RFP-1051

MASTER

LITERATURE SURVEY:
PHYSICAL PROPERTIES OF LITHIUM AND
BERYLLIUM AT LOW TEMPERATURES

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ROCKY FLATS DIVISION
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U.S. ATOMIC ENERGY COMMISSION
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Printed in the United States of America

Available from

Clearinghouse for Federal Scientific and Technical Information

National Bureau of Standards, U. S. Department of Commerce

Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

December 6, 1967

RFP-1051
UC-4 CHEMISTRY
TID-4500

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Layman A. Lott

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Literature Survey: Physical Properties of Lithium and Beryllium at Low Temperatures

Layman A. Lott

Abstract. A literature search was made of physical properties of lithium and beryllium in the cryogenic temperature range of 0°K to 130°K (-273°C to -143°C). This report summarizes information on such properties as thermal expansion, phase transformations, and mechanical strength of these materials.

INTRODUCTION

A literature search was made of certain physical properties of lithium and beryllium at low temperatures. The properties sought were primarily mechanical properties which would be pertinent in the consideration of these materials for structural applications at low temperatures.

The primary sources of references were two computer processed bibliographies prepared by the Cryogenic Data Center, National Bureau of Standards (NBS), Boulder, Colorado. The first of these, prepared in June 1966, was entitled "Bibliography of References for Low Temperature Properties of Lithium." The properties listed in this bibliography included thermal expansion, tensile properties, modulus of elasticity, fatigue properties, mechanical properties, and impact strength. *Chemical Abstracts* were searched for references appearing after the date of this bibliography. The other bibliography, prepared in May 1967, contained references on low temperature properties of beryllium and lithium alloys. The specific properties listed included mechanical properties, thermal expansion, solid transitions, crystal-lattice effects, and size effects.

The NBS bibliographies and this survey are primarily concerned with properties of the materials in the cryogenic temperature range of 0 to 130°K (-273 to -143°C).

CRYOGENIC PROPERTIES OF LITHIUM

GENERAL PROPERTIES OF LITHIUM — A review of the physical properties of lithium at all temperatures is given by Fenn.¹ Prominent features of lithium include low density (it is the lightest metal), low melting point, and it has the highest specific

heat of any solid element. It is very soft, ductile, and malleable. Room temperature is considered a high temperature for lithium because it behaves more like other metals, as far as mechanical properties are concerned, at cryogenic temperatures. For example, it recrystallizes at room temperature to its normal body-centered cubic phase, from phase transformations induced at low temperatures.

THERMAL EXPANSION — Laquer² investigated the thermal expansion of extruded lithium at temperatures from 0°K to 300°K with a quartz tube dial gage dilatometer. He made actual measurements from 300°K to 20°K and extrapolated these data to zero temperature. The results of these values are shown in the appendix and are compared with expansion data for other common metals. It can be seen that lithium has quite a high thermal expansion coefficient; expanding almost twice as much as aluminum between 0°K and room temperature.

X-ray measurