0003 tr. <0·0001	 0·0010 0·0022

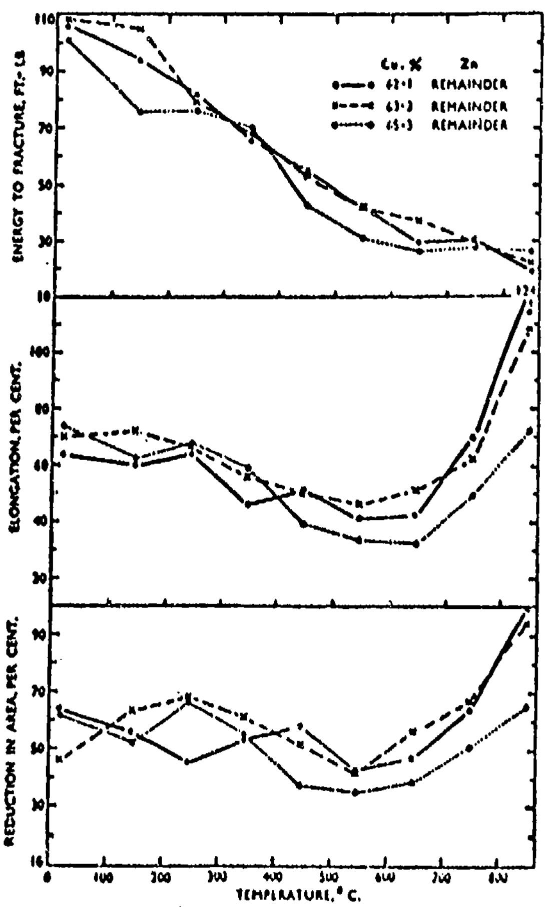


Fig. 4.—Impact Tensile Tests on Some Cast Brasses.

Impact Shear	SLATER and JOHNSON (1967), [35]	30

<u>Apparatus</u>: Linear induction motor accelerating a hammer of mass 21.5 lb. K. E. acquired is utilized for dynamic or impact blanking. Max. impact speed = 50'/sec:; $\dot{\gamma} = 10^3$ sec^{-1}.

<u>Mat.</u>: Commercially pure aluminum; Copper; Black mild steel.

<u>Spec.</u>: Circular disks 2.5" dia. for quasi-static blanking; 3" square for dynamic blanking.

<u>Heat</u>: Spec. heated in separate furnace to 50-100° C above required temp., while blanking tool was preheated using a series of bars; spec. were transferred quickly into position and blanking performed.
Test temp.: Alum., 20-500; Copper 20-800; Steel 2 -1100° C

<u>Measurements</u>: Phase voltage applied to motor (V_p), from which the impact vel. of accelerated mass is determined ($u_m = V_p/6.75$ ft/sec) and consequently K. E. available at impact.

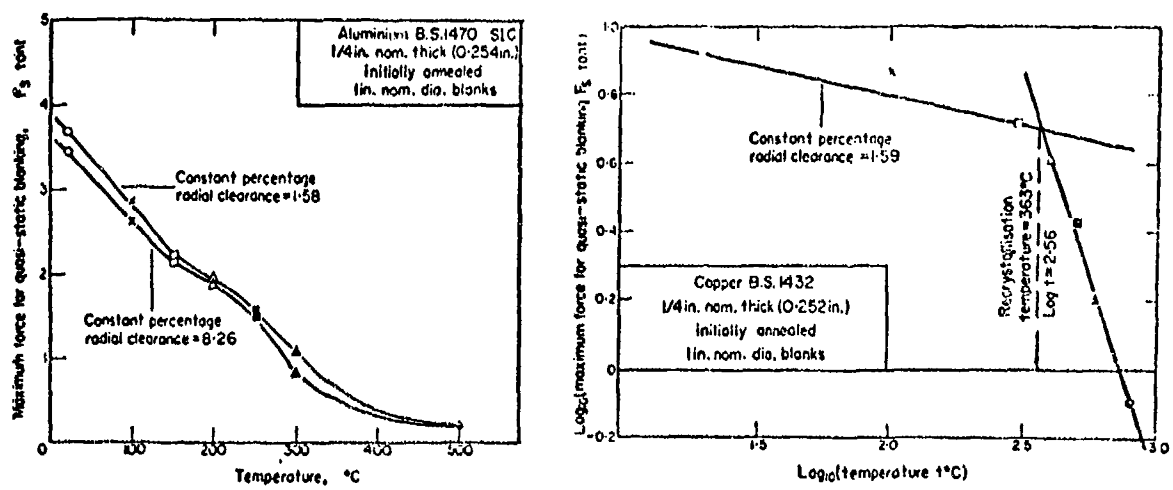
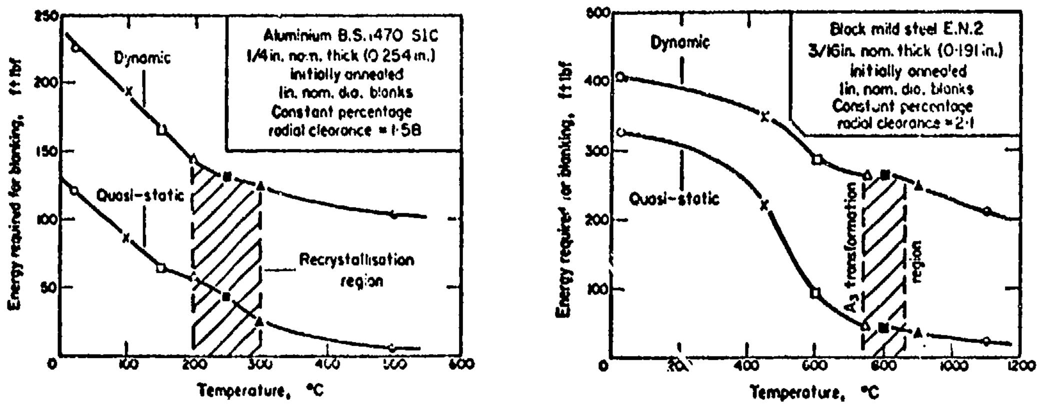
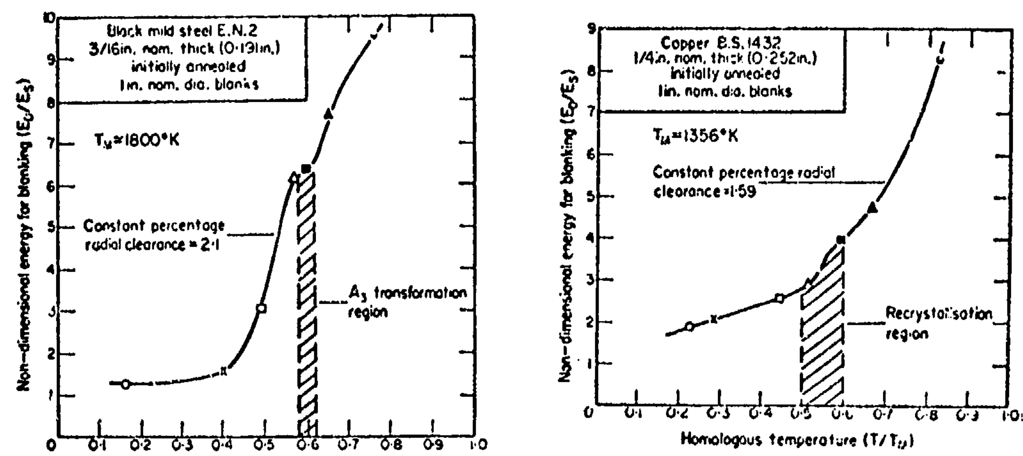
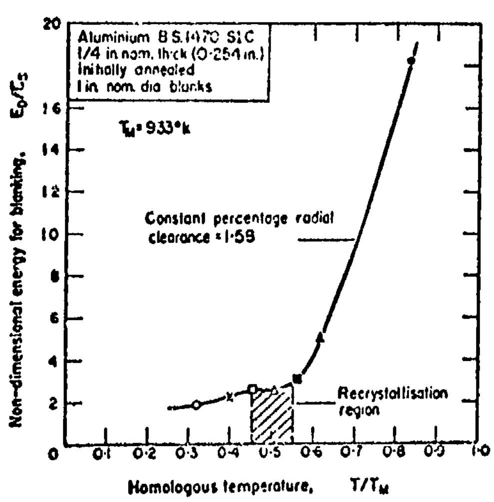


FIG. 17. Relation between maximum force for quasi-static blanking and temperature at constant percentage radial clearance (aluminium B.S. 1470 SIC).



Comparison between the energy required for quasi-static and dynamic blanking at elevated temperatures





Relation between non-dimensional energy for blanking (E_D/E_S) and homologous temperature (T/T_M) at constant percentage radial clearance

Dynamic Double Shear	CAMPBELL and FERGUSON (1970), [10]	31

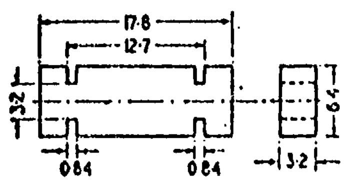
<u>Apparatus</u>: Universal rapid load testing machine, hydraulically operated
Mean $\dot{\varepsilon} \approx 2\text{-}6 \times 10^{2}$ sec^{-1}

<u>Mat.</u>: Mild Steel

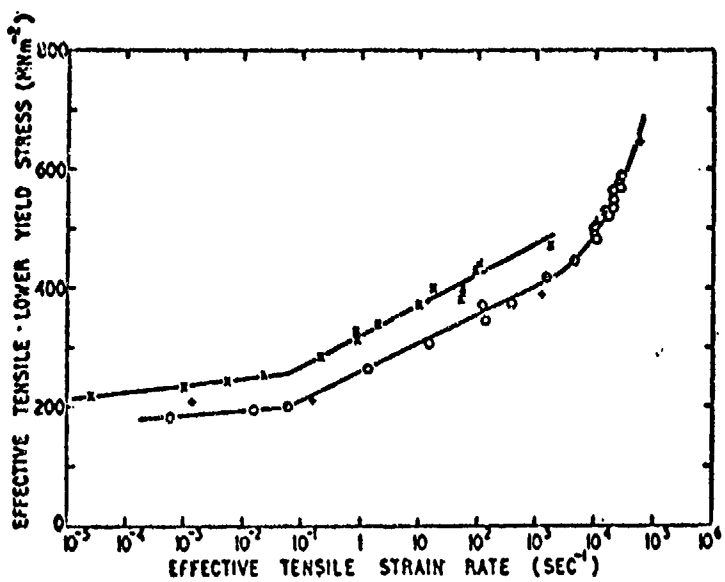
<u>Spec.</u>: Of special type with very small active gauge length (0.84 mm)
vacuum annealed at 900°C × 1 hr, furnace cooled.

<u>Heat</u>: Spec. enclosed within a small resistance furnace
Test temp.: 195, 225, 293, 373, 493, 713°K

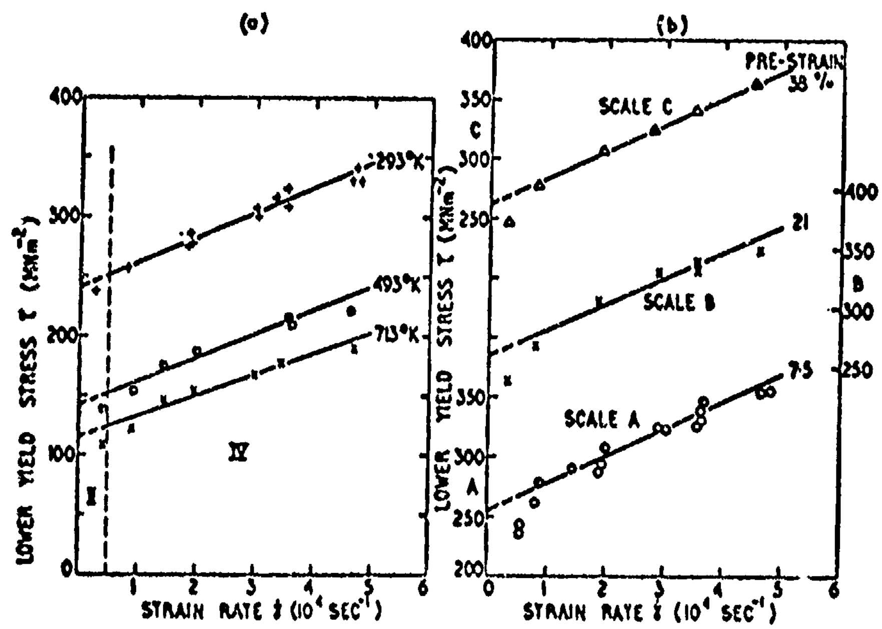
<u>Measurements</u>: - Load: strain gage dynamometer
- Crosshead velocity: with an electromagnetic transducer.
Outputs fed in CRO & recorded on film.



Design of shear specimen (dimensions in millimetres)



Comparison of results of tension (×) and punch (+) tests (Campbell and Cooper 1966, Dowling and Harding 1967) with present shear test data obtained at room temperature.



Variation of lower yield stress with strain rate (region IV). (*a*) Zero pre-strain; temperature 293, 493, 713°K. (*b*) Pre-strain 7·5, 21, 38 %; temperature 293°K.

Impact Double Shear	CAMPBELL and FERGUSON (1970), [10]	32

Apparatus: Drop wt tester & modified split Hopkinson pressure bar
Loading: by dropping weights from 0.3-25 m.
$\dot{\varepsilon} = 4 \times 10^{4}\ \text{sec}^{-1}$

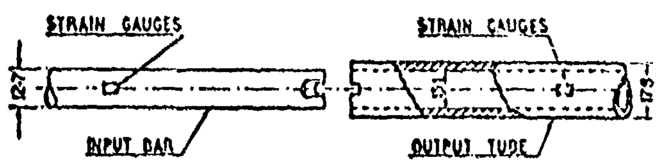
Mat.: Mild Steel

Spec.: Of special type with very small active gauge length (0.84 n/m) vacuum annealed at 900°C × 1 hr, furnace cooled.

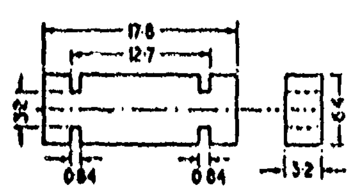
Heat: By enclosing the specimens with a small electric furnace; water cooling jackets placed adjacent to strain gauges for protection.
Test temp.: 195, 225, 293, 493, 713°K

Meas. Instr.: Strain gauges at 2 stations, output fed to CRO; ε_I, ε_R and ε_T recorded on film.

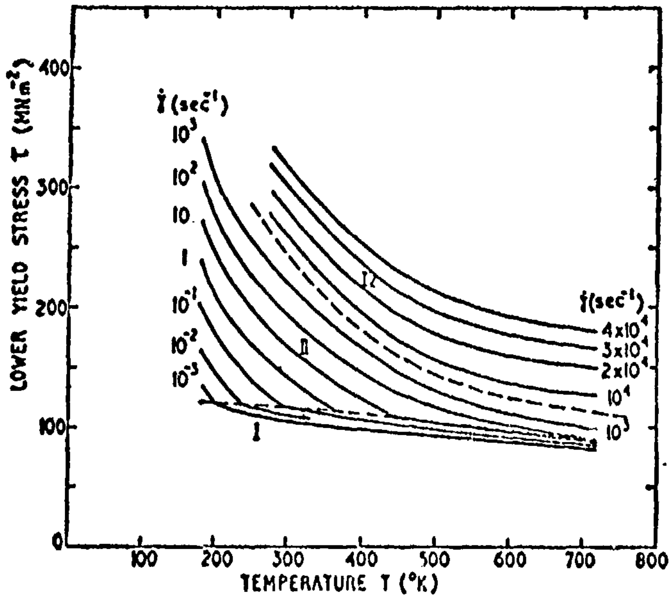
[NB. Effect of temp. gradient studied and a correction factor derived for determining the load at the end of the tube in terms of that measured at the strain gauges, the factor is small for temp. up to 713°K. Possible error at 713°K neglecting correction is ±2%. Usual analysis for computing σ_s & ε_s is used.]



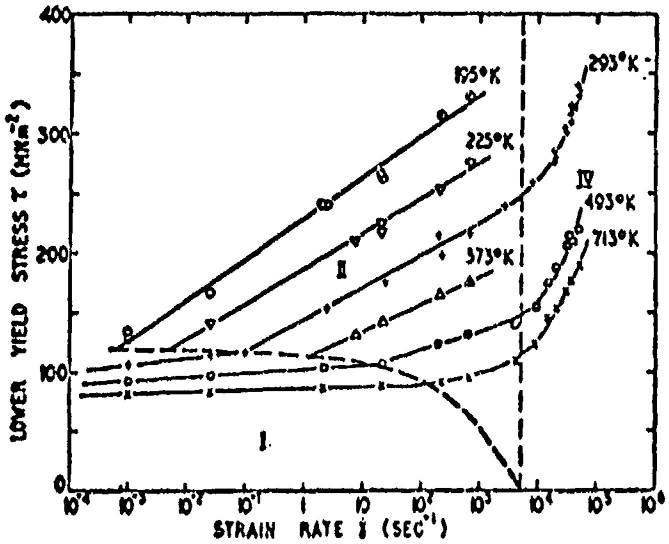
Design of split Hopkinson-bar apparatus (dimensions in millimetres)



Design of shear specimen (dimensions in millimetres).



Variation of lower yield stress with temperature, at constant strain rate.



Variation of lower yield stress with strain rate, at constant temperature.

Dynamic Torsion	HUGHES (1951), [17]	33

Apparatus: Hot torsion testing machine. Speed 12.000 rpm

Mat.: Mild Steel, 3/4" ϕ hot rolled rod. (Steel R)
High Carbon Chromium steel, 3/4" ϕ hot rolled rod. (Steel X)

Spec.: Standard test piece with central reduced portion.

Heat: Platinum wound electric furnace, filled with dry nitrogen, surrounds the spec. Temp. variation along length of specimen ∿ 4° C at 1350° C
Time at temp. = 5 min.
Test temp.: 950, 1050, 1150, 1250, 1350° C.

Meas. Instr.: - Torque: recorded electrically by means of a slide wire on a "weighing machine."
- Revolutions to fracture: using a counter.

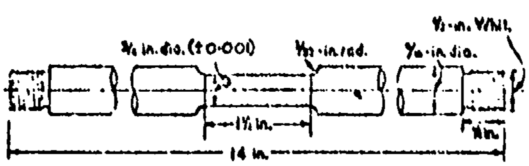


Fig. 2—Standard steel torsion test piece

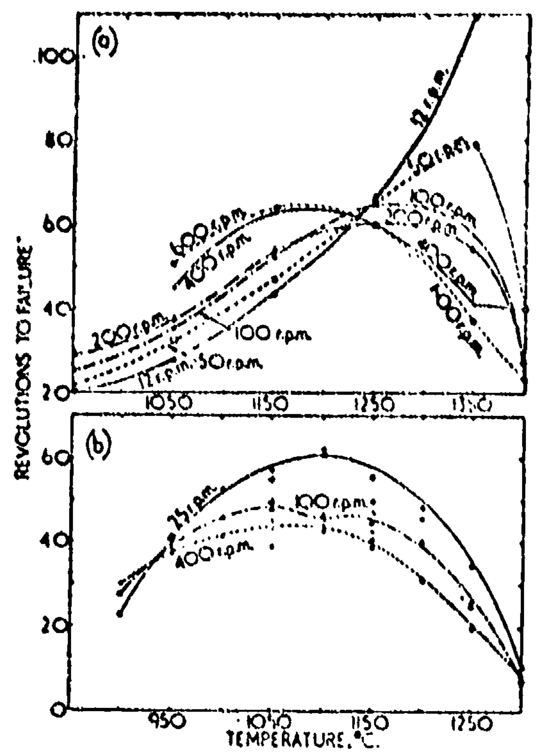


Fig. 3—Effect of testing temperature on revolutions to failure in torsion (standard ¾-in. dia. test pieces). (a) Steel R; (b) steel X

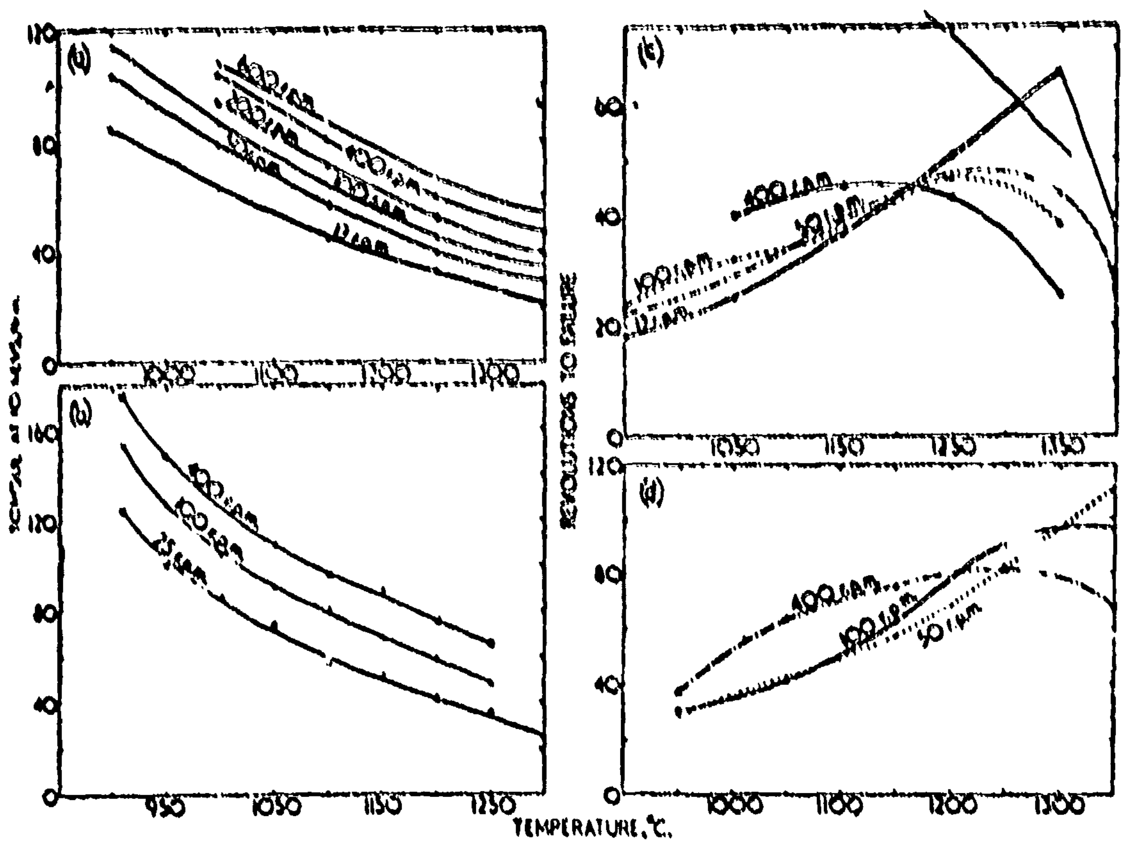


Fig. 5—Effect of testing temperature (a) on the torque at 10 revs. for steel *R* (standard test pieces); (b) on the torque at 10 revs. for steel *X* (standard test pieces); (c) on revolutions to failure in torsion for -in. dia. test pieces (steel *R*); (d) on revolutions to failure in torsion for -in. dia. test pieces (steel *R*)

Dynamic Torsion	WORK and DOLAN (1953), [44]	34

Apparatus: Torsion machine of special design.
$\dot{\epsilon}$: const., $\dot{\gamma}$ = 0.0001/12.5 sec^{-1}

Mat.: SAE 1018 Steel, 5/8" hot rolled bars

Spec.: Cylinders: D = 0.25", GL = 1"

Heat: Spec. heated in furnace during testing.
a) held at test temp. for 1/2 hr. before loading
b) given a 200 hr. aging treatment at test temp. before loading.
Test temp.: 75, 400, 700, 1000° F

Meas. Instr.: Torque: Resistance wire gages mounted outside furance, on surface of weighbar gripping one end of the specimen; output continuously recorded on photosensitive paper in oscillograph.
[Data scaled from each record plotted as torque twist curve
$\tau = \frac{Tc}{J}$, $\gamma = \frac{c\theta}{L}$; c: radius, θ = angle of twist, L = 1"]

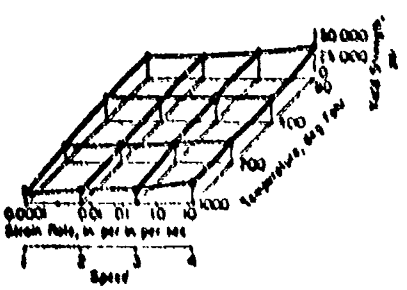


FIG. 4.—Combined Effects of Rate of Strain and Temperature on the Shearing Yield Strength of SAE 1018 Steel in Torsion.

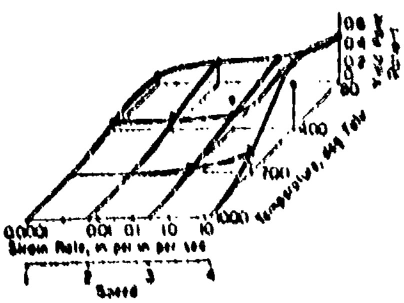


FIG. 5.—Combined Effects of Rate of Strain and Temperature on the Yield Point Ratio for SAE 1018 Steel in Torsion.

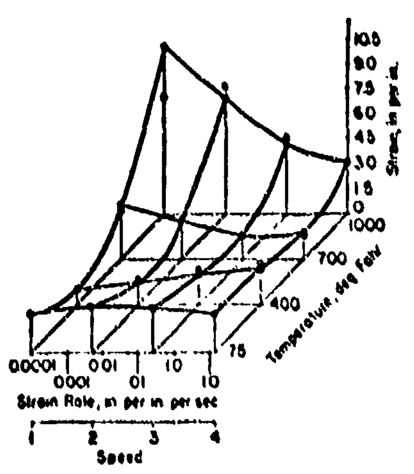


FIG. 6.—Combined Effects of Rate of Strain and Temperature on the Total Shearing Strain of SAE 1018 Steel in Torsion.

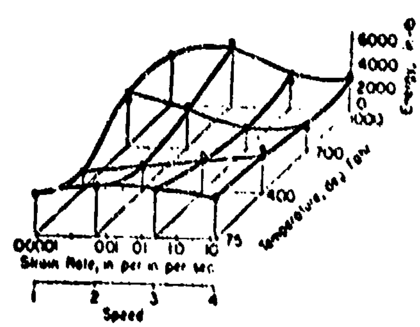


FIG. 9.—Combined Effects of Rate of Strain and Temperature on the Energy Absorbed in Specimens of SAE 1018 Steel in Torsion.

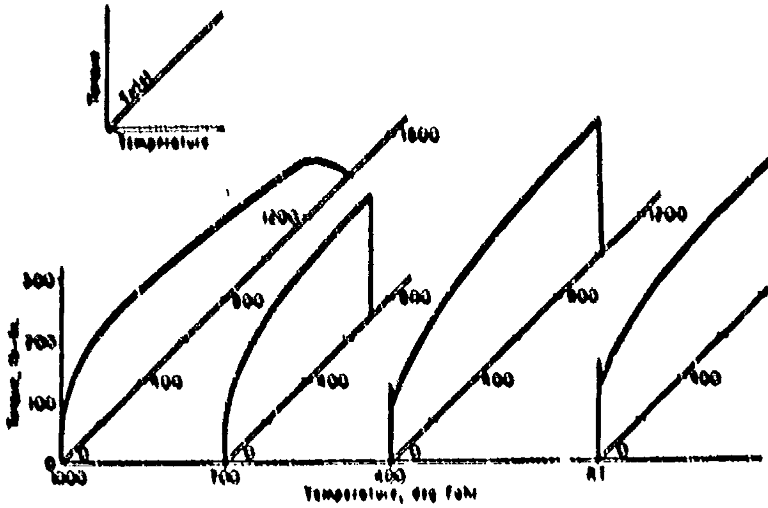
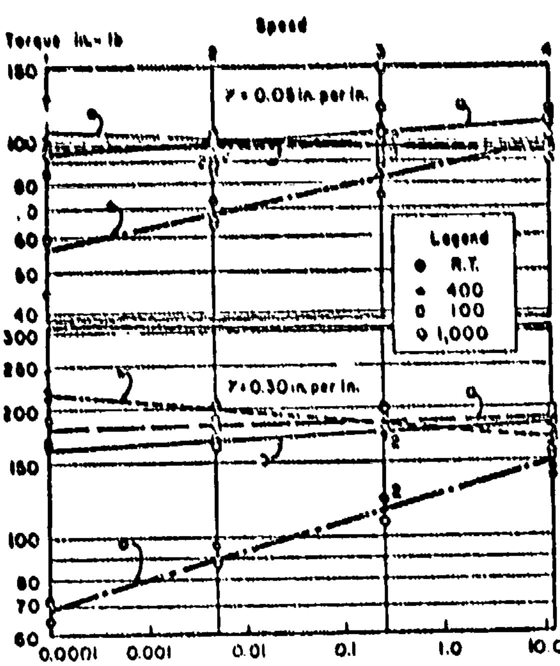
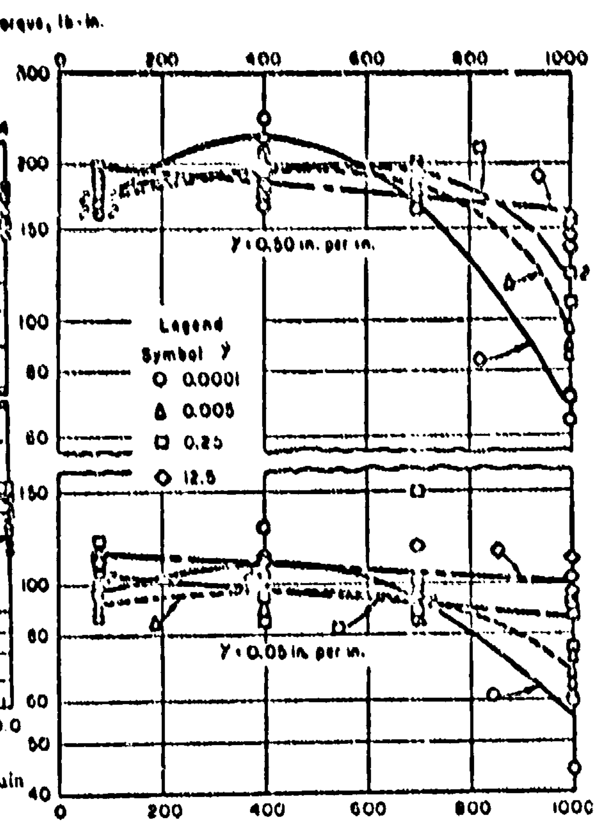


Fig. 10.—Torque-Twist Curves for Fourth Speed Torsion Tests of SAE 1018 Steel at Four Temperatures.



Effect of Rate of Strain on the Torque at Constant Shearing Strain SAE 1018 Steel.



Effect of Temperature on the Torque at Constant Shearing Strain SAE 1018 Steel.

Dynamic Torsion	ORMEROD and TEGART (1960) [30]	35

Apparatus: Hot torsion dynamic testing machine, of the type described by Hughes [65].
    Speed: 66 - 524 rpm ↔ $\dot{\gamma}$ = 0.86 - 7.1 sec^{-1}

Mat.: Super Pure Aluminum, extruded bar, D = $\frac{3}{4}$"

Spec.: Torsion spec. with reduced central gauge length to confine deformation to a given value maintained at const. temp.
    Gage length $\phi = \frac{3}{8}$", L = $1\frac{1}{2}$"

    Strained 2% in tension, annealed 2hr. x 575° C

Heat: Spec. enclosed in a furnace during test
    Test temp.: 195, 280, 390, 480, 550° C.

Meas. Instr.: Four strain gauges mounted on a cantilever dynamometer actuated by a torque arm following torque changes. Output is fed to recorder.
    [True $\tau - \gamma$ curves calculated from torque - revs curves
    $\tau = (3 + n)T/2\pi R^3$; $T = T_0\dot{\theta}^n$; $\gamma = R\theta/L$; $\dot{\gamma} = R\dot{\theta}/L$; T: torque, R: radius, $\dot{\theta}$: ang. velocity]

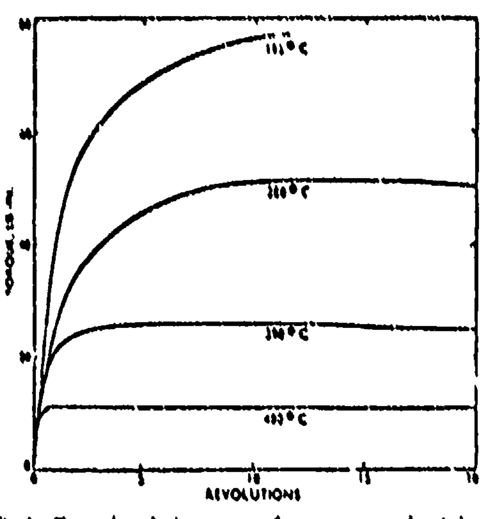


Fig. 1 Torque/revolutions curves for super-pure aluminium specimens twisted at 66 rpm.

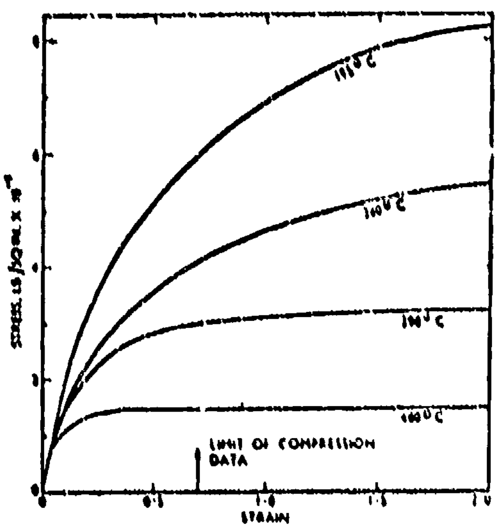


Fig. 3 True-stress/true-strain curves for super-pure aluminium at a strain rate of 0·5/sec, calculated from data of Fig. 1.

TABLE I

Values of n Derived from Tension, Torsion, and Compression Experiments on Mild Steel

Temp., °C	Tension ($\epsilon \simeq 0.8$) (Ref. 2)	Torsion ($\epsilon > 0.7$) (Ref. 3)	Compression ($\epsilon \simeq 0.7$) (Ref. 4)
950	...	0·125	0·11
1000	...	0·15	0·125
1100	0·15	0·17	0·16
1200	...	0·19	0·20

TABLE II

Values of n Derived from Torsion and Compression Experiments on Aluminium

Temp., °C	Torsion (Present Work)	Compression ($\epsilon \simeq 0.7$) (Ref. 4)
195	0·02	0·03
280	0·07	0·06
390	0·10	0·10
450	0·13	0·125
480	0·17	0·14
550	0·18	0·155

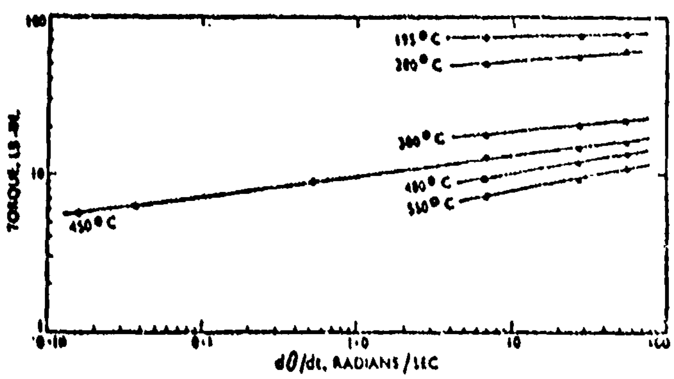


Fig. 2 Plot of $\log_{10} T$ against $\log_{10} \dot{\theta}$, to test validity of relation $T = T_0\dot{\theta}^n$.

Impact Torsion	HODIERNE (1962), [16]	36

Apparatus: Torsion machines of special design.
$\dot{\varepsilon}$: constant; slow machine: up to 10 sec^{-1}; fast: 10/1000 sec^{-1}

Mat.: Aluminum, Copper, Lead

Spec.: Tubular, D = o. 375", L = o.125", K = 0.0625"

Heat: Specimen heated in furnace during test.
Testing temp.: up to 700° C

Meas. Instr.: - Torque: resistance wire strain gauges; on a torque beam in slow machine; on hollow water cooled shaft close to one end of the specimen in fast machine.
- Strain: wire wound potentionutes for angle of twist in slow machine; tooth wheel revolving past a magnetic pick.up in fast machine.
Outputs fed to oscilloscope, and recorded on film.
[Shearing stress and strain are calculated from torque and angle of twist recorded, using the relations $\tau = 3T/2\pi(r_1^3 - r_2^3)$; $\gamma = r\theta/L$]

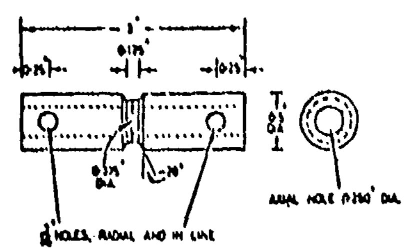


Fig. 1 Test-piece dimensions.

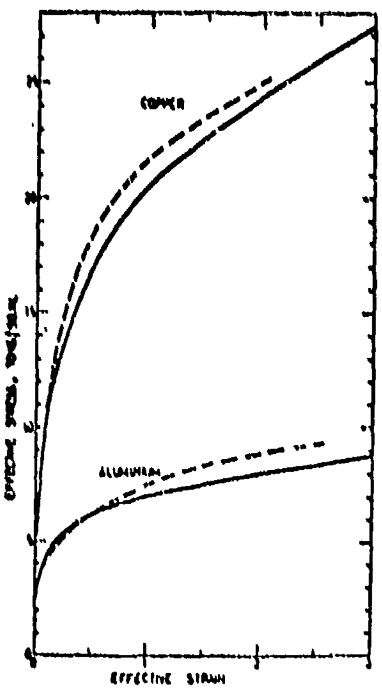


Fig. 6 Comparison of torsion (—) and plane compression (- - -)

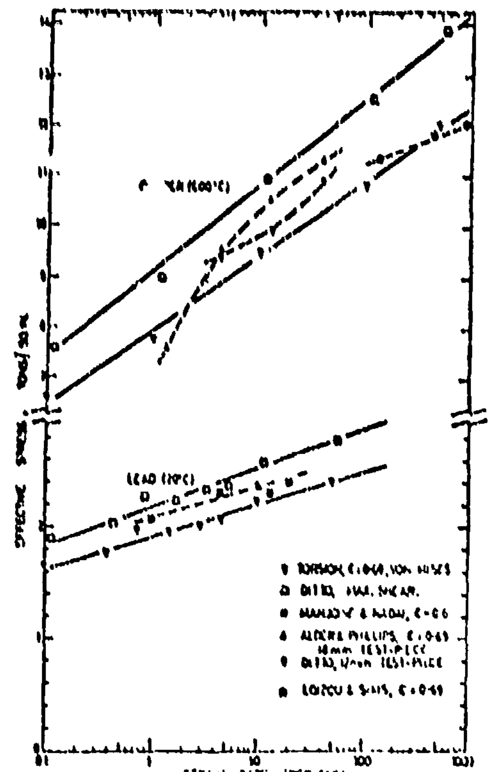


Fig. 7 Comparisons of effective stress values under dynamic conditions.

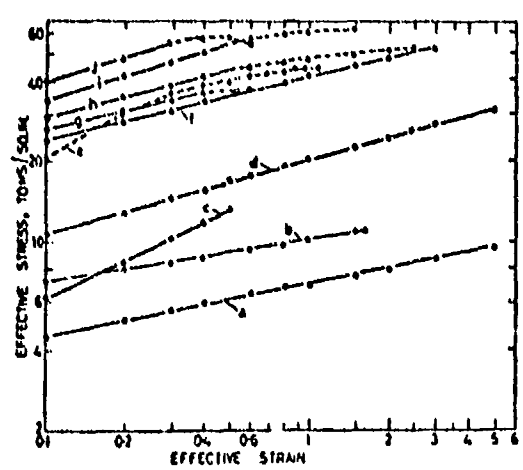


Fig. 8 Log-log Stress/Strain Plots.

a	Aluminium	f	Nickel
b	Aluminium-magnesium-silicon alloy	g	Zirconium
c	Magnox	h	Monel
d	Copper	i	Inconel
e	Mild steel	j	Uranium

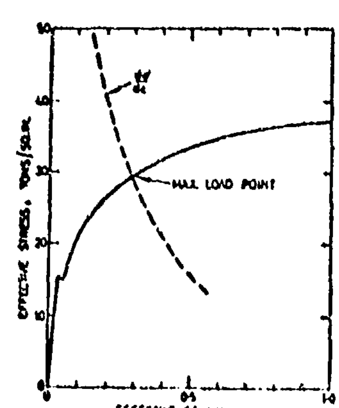


Fig. 9 Determination of uniform strain (mild steel).

SECTION IV

TEMPERATURE DEPENDENCE OF THE STRAIN-RATE SENSITIVITY

Most metals are believed to be strain-rate sensitive. How this sensitivity is affected by temperature is the concern of this Appendix. To avoid much confusion in comparing the results obtained for the same metal by different investigators, a unified definition for strain-rate sensitivity and temperature is adopted and computed for the available published data which has been surveyed. For strain-rate sensitivity, the ratio of the dynamic flow stress to the quasi-static flow stress, measured at the same temperature, was taken as the criterion. For temperature, a corresponding non-dimensional term was adopted in order to locate the point on a common temperature scale at which tests had been conducted. This non-dimensional term is the homologous temperature, T_H, defined as the ratio of the testing temperature, T, to the melting-point temperature of the tested material, T_m, on the absolute Kelvin scale.

It is believed that this procedure will facilitate comparisons between various results obtained for the same metal, as well as for different ones. A word of caution, however, is worth-mentioning here. When comparison is made, using the following tables, it is important to keep in mind the level and range of strain-rate and the level of strain to which any one result belongs, since these two parameters considerably affect the strain-rate sensitivity.

Illustrative data pertaining to different metals and alloys, together with some important related information, were arranged in the comparison tables which are presented next, in the following order:

Table 1 : Aluminum
2 : Aluminum alloys
3 : Beryllium
4 : Copper
5 : Copper alloys
6 : Iron
7 : Lead
8 : Magnesium
9 : Molybdenum
10 : Nickel
11 : Niobium
12 : Steels
13 : Titanium alloys

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TABLE 1 - ALUMINUM (Face-Centered Cubic)

Mat.: Aluminum		Melting Point, T_m		Ref.	Investigator	Mode of	Illustrative Data									Ref. Sheet
							ϵ	$\dot{\epsilon}$	T		$T_H=$	σ_{st}	σ_{dy}	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\epsilon}_{dy}}{\dot{\epsilon}_{st}}$	
Type	Condition	°C	°K	No.		Loading	(true)	sec^{-1}	°C	°K	T/T_m	ksi	ksi			No.
Super Pure (a)	Annealed	660 (b)	933	30	Ormerod and Tegart (1960)	Torsion	1.5	.5	195 480	468 753	.50 .81	- -	7.4 1.5	-	-	35
				6,7	Bailey and Singer (1963)	Plane Strain Comp. (c)	.5	.4 311	22	295	.32	9	12	1.34	778	19
								.4 311	200	473	.51	8.4	13	1.55		
								.4 311	500	773	.83	2	6.5	3.25		
							1.5	.4 311	22	295	.32	14	18	1.29		
								.4 311	200	473	.51	11	16	1.46		
								.4 311	500	773	.83	2	6.8	3.4		
				8	Baraya, Johnson and Slater (1965)	Comp.	at yield	static 105 643	500	773	.8	.25	3.48 7.95	13.9 31.8	-	11
				5	Bailey (1967)	Plane Strain Comp. (c)	1.5	.25 8.0	200	473	.51	10.5	12.5	1.19	32	20
								.25 8.0	500	773	.83	1.8	4.2	2.33		

(a) Composition : at least 99.99% Alum.
(b) For 99.996% Al content
(c) Values shown are plane strain values of stress, strain and strain rate.

TABLE 2 - ALUMINUM ALLOYS

Mat.: Alum. Alloy		Melting Point, T_m		Ref. No.	Investigator	Mode of Loading	Illustrative Data										Ref. Sheet No.
Type	Condition	°C	°K				ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\epsilon}_{dy}}{\dot{\epsilon}_{st}}$		
1100 (a)	Annealed	643 (b)	916	27, 28	Nadai and Manjoine (1941)	Tension	at max. stress (.6)	.001 1000	200	473	.52	6	12.5	2.08	10^6		25
								.001 1000	400	673	.73	1.7	8.4	4.9			
				3 (c)	Alder and Phillips (1954)	Comp.	.5	1.34 39.3	250	523	.57	12.1	13.8	1.14	29.3		1
								1.34 39.3	450	723	.79	4.6	6.7	1.46			
				4	Arnold and Parker (1960)	Comp.	.5	1 30	300	573	.63	3.65	5.2	1.42	30		3
								1 30	400	673	.73	2.3	3.4	1.48			
				11 (d)	Chiddister and Malvern (1963)	Comp.	.05	378 1740	250	523	.57	10.25	11	1.07	4.6		13
								361 1830	450	723	.79	7.5	8.35	1.11	5.1		
				41	Suzuki et al. (1968)	Comp. (e)	.5	.2 650	200	473	.52	7.3	12.8	1.76	3250		8
								.2 650	400	673	.73	2.5	6.5	2.6			

(a) Common name : Commercially pure aluminum ; Alum. content : 99.0+
(b) Solidus temp., from Ref. (45) ; Liquidus temp. = 657 C .
(c) Composition of material used : Al: 99.21 , Cu: .10 , Si: .20 , Mn: .02 , Fe: .46 , Zn: .01 %
(d) Aluminum content in material used : 99.00 %
(e) Values shown for stress are in kg/mm^2

TABLE 2 (Cont'd) - ALUMINUM ALLOYS

Mat.: Alum. Alloy Type	Condition	Melting Point, T_m °C	Melting Point, T_m °K	Ref No.	Investigator	Mode of Loading	Illustrative Data: ε (true)	$\dot{\varepsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\varepsilon}_{dy}/\dot{\varepsilon}_{st}$	Ref. Sheet No.
1100 (Cont'd)	Annealed	643	916	22	Lindholm and Yeakley (1968)	Comp.	.05	.004 / 1000	126	399	.44	8	11.7	1.46	2.5.10^5	16
								.004 / 1000	399	672	.73	1.8	7.5	4.17		
				33	Samanta (1969)	Comp. (a)	.5	.066 / 260	250	523	.57	4.7	10.7	2.28	3950	9
								.066 / 260	450	723	.79	2.15	6	2.79		
				34	Schultz (1969)	Tension	at max. stress	static / dyn.	287	560	.61	2.7	6.7	2.48	-	28
								static / dyn.	426	699	.76	1.8	4.8	2.67		
				15	Hockett (1966)	Comp.	.5	.095 / 212	200	573	.52	13.7	16.3	1.19	2240	4
								.114 / 216	400	773	.73	4.7	9.6	2.05	1890	

(a) Values shown for stress are in kg/mm^2

TABLE 2 (Cont'd) - ALUMINUM ALLOYS

Mat.: Alum. Alloy Type	Condition	Melting Point, T_m °C	°K	Ref. No.	Investigator	Mode of Loading	Illustrative Data: ε (true)	$\dot{\varepsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\varepsilon}_{dy}/\dot{\varepsilon}_{st}$	Ref. Sheet No.
2024	Annealed	541	814	6,7	Bailey and Singer (1963)	Plane Strain Comp. (b)	.5	.4 / 311	350	623	.77	13.5	24	1.78	778	19
								.4 / 311	500	773	.95	7	18.5	2.64		
							1.5	.4 / 311	350	623	.77	12.5	21.5	1.72		
								.4 / 311	500	773	.95	6.5	14	2.15		
				5	Bailey (1967)	Plane Strain Comp. (b)	.5	.25 / 8.0	350	623	.77	13	22	1.69	32	20
								.25 / 8.0	500	773	.95	7	14	2.00		
							1.5	.25 / 8.0	350	623	.77	17	28	1.65		
								.25 / 8.0	500	773	.95	10	16	1.60		
				41	Suzuki et al. (1968)	Comp. (c)	.1	.2 / 30	300	573	.70	13.7	20.3	1.48	150	8
								.2 / 30	500	773	.95	3.3	17.8	5.39		
							.5	.2 / 30	300	573	.70	11.7	6.15	.53		
								.2 / 30	500	773	.95	3	5.5	1.83		
		502	775	34	Schultz (1969)	Tension	at max. stress	static / dyn.				14.5	20.5		-	28
								static / dyn.				6.0	20.8			

(a) Composition of 2024 Alum. alloy : Al: 93.4 , Cu: 4.5 , Mg: 1.5 , Mn: .6 % ; from Ref. (45)
(b) Values shown are plane strain values for stress, strain and strain rate. (c) Stress values in kg/mm^2.

TABLE 2 (Cont'd) - ALUMINUM ALLOYS

Mat.: Alum. Alloy Type	Condition	Melting Point, T_m °C	°K	Ref. No.	Investigator	Mode of Loading	ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\epsilon}_{dy}}{\dot{\epsilon}_{st}}$	Ref. Sheet No.
3xxx (a)	Annealed	643 (b)	916	4 (c)	Arnold and Parker (1960)	Comp. (d)	.1	1 30	300	573	.63	4.3	5.5	1.28	30	3
								1 30	500	773	.84	2.2	3.0	1.36		
							.5	1 30	300	573	.63	4.8	6.25	1.30		
								1 30	500	773	.84	2.65	3.4	1.28		
5xxx (e)		593 (f)	866	4 (g)	Arnold and Parker (1960)	Comp. (d)	.1	1 30	300	573	.66	13	14.4	1.11	30	3
								1 30	500	773	.89	4.8	7.35	1.53		
							.5	1 30	300	573	.66	14.1	15.5	1.10		
								1 30	500	773	.89	4.3	7	1.63		
6xxx (h)		552 (i)	825	4 (j)	Arnold and Parker (1960)	Comp. (d)	.1	1 30	300	573	.69	4.3	5.4	1.26	30	3
								1 30	500	773	.94	2.3	3.6	1.57		
							.5	1 30	300	573	.69	4.7	6.5	1.38		
								1 30	500	773	.94	2.4	3.75	1.56		

(a) 3xxx Alloy composition: 1.2 % Mn, (45) . (b) Solidus temp., from Ref. (45) ; Liquidus temp. = 654 C
(c) Composition of Al-Mn used: Cu: .04, Mn: 1.36, Si: .30, Fe: .33 . (d) Values shown for stress are in tons/in^2 .
(e) 5052 Alloy composition: 2.5 % Mg, .25 % Cr, (45) . (f) Solidus temp., from Ref. (45) ; Liquidus temp. = 649 C .
(g) Composition of Al-2.25% Mg used: Cu: .06, Mn: .17, Mg: 2.35, Si: .22, Fe: .32 . (h) Alloy containing Mg and Si .
(i) Solidus temp. of 6151 Alloy, from Ref. (45) ; Liquidus temp. = 649 C .
(j) Composition of Al-Si-Mg alloy used : Cu: .07, Mn: .53, Mg: .73, Si: 1.04, Fe: .36 .

TABLE 2 (Cont'd) - ALUMINUM ALLOYS

Mat.: Alum. Alloy Type	Condition	Melting Point, T_m °C	Melting Point, T_m °K	Ref. No.	Investigator	Mode of Loading	ε (true)	$\dot{\varepsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\varepsilon}_{dy}/\dot{\varepsilon}_{st}$	Ref. Sheet No.
6061 - T 6 (a)	Annealed	582 (b)	855	13	Green and Babcock (1966)	Comp.	.02	.011 1000	149	422	.49	43.2	45.5	1.05	9×10^4	15
								.002 1200	288	561	.66	20	27.8	1.39	6×10^5	
							.1	.001 1000	149	422	.49	51.5	56	1.09	9×10^4	
								.002 1200	288	561	.66	23.4	34	1.45	6×10^5	
7075 - T 6 (c)	Annealed	593	866	7 (d)	Bailey and Singer (1963)	Plane Strain Comp. (e)	.5	.4 311	400	673	.78	15	25.5	1.70	779	15
								.4 311	550	823	.95	4.6	11.7	2.54		
							1.5	.4 311	400	673	.78	13	24	1.85		
								.4 311	550	823	.95	4.2	9.4	2.24		
		476 (f)	749	13	Green and Babcock (1966)	Comp.	.02	.002 400	149	422	.56	72.5	77.5	1.07	2 10^5	15
								.12 1000	288	561	.75	15.8	32.2	1.92	8333	
							.1	.002 400	149	422	.56	86.5	96	1.11	2 10^5	
								.12 1000	288	561	.75	19.6	42.5	2.17	8333	

(a) 6061 Alloy composition: Mg: 1.00, Si: .6, Cu: .25, Cr: .25 ,from Ref. (45) .
(b) Solidus temp., from Ref. (45) ; Liquidus temp. = [illegible] C .
(c) 7075 Alloy composition: Zn: 5.5, Mg: 2.5, Cu: 1.5, Cr: .3 ,from Ref. (45) .
(d) Material used: Al-5.7% Zn .
(e) Values shown are plane strain values for stress, strain and strain rate .
(f) Solidus temp., from Ref. (45) ; Liquidus temp. = 638 C .

TABLE 3 - BERYLLIUM (Close-Packed Hexagonal)

Mat.: Beryllium Type	Condition	Melting Point, T_m °C	Melting Point, T_m °K	Ref. No.	Investigator	Mode of Loading	ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\epsilon}_{dy}/\dot{\epsilon}_{st}$	Ref. Sheet No.
I - 400		1278	1551	13	Green and Babcock (1966)	Comp.	at Yield	.006 800	149	422	.27	48	60	1.25	1.3×10^3	15
								.006 1100	315	588	.38	24	49	2.04	1.8×10^5	
							.04	.006 800	149	422	.27	77.5	105	1.35	1.3×10^5	
								.005 1100	315	588	.38	35	95	2.71	1.8×10^5	
						Tension	at Yield	.001 2.0	149	422	.27	44.5	47	1.06	2000	22
								.001 2.5	315	588	.38	39	40	1.03	2500	
							.02	.001 2.0	149	422	.27	57	61.5	1.08	2000	
								.001 2.5	315	588	.38	40.5	49.5	1.22	2500	
S-200 E	Hot - Pressed Block (a)	1278	1551	23	Lindholm and Yeakley (1971)	Tension	.002	.001 10	315	588	.38	27.5	38.5	1.40	10^4	26
								.001 10	538	811	.52	21	30	1.43		
							.01	.001 10	315	588	.38	29.3	43.5	1.48		
								.001 10	538	811	.52	23	35	1.52		
						Biaxial Tension	.002 (ϵ_{LT})	.001*	315 538	588 811	.38 .52	33.5 21.5	-	-	-	
						Biaxial Torsion	.002 (ϵ_{LT})	.001	315 538	588 811	.38 .52	15.5 13.5	-	-		

(a) Specimen machined from longitudinal direction
* Effective strain rate

TABLE 3 (Cont'd) - BERYLLIUM

Mat.: Beryllium		Melting Point, T_m		Ref.	Investigator	Mode of Loading	Illustrative Data									Ref. Sheet No.
Type	Condition	°C	°K	No.			ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\epsilon}_{dy}}{\dot{\epsilon}_{st}}$	
S-200 E (Cont'd)	Hot-pressed Block (a)	1278	1551	23	Lindholm and Yeakley (1971)	Tension	.002	.001 10	315	588	.38	31.5	37	1.17	10^4	25
								.001 10	538	811	.52	21	30	1.43		
							.01	.001 10	315	588	.38	28.5	43	1.51		
								.001 10	538	811	.52	24	32	1.33		
	Extruded	1278	1551	23	Lindholm and Yeakley (1971)	Tension	at upper yield	.001 10	315	588	.38	56.5	80	1.42	10^4	25
								.001 10	538	811	.52	31	60	1.94		
							.01	.001 10	315	588	.38	51.5	71	1.38		
								.001 10	538	811	.52	36	55	1.53		
						Biaxial Tension	.01 (ϵ_L)	.001*	315 538	588 811	.38 .52	46 37	-	-	-	
						Biaxial Torsion	.01 (ϵ_{LT})	.001	315 538	588 811	.38 .52	18.5 17	-	-		

(a) Specimen machined from transverse direction .
* Effective strain rate

TABLE 4 - COPPER (Face-Centered Cubic)

Mat.: Copper Type	Condition	Melting Point, T_m °C	°K	Ref. No.	Investigator	Mode of Loading	ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\epsilon}_{dy}/\dot{\epsilon}_{st}$	Ref. Sheet No.
High Purity (99.99 % Cu)	Annealed	1083	1356	41	Suzuki et al. (1968)	Comp. (a)	.1	.1 / 2.5	18	291	.21	13.3	15	1.13	25	8
								.1 / 2.5	400	673	.50	11.6	12.5	1.08		
								.1 / 2.5	800	1073	.79	2	4.5	2.30		
							.5	.1 / 2.5	18	291	.21	34	35.2	1.04		
								.1 / 2.5	400	673	.50	17.8	19.6	1.10		
								.1 / 2.5	800	1073	.79	1.8	3.5	1.94		
High Purity Bridgeport Cu	Annealed	1083	1356	43	Watson and Ripperger (1969)	Comp.	.003	10^{-5} / 500	25	298	.22	42	47.5	1.13	5.10^7	14
								10^{-5} / 500	205	478	.35	36	61	1.69		
								10^{-5} / 600	427	700	.52	18.5	33	1.78	6.10^7	

(a) Values shown for stress are in kg/mm^2.

TABLE 5 - COPPER ALLOYS

Mat.: Copper Alloy		Melting Point, T_m		Ref. No.	Investigator	Mode of Loading	Illustrative Data										Ref. Sheet No.
Type	Condition	°C	°K				ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\epsilon}_{dy}/\dot{\epsilon}_{st}$		
Pure (99.9 % Cu)	Annealed	1083	1356	41	Suzuki et al. (1968)	Comp. (a)	.1	.1 / 2.5	18	291	.21	17.2	17.2	1	25		8
								.1 / 2.5	400	673	.50	11.2	12	1.07			
								.1 / 2.5	800	1073	.79	4	5.5	1.38			
							.5	.1 / 2.5	18	291	.21	35.5	38	1.07			
								.1 / 2.5	400	673	.50	15.8	18.5	1.17			
								.1 / 2.5	800	1073	.79	3	4.5	1.50			
				33	Samanta (1969)	Comp. (a)	.1	.066 / 600	450	723	.53	9.2	13.4	1.46	9000		9
								.066 / 600	600	873	.64	6.9	11.6	1.68			
								.066 / 600	900	1173	.86	3.2	8	2.50			
							.5	.066 / 600	450	723	.53	10.5	20.8	1.98			
								.066 / 600	600	873	.64	7.3	21	2.88			
								.066 / 600	900	1173	.86	3.5	11.5	3.29			

(a) Values shown for stress are in kg/mm^2 .

TABLE 5 (Cont'd) - COPPER ALLOYS

Mat.: Copper Alloy		Melting Point, T_m		Ref.	Investigator	Mode of Loading	Illustrative Data									Ref. Sheet No.
Type	Condition	°C	°K	No.			ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\epsilon}_{dy}/\dot{\epsilon}_{st}$	
Comm. Pure	Annealed	1083	1356	27, 28	Nadai and Manjoine (1941)	Tension	at max. stress (.6)	.00085 .51 1000	24	297	.22	44	47.5 50	1.08 1.14	6.10^2 1.10^6	25
								.00085 .51 1000	500	773	.57	9	16 27.5	1.78 3.06	6.10^2 1.10^6	
								.00085 .51 1000	1000	1273	.94	1.5	4 14	2.67 9.33	6.10^2 1.10^6	
Comm. Pure (Phosphorous deoxidised)	Annealed	1083	1356	3	Alder and Phillips (1954)	Comp.	.7	4.35 23.1	18	291	.21	56.0	57.1	1.02	5.3	1
								4.35 39.3	450	723	.53	29.0	30.1	1.04	9	
								4.35 39.3	900	1173	.87	6.7	11.0	1.64		
				16	Hodierne (1962)	Torsion	.69	.1 1 10 100 500	600	873	.64	6.5	7.8 9.4 10.8 12	1.2 1.45 1.66 1.85	10 100 1000 5000	36

TABLE 5 (Cont'd) - COPPER ALLOYS

Mat.: Copper Alloy Type	Condition	Melting Point, T_m °C	Melting Point, T_m °K	Ref. No.	Investigator	Mode of Loading	Illustrative Data: ε (true)	$\dot{\varepsilon}$ sec^{-1}	T °C	T °K	$T_H=$ T/T_m	σ_{st} ksi	σ_{dy} ksi	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\varepsilon}_{dy}}{\dot{\varepsilon}_{st}}$	Ref. Sheet No.
B S 1433	Annealed	1083	1356	25	Mahtab et al. (1965)	Comp. (a)	-	static 2400(b)	20	293	.22	.94*	4.7*	5	-	10
								static 2400	400	673	.50	.36	2.85	8		
								static 2400	600	873	.64	.14	2.2	16		
B S 1432 (High Conductivity)	Annealed	1083	1356	35	Slater and Johnson (1967)	Shear (c)	-	static (d) dyn.	20	293	.22	250**	460**	1.84	-	30
								static dyn.	400	673	.50	110	310	2.82		
								static dyn.	800	1073	.79	25	200	8.0		
				14	Hawkyard et al. (1968)	Comp. (e)	at yield	static 7140(b)	20	293	.22	12.5	26.5	2.12	-	12
								static 6060	400	673	.50	18	12.8	.71		
								static 6560	600	873	.64	2.5	10.2	4.08		

(a) Indentation tests .
(b) Impact velocity , in/sec.
(c) Blanking tests .
(d) Strain rate : Static 10^{-3} sec^{-1} , dynamic $4 . 10^3$ sec^{-1} .
(e) Mushrooming tests .

* Mean effective pressure, 10^5 psi .

** Energy required for blanking , ft lbf .

TABLE 5 (Cont'd) - COPPER ALLOYS

Mat.: Copper Alloy		Melting Point, T_m		Ref.	Investigator	Mode of Loading	Illustrative Data									Ref. Sheet No.
Type	Condition	°C	°K	No.			ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\epsilon}_{dy}/\dot{\epsilon}_{st}$	
Brass (80 % Cu 20 % Zn)	Cast	965	1238	20	Leech et al. (1954)	Tension	at fracture	250	50 450 850	323 723 1123	.26 .58 .91	-	61 * 55 29	-	-	29
	Cold Drawn : Annealed	965	1238	41	Suzuki et al. (1968)	Comp. (a)	.1	.1 10	18	291	.24	20.8	22	1.06	100	8
								.1 10	400	673	.54	18.3	19.8	1.08		
								.1 10	800	1073	.87	4.8	9.5	1.98		
							.5	.1 10	18	291	.24	53.2	56.5	1.06		
								.1 10	400	673	.54	32.4	36.4	1.12		
								.1 10	800	1073	.87	3.9	11.2	2.87		

(*) Energy to fracture, ft-lb .

(a) Values shown for stress are in kg/mm^2 .

TABLE 5 (Cont'd) - COPPER ALLOYS

Mat.: Copper Alloy		Melting Point, T_m		Ref.	Investigator	Mode of Loading	Illustrative Data										Ref. Sheet
Type	Condition	°C	°K	No.			ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\epsilon}_{dy}}{\dot{\epsilon}_{st}}$		No.
Bronze (95 % Cu 5 % Sn)	Cast	950	1223	20	Leech et al. (1954)	Tension	at fracture	250	50 450 850	323 723 1123	.26 .59 .92	-	80* 41 4	-	-		29
	Cold Drawn ; Annealed	950	1223	41	Suzuki et al. (1968)	Comp. (a)	.1	.1 10	18	291	.24	30.6	35.6	1.16	100		8
								.1 10	400	673	.55	24	26.5	1.10			
								.1 10	800	1073	.88	8	19.5	2.44			
							.5	.1 10	18	291	.24	66.5	71.5	1.08			
								.1 10	400	673	.55	43	53.8	1.25			
								.1 10	800	1073	.88	7.5	19	2.53			
90 % Cu 10 % Al	Cast (b)	1030	1303	20	Leech et al. (1954)	Tension	at fracture	250	50 450 850	323 723 1123	.25 .55 .86	- - -	103* 90 39	- - -	-		29
.0051 % Bi (c)				20	Leech et al. (1954)	Tension	at fracture	250	350 550 750	623 823 1023		-	40* 15 45	-	-		29

* Energy required to fracture , ft-lb .
(a) Values shown for stress are in kg/mm^2 .
(b) Known as Alum-Bronze Copper .
(c) Known as Bismuth Bearing Copper .

TABLE 6 - IRON (Body-Centered Cubic)

Mat.: Iron		Melting Point, T_m		Ref. No.	Investigator	Mode of Loading	Illustrative Data									Ref. Sheet No.
Type	Condition	°C	°K				ε (true)	$\dot{\varepsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\varepsilon}_{dy}/\dot{\varepsilon}_{st}$	
High Purity	Hot Rolled ; normalised	1530	1703	31	Pugh et al. (1962)	Tension	at upper yield	.000097 .37	-196	77	.05	72	72	1.0	3800	22
								.000097 .37	20	293	.17	20	41.5	2.08		
								.000097 .37	200	473	.28	15	21	1.40		
							at lower yield	.000097 .37	-196	77	.05	65	65	1.0		
								.000097 .37	20	293	.17	17	32	1.88		
								.000097 .37	200	473	.28	13	15	1.15		
	Annealed			29 (a)	Nagata et al. (1969)	[illegible] (b)	at lower yield	.00033 700	-196	77	.05	68	68	1.0	2.10^6	17
								.00033 700	20	293	.17	21	48	2.29		
								.00033 700	200	473	.28	13	21	1.62		
High Purity	Annealed	1535	1808	26 (c)	Muller (1971)	Comp. (b)	Upper Yield	.00225* 550 5000	24	297	.165	24	37 60	1.54 2.5	25.10^4 22.10^5	18
								780 5800	200	473	.261		25 38	-	-	
								700 6100	500	773	.428		15 20	-	-	
							Lower Yield	.00225* 550 5000	24	297	.165	19	36.5 59.5	1.92 3.14	25.10^4 22.10^5	
								780 5800	200	473	.261		22 33	-	-	
								700 6100	500	773	.428		15 20	-	-	

(a) Material Composition : .0002 - .05 wt. % C . (b) Values shown for stress are in kg/mm^2.
(c) Material Tested : "Ferrovac-E" Iron, a vacuum-melted electrolytic iron with 99.95 % purity.
* Tension test at 2.25 . 10^{-3}/sec.

TABLE 6 (Cont'd) - IRON

Mat.: Iron Type	Condition	Melting Point, T_m °C	°K	Ref. No.	Investigator	Mode of Loading	Illustrative Data ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\epsilon}_{dy}}{\dot{\epsilon}_{st}}$	Ref. Sheet No.
Pure	Annealed	1530	1703	43 (a)	Watson (1967)	Comp.	.003	.00001 100 1000	25	298	.18	26	52 68	10^7 10^8		14
								.00001 100 1000	204	477	.28	22	37 61	1.68 2.77	10^7 10^8	
								.00001 100 1000	538	811	.48	15	29 46	1.93 3.07	10^7 10^8	
Pure	Annealed	1530	1703	27, 28 (b)	Nadai and Manjoine (1941)	Tension	at	.00085 150	20	293	.17	37	58	1.57	$1.8 \cdot 10^5$	25
							max.	.00085 150	200	473	.28	52	45	.87		
							stress	.00085 150	800	1073	.63	3	22	7.33		

(a) Material tested : "Armco" Iron
(b) Material tested : "Wemco Research" Iron.

TABLE 7 - LEAD (Face-Centered Cubic)

Mat.: Lead		Melting Point, T_m		Ref.	Investigator	Mode of Loading	Illustrative Data										Ref.
							ε	$\dot{\varepsilon}$	T		$T_H=$	σ_{st}	σ_{dy}	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\varepsilon}_{dy}}{\dot{\varepsilon}_{st}}$		Sheet
Type	Condition	°C	°K	No.			(true)	sec^{-1}	°C	°K	T/T_m	ksi	ksi				No.
High Purity	Heat Treated	327	600	6, 7	Bailey and Singer (1963)	Plane Strain Comp. (a)	.5	.4 / 311	22	295	.49	3.7	5	1.35	778		19
								.4 / 311	170	443	.74	1.5	4.5	3.0			
								.4 / 311	300	573	.96	.4	2.35	5.88			
							2	.4 / 311	22	295	.49	5	7	1.40			
								.4 / 311	170	443	.74	1.4	3.6	2.57			
								.4 / 311	300	573	.96	.3	2.2	7.33			

(a) Values shown are plane strain values for stress, strain and strain rate .

TABLE 8 - MAGNESIUM (Close-Packed Hexagonal)

Mat.: Magnesium		Melting Point, T_m		Ref.	Investigator	Mode of Loading	Illustrative Data									Ref. Sheet
Type	Condition	°C	°K	No.			ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\epsilon}_{dy}}{\dot{\epsilon}_{st}}$	No.
Pure	Annealed	651	924	41	Suzuki et al. (1968)	Comp. (a)	.1	.1 2.5	250	523	.57	6.2	8.4	1.35	25	8
								.1 10	500	773	.84	.7	2.3	3.29	100	
							.5	.1 2.5	250	523	.57	7	8.8	1.26	25	
								.1 10	500	773	.84	.4	2.5	6.25	100	

(a) Values shown for stress are in kg/mm^2.

TABLE 9 - MOLYBDENUM (Body-Centered Cubic)

Mat.: Molybdenum		Melting Point, T_m		Ref.	Investigator	Mode of Loading	Illustrative Data										Ref. Sheet
Type	Condition	°C	°K	No.			ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\epsilon}_{dy}/\dot{\epsilon}_{st}$		No.
Sintered No.	Annealed	2620	2893	9	Campbell and Briggs (1969)	Comp.	at lower yield	.00017 100	127	400	.14	31	77	2.48	6.10^5		6
								.00017 100	327	600	.21	25	44	1.76			
							.08	.00017 100	127	400	.14	53.5	97	1.81			
								.00017 100	327	600	.21	43	58	1.35			

TABLE 10 - NICKEL (Face-Centered Cubic)

Mat.: Iron		Melting Point, T_m		Ref.	Investigator	Mode of	Illustrative Data									Ref.
Type	Condition	°C	°K	No.		Loading	ε (true)	$\dot{\varepsilon}$ sec^{-1}	T °C	T °K	$T^* = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\varepsilon}_{dy}/\dot{\varepsilon}_{st}$	Sheet No.
High Purity	Annealed	1455	1728	26 (a)	Muller (1971)	Comp. (b)	.01	.00225* 500 6400	24	297	.17	6.5	11 16	1.69 2.46	22.10^4 29.10^5	18
								600 5530	200	473	.27		8.5 12.5	-	-	
								460 5530	500	773	.45		7.5 11	-	-	
							.05	.00225* 500 6400	24	297	.17	16	24 29	1.5 1.21	22.10^4 29.10^5	
								600 5530	200	473	.27		11.5 15	-	-	
								460 5530	500	773	.45		17 20	-	-	

(a) Material Tested : "Nickel-6", a vacuum melted electrolytic nickel with 99.95 % purity.
(b) Values shown for stress are in kg/mm^2.
* Tension test at $2.25 \cdot 10^{-3}$/sec.

TABLE 11 - NIOBIUM (Body-Centered Cubic)

Mat.: Niobium (a) Type	Condition	Melting Point, T_m °C	°K	Ref. No.	Investigator	Mode of Loading	ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\epsilon}_{dy}/\dot{\epsilon}_{st}$	Ref. Sheet No.
Electron Beam Melted Niobium	Annealed	2500	2773	9	Campbell and Briggs (1969)	Comp.		.00017 100	50	323	.12	18.5	42	2.27	6 10^5	6
								.00017 100	227	500	.18	13	23.5	1.81		
							.08	.00017 100	50	323	.12	36	57.5	1.60		
								.00017 100	227	500	.18	35	40	1.14		

(a) Also known as Columbium .

TABLE 12 - STEELS

Mat.: Low Carbon St. Type	Condition	Melting Point, T_m °C	°K	Ref. No.	Investigator	Mode of Loading	Illustrative Data: ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	°K	$T^* = T/T_m$	σ_{st} ksi	σ_{dy} ksi	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\epsilon}_{dy}}{\dot{\epsilon}_{st}}$	Ref. Sheet No.
.08 % C	Annealed			41 (a)	Suzuki et al. (1968)	Comp. (c)	.1	10^{-3}	800	1073		9	11.5	1.28	33.3	8
								2^{-3}	1000	1273		6.5	7.65	1.18	6.7	
								10^{-3}	1200	1473		4.5	6.3	1.40	33.3	
							.5	10^{-3}	800	1073		11.1	17	1.53	33.3	
								10^{-3}	1000	1273		7.15	12.1	1.69		
								10^{-3}	1200	1473		4.6	9.5	2.07		
.15 % C	Annealed			41 (b)	Suzuki et al. (1968)	Comp. (c)	.1	10^{-3}	800	1073		12	16.2	1.35	33.3	8
								2^{-3}	1000	1273		8.8	8.8	1.0	6.7	
								10^{-3}	1200	1473		6	7.2	1 2	33.3	
							.5	10^{-3}	800	1073		16.8	23	1.37	33.3	
								2^{-3}	1000	1273		11.9	13	1.09	6.7	
								10^{-3}	1200	1473		5.65	10.2	1.8	33.3	

(a) Composition of Steel tested : C: .087, Si: .003, Mn: .34, P: .025, S: .02
(b) Composition of Steel tested : C: .147, Si: .27, Mn: .48, P: .014, S: .03, Cu: .275, Cr: .07, Ni: .099
(c) Values shown for stress are in kg/mm^2 .

TABLE 12 (Cont'd) - STEELS

Mat.: Low Carbon St. Type	Condition	Melting Point, T_m °C	°K	Ref. No.	Investigator	Mode of Loading	ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\epsilon}_{dy}/\dot{\epsilon}_{st}$	Ref. Sheet No.
.25 % C	Annealed			41 (a)	Suzuki et al. (1968)	Comp. (b)	.1	3.5 / 30	1000	1273		8.15	11.8	1.45	8.6	3
								3.5 / 30	1200	1473		4.3	5.92	1.38		
							.5	3.5 / 30	1000	1273		13.1	15.8	1.21		
								3.5 / 30	1200	1473		7.5	8.6	1.15		
Commercial Mild Steel	Heat Treated			27, 28	Nadai, and Manjoine (1941)	Tension	at max. stress (.1)	.00085 / .51	24	297		53	57	1.08	600	25
								.00085 / .51	600	873		16.5	37.5	2.27		
								.00085 / .51	1000	1273		3	10	3.33		
	Annealed			19 (c)	Kendall (1970)	Tension	at upper yield	.0003 / .8 (d)	27	300		3.5	41.2	11.77	2667	24
								.0003 / .8	121	394		3.38	3.78	1.12		
								.0003 / .8	315	588		3.28	3.34	1.02		
				34 (e)	Schultz (1969)	Tension	at max. stress	static / dyn.	221	494		45	48	1.07	-	25
								static / dyn.	760	1033		6.5	39	6.0		

(a) Composition of Steel tested : C: .25, Si: .08, Mn: .45, P: .012, S: .025
(b) Values shown for stress are in kg/mm^2 .
(c) Steel tested: Grade 1018 : C: .15, Mn: .65, N_2: 13 ppm, O_2: 205 ppm
(d) Values shown are elastic strain rates .
(e) Steel tested: Grade 1010 .

TABLE 12 (Cont'd) - STEELS

Mat.: Low Carbon St. Type	Condition	Melting Point, T_m °C	°K	Ref. No.	Investigator	Mode of Loading	ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	T_H = T/T_m	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\epsilon}_{dy}/\dot{\epsilon}_{st}$	Ref. Sheet No.
Commercial Mild Steel	as received			3 (a)	Alder and Phillips (1954)	Comp.	.1	4.35 23.1	930	1203		18.6	21.6	1.16		
								4.35 23.1	1060	1333		12.8	15.4	1.2		
								4.35 23.1	1200	1473		9.0	10.9	1.21	5.3	1
							.5	4.35 23.1	930	1203		24.1	29.4	1.22		
								4.35 23.1	1060	1333		16.3	22.1	1.36		
								4.35 23.1	1200	1473		10.1	14.0	1.39		
	Annealed			12 (b)	Cook (1957)	Comp.	.1	1.5 100	900	1173		7.7	11.6	1.51		
								1.5 100	1000	1273		6.25	9.5	1.52		
								1.5 100	1200	1473		3.5	6.5	1.86	67	2
							.5	1.5 100	900	1173		11	16	1.45		
								1.5 100	1000	1273		8.35	13.1	1.57		
								1.5 100	1200	1473		3.9	8.8	2.26		

(a) Composition of [illegible]el tested : C: .17, Si: .153, Mn: .62, S: .054, P: .032 .

(b) Composition of Steel tested : C: .15, Si: .12 , Mn: .68, S: .034, P: .025 .

TABLE 12 (Cont'd) STEELS

Mat.: Low Carbon St. Type	Condition	Melting Point, T_m °C	Melting Point, T_m °K	Ref. No.	Investigator	Mode of Loading	ε (true)	$\dot{\varepsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\varepsilon}_{dy}/\dot{\varepsilon}_{st}$	Ref. Sheet No.
0.10% C	Annealed			17 (a)	Hughes (1951)	Torsion	at 10 revs.	12 (b) 600	950	1223		82 (c)	-	-	500	33
								12 600	1150	1423		45	85	1.89		
								12 600	1350	1623		22	55	2.50		
SAE 1018	As received			44 (d)	Work and Dolan (1953)	Torsion (e)	at yield	.0001 10	27	300		25	35	1.40	10^5	34
								.0001 10	204	477		23	25	1.09		
								.0001 10	538	811		12.5	24	1.92		
En 1 A	Bright drawn	1527	1800	14 (f)	Hawkyard et al. (1968)	Comp. (g)	at yield	static dyn.	20	293	.16	55	87*	1.58	-	32
								static dyn.	400	673	.37	33	33	1		
								static dyn.	700	973	.54	6	26	4.33		
En 3 B				10 (h)	Campbell and Ferguson (1970)	Shear (i)	at lower yield	.001 1000	20	293		107	225	2.10	10^6	31
								.001 1000	220	473		87	132	1.52		
								.001 1000	440	713		83	100	1.20		

(a) Composition of Steel tested: C: .10, Si: .22, Mn: .37, S: .45, P: .013, Cr: .02, Ni: .08 .
(b) Strain rate in rpm. (c) Torque at 10 revs, in lb in. (d) SAE 1018 St.: C: .16, Mn: .75, P: .012, S: .024, Si: .04
(e) Values shown are shear values for stress, strain and strain rate. (i) Same as (e), in MNm^{-2}. (g) Mushrooming tests
(f) En 1A: C: .11, Si: .02, Mn: 1.24, S: .281, P: .01 (h) En 3B: C: .12, Si: .10, Mn: .62, S: .029, Pb: .004 (*) In $tons/in^2$

TABLE 12 (Cont'd) STEELS

Mat.: Low Carbon St. Type	Condition	Melting Point, T_m °C	°K	Ref. No.	Investigator	Mode of Loading	ε (true)	$\dot{\varepsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\varepsilon}_{dy}/\dot{\varepsilon}_{st}$	Ref. Sheet No.
En 2 (Black mild steel)	Annealed	1527	1800	30 (a)	Slater and Johnson (1967)	Shear (b)	-	static (c) dyn.	20	293	.16	330*	407	1.23	-	30
								static dyn.	600	873	.49	90	285	3.17		
								static dyn.	1100	1373	.76	20	210	10.5		
		1527	1800	14	Hawkyard et al. (1968)	Comp. (d)	at yield	static dyn.	20	293	.16	33.5**	45**	1.34	-	12
								static dyn.	400	673	.37	25.8	32.5	1.26		
								static dyn.	700	973	.54	-	27.7	-		
SIS 1311	Annealed			32 (e)	Samanta (1969)	Comp. (f)	.1	.066 430	20	293		40	72	1.80	6515	9
								.066 430	630	873		13.5	30	2.22		
								.066 430	1055	1328		2.5	10	4.0		
							.5	.066 430	20	293		60	-	-		
								.066 430	630	873		19.5	50	2.56		
								.066 430	1055	1328		3	17	5.67		

(a) Composition of Steel tested: C: .132, Si: .25, Mn: .55, S: .034, P: .025 (b) Blanking tests.
(c) Static rate: 10^{-3} sec^{-1}; dynamic: 4 10^3 sec^{-1}. (d) Mushrooming tests.
(e) Material tested: Steel SIS 1311, Swedish Standard, C: .10, Si: .24, Mn: .36, P: .013, S: .038 (f) Stress in kg/mm^2.
* Energy required for blanking, in ft.lbf. ** Stress values expressed in tons/in^2.

TABLE 12 (Cont'd) - STEELS

Mat.: Carbon St. Type	Condition	Melting Point, T_m °C	Melting Point, T_m °K	Ref. No.	Investigator	Mode of Loading	ε (true)	$\dot{\varepsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\varepsilon_{dy}}{\dot{\varepsilon}_{st}}$	Ref. Sheet No.
High Carbon Steel (a)	Annealed			12	Cook (1957)	Comp. (b)	.1	1.5 100	900	1173		9	16.5	1.83	67	2
								1.5 100	1000	1273		6.8	12.4	1.82		
								1.5 100	1200	1473		3.5	7.5	2.14		
							.5	1.5 100	900	1173		10.4	18	1.73		
								1.5 100	1000	1273		7.5	14	1.87		
								1.5 100	1200	1473		3.5	8.2	2.34		
Medium Carbon Steel (c)	Annealed			12	Cook (1957)	Comp. (b)	.1	1.5 100	900	1173		8.4	15	1.79	67	2
								1.5 100	1100	1273		6.5	11.7	1.8		
								1.5 100	1200	1473		2.8	7.5	2.68		
							.5	1.5 100	900	1173		11	18.2	1.65		
								1.5 100	1000	1273		7.6	13.6	1.79		
								1.5 100	1200	1473		4.2	8.8	2.1		

(a) Composition of Steel tested: C:1.0, Si: .19, Mn: .17, S: .027, P: .023, Cr: .10, Ni: .09

(b) Values shown for stress are in tons/in^2.

(c) Composition of Steel tested: C: .56, Si: .26, Mn: .28, S: .014, P: .013, Cr: .12, Ni: .09 .

TABLE 12 (Cont'd) - STEELS

Mat.: Stainless St.		Melting Point, T_m		Ref.	Investigator	Mode of Loading	Illustrative Data									Ref. Sheet No.
							ε	$\dot{\varepsilon}$	T		TH=	σ_{st}	σ_{dy}	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\varepsilon}_{dy}}{\dot{\varepsilon}_{st}}$	
Type	Condition	°C	°K	No.			(true)	sec^{-1}	°C	°K	T/T_m	ksi	ksi			
18 % Cr 8 % Ni	Annealed			12 (a)	Cook (1957)	Comp. (b)	.1	1.5 100	900	1173		13.2	14.5	1.10	67	2
								1.5 100	1000	1273		10	13	1.30		
								1.5 100	1200	1473		5.2	9	1.73		
							.5	1.5 100	900	1173		16.4	20.8	1.27		
								1.5 100	1000	1273		12.6	17.9	1.42		
								1.5 100	1200	1473		6.6	10.6	1.61		
18 % Cr 8 % Ni (Austenitic)	Annealed			32 (c)	Samanta	Comp. (d)	.1	.066 430	524	797		36.5	40	1.10	6515	9
								.066 430	765	1038		29	25	.86		
								.066 430	1055	1328		7.5	17.5	2.33		
							.5	.066 430	524	797		47.5	62.5	1.32		
								.066 430	765	1038		39	44	1.13		
								.066 430	1055	1328		9.4	33	3.51		

(a) Composition of Steel tested: C: .07, Si: .43, Mn: .48, Cr: 18.6, Ni: 7.70, P: nil, S: nil .
(b) Values shown for stress are in tons/in^2.
(c) Material tested: Type SIS 2333, Swedish Standard, C: .46, Si: .5, Mn: .42, P: .012, S: .008, Cr: 18.8, Ni: 9.2, Mo: .27, W: nil, V: nil .
(d) Values shown for stress are in kg/mm^2.

TABLE 12 (Cont'd) STEELS

Mat.: Stainless St.		Melting Point, T_m		Ref.	Investigator	Mode of Loading	Illustrative Data									Ref. Sheet No.
Type	Condition	°C	°K	No.			ϵ (true)	ϵ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\epsilon_{dy}}{\epsilon_{st}}$	
316	Annealed	1385	1658	42	Thiruvengadam and Conn (1971)	Tension	at max. stress	static dyn.	24	297	.18	81.2	138	1.70	-	27
								static dyn.	704	977	.59	46.0	109.2	2.37		
18 % Cr 8 % Ni	Annealed			27, 28	Nadai and Manjoine (1941)	Tension	at max. stress (.1)	.00085 .51	24	297		68	73.5	1.08	600	25
								.00085 .51	600	873		44.5	47.5	1.07		
								.00085 .51	1000	1273		7	26.5	3.79		
				41 (a)	Suzuki et al. (1968)	Comp. (b)	.1	.2 100	0	273		52	57	1.10	500	8
								.2 100	400	673		28	31.2	1.11		
								.2 100	800	1073		13	22	1.69		
								.2 100	1200	1473		6.8	11	1.62		
							.5	.2 100	0	273		104	114	1.10		
								.2 100	400	673		45	58.5	1.30		
								.2 100	800	1073		27.7	33.5	1.21		
								.2 100	1200	1473		8.4	14	1.67		

(a) Composition of Steel tested: C: .08, Si: .49, Mn: 1.06, Cr: 18.37, Ni: 9.16, P: .037, S: .005 .
(b) Values shown for stress are in kg/mm^2 .

TABLE 12 (Cont'd) - STEELS

Mat.: Alloy St. Type	Condition	Melting Point, T_m °C	°K	Ref. No.	Investigator	Mode of Loading	ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\epsilon_{dy}/\epsilon_{st}$	Ref. Sheet No.
18/4/1 High Speed Steel				12 (a)	Cook (1957)	Comp. (b)	.1	1.5 100	900	1173		22	28.2	1.28	67	2
								1.5 100	1000	1273		17.2	23.5	1.37		
								1.5 100	1200	1473		9	14.9	1.66		
							.5	1.5 100	900	1173		20.7	30.8	1.49		
								1.5 100	1000	1273		16	24.8	1.55		
								1.5 100	1200	1473		7.8	15	1.92		
SIS 2722 High Speed Steel				32 (c)	Samanta (1968)	Comp. (d)	.1	.066 430	524	797		25	50	2	6515	9
								.066 430	765	1038		23	50	2.17		
								.066 430	1055	1328		3	28.5	9.50		
							.5	.066 430	524	797		39.5	-	-		
								.066 430	765	1038		28	55	1.96		
								.066 430	1055	1328		5	40	8		

(a) Composition of 18/4/1 HSS tested: C: .80, Si: .28, Mn: .32, Cr: 4.3, Ni: .18, Mo: .55, W: 18.4, V: 1.54
(b) Values shown for stress are in tons/in^2.
(c) SIS 2722, Swedish Standard: C: .86, Si: .21, Mn: .34, P: .023, S: .02, Cr: 4.07, Ni: .32, Mo: 5.5, W: 6.63, N: .045, V: 2.05
(d) Values shown for stress are in kg/mm^2.

TABLE 12 (Cont'd) - STEELS

Mat.: Alloy St. Type	Condition	Melting Point, T_m °C	°K	Ref. No.	Investigator	Mode of Loading	ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\epsilon}_{dy}}{\dot{\epsilon}_{st}}$	Ref. Sheet No.
High Carbon Chromium				17 (a)	Hughes (1952)	Torsion	at 10 revs.	25 400 (b)	850	1123		125*	175*	1.40	16	33
								25 400	1050	1323		70	110	1.57		
								25 400	1250	1523		30	68	2.27		
En 31 High Carbon Chromium Steel				12 (c)	Cook (1957)	Comp. (d)	.1	1.5 100	900	1173		10	17	1.70	67	2
								1.5 100	1000	1273		6.8	12.5	1.84		
								1.5 100	1200	1473		3.4	7.8	2.29		
							.5	1.5 100	900	1173		12.2	19.5	1.60		
								1.5 100	1000	1273		8.4	13	1.55		
								1.5 100	1200	1473		4	8.35	2.09		

(a) Composition of alloy tested: C: 1.14, Si: .23, Mn: .48, S: .031, P: .034, Cr: 1.33, Ni: .18
(b) Strain rate values shown are in rpm .
(c) Composition of alloy tested: C: 1.06, Si: .22, Mn: .46, S: .019, P: .031, Cr: .17 .
(d) Values shown for stress are in tons/in^2 .
* Values shown are for the torque at 10 revs, in lb.in.

TABLE 12 (Cont'd) - STEELS

Mat.: Alloy St.		Melting Point, T_m		Ref.	Investigator	Mode of Loading	Illustrative Data									Ref. Sheet No.
Type	Condition	°C	°K	No.			ε (true)	$\dot{\varepsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\varepsilon}_{dy}/\dot{\varepsilon}_{st}$	
SIS 2244 Construc-tion Steel	Annealed			32 (a)	Samanta (1968)	Comp. (b)	.1	.066 430	765	1038		16.5	40	2.42	6515	9
								.066 430	865	1138		13	33.5	2.58		
								.066 430	1055	1328		6.3	16	2.54		
							.5	.066 430	765	1038		21.5	-	-		
								.066 430	865	1138		16	49	3.06		
								.066 430	1055	1328		8.3	30	3.61		
4340 Construc-tion St.	Heat treated (c)			19 (d)	Kendall (1970)	Tension	.002 Offset	.0003* 3	27	300		158	1425	.90	10^4	24
								.0003 3	317	590		164	143	.87		
Grade 300 Steel	Heat treated (e)			19 (f)	Kendall (1970)	Tension	.002 Offset	.0003* 3	27	300		272.5	292	1.07	10^4	24
								.0003 3	317	690		248.5	237.5	.96		

(a) SIS 2244, Swedish Standard: C: .40, Si: .38, Mn: .79, Cr: .98, Mo: .19 .
(b) Values shown for stress are in kg/mm^2 .
(c) After treatment, ASTM grain size No. 8 .
(d) Composition of alloy 4340 tested: C: .44, Si: .30, Mn: .75, Cr: .85, MO: .21, Ni: 1.65 .
(e) After treatment, ASTM grain size No. 8/9 .
(f) Composition of Grade 300 Maraging steel tested: C: .02, Mn: .08, Si: .08, Ni: 18.5, Mo: 5.0, Co: 9.0, Ti: .6, Zr: .01, B: .003 .
* Values shown are elastic strain rates .

TABLE 12 (Cont'd) - STEELS

Mat.: Alloy St. Type	Condition	Melting Point, T_m °C	Melting Point, T_m °K	Ref. No.	Investigator	Mode of Loading	Illustrative Data: ϵ (true)	$\dot{\epsilon}$ sec^{-1}	T °C	T °K	$T_H = T/T_m$	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\epsilon}_{dy}/\dot{\epsilon}_{st}$	Ref. Sheet No.
AISI H-11 Tool St. (a)	Heat treated (b)			19	Kendall (1970)	Tension	.002 Offset	.0003* 3	27	300		246.8	264.5	1.07	10^4	24
								.0003 3	317	590		228	228	1.00		
SIS 2242 Tool St. (c)	Annealed			32	Samanta (1968)	Comp. (d)	.1	.066 430	524	797		24	49.5	2.06	6515	[illegible]
								.066 430	765	1038		13	33.5	2.58		
								.066 430	1055	1328		3.5	25	7.14		
							.5	.066 430	524	797		28.5	50	1.75		
								.066 430	765	1038		16	45	2.81		
								.066 430	1055	1328		4.3	35	8.14		
Alum. killed Sheet St. (e)	Temper rolled			24	MacDonald et al. (1957)	Tension	.01	.002 .8	24	297		19	29	1.53	400	21
								.002 .8	149	422		19	20	1.05		
							.05	.002 .8	24	297		28	37	1.32		
								.002 .8	149	422		25	28	1.12		

(a) H-11 AISI type, High Chromium tool steel : C: .40, Cr: 5.0, Mo: 1.3, V: .5 (b) After treatment, ASTM grain size 7/[illegible]
(c) SIS 2242 Tool St., Swedish Standard: C: .39, Cr: 5.29, Mo: 1.35, V: .83, Si: 1.02, Mn: .60, P: .016, S: .020, Ni: [illegible] .
(d) Values shown for stress are in kg/mm^2. (e) Used mostly in deep drawing operations . (*) [illegible] strain rates .

TABLE 13 - TITANIUM ALLOYS .

Mat.: Titanium Alloy		Melting Point, T_m		Ref.	Investigator	Mode of Loading	Illustrative Data									Ref. Sheet No.
Type	Condition	°C	°K	No.			ε (true)	$\dot{\varepsilon}$ sec^{-1}	T °C	T °K	T_{hr} T/T_m	σ_{st} ksi	σ_{dy} ksi	$\frac{\sigma_{dy}}{\sigma_{st}}$	$\frac{\dot{\varepsilon}_{dy}}{\dot{\varepsilon}_{st}}$	
6 Al - 4 V	Annealed	1660 (a)	1933	13	Green and Babcock (1966)	Comp.	.31	.006 800	149	422	.22	115	144	1.25	1.3×10^5	7
								.009 900	316	589	.31	91	117	1.29	2.3×10^5	
							.35	.006 800	149	422	.22	141	164	1.16	1.3×10^5	
								.004 900	316	589	.31	113	135	1.19	2.3×10^5	
						Tension	.01	.001 10	149	422	.22	104	130	1.25	10^4	
								.002 10	316	589	.31	84	95	1.13	5×10^3	
							.05	.001 10	149	422	.22	118	136	1.15	10^4	
								.002 10	316	589	.31	95	106	1.12	5×10^3	
6 Al - 2 Mo - 4 Zr - 2 Sn	As Received			42	Thiruvengadam and Conn (1971)	Tension	at max. stress	static 10^3	24	297		152	229	1.51	-	27
								static 10^3	482	755		106	167	1.57		

(a) Liquidus temp., from Ref. (45) .

TABLE 13 (Cont'd) - TITANIUM ALLOYS .

Mat.: Titanium Alloy Type	Condition	Melting Point, T_m °C	Melting Point, T_m °K	Ref. No.	Investigator	Mode of Loading	Illustrative Data: ε (true)	$\dot{\varepsilon}$ sec^{-1}	T °C	T °K	T/T_m	σ_{st} ksi	σ_{dy} ksi	σ_{dy}/σ_{st}	$\dot{\varepsilon}_{dy}/\dot{\varepsilon}_{st}$	Ref. Sheet No.
Commercial	Hot rolled ; annealed			41 (a)	Suzuki et al. (1968)	Comp. (b)	.1	.1 2.5	400	673		19	22	1.16	25	8
								.1 2.5	600	873		12.2	14.5	1.19		
								.1 2.5	800	1073		3	5.5	1.83		
							.5	.1 2.5	400	673		34	40	1.18		
								.1 2.5	600	873		16.8	21	1.25		
								.1 2.5	800	1073		3.7	9	2.43		

(a) Composition of alloy tested: Ti: Bal., Fe: .03, N: .0084, H: .0025 .

(b) Values shown for stress are in kg/mm^2 .

SECTION VI

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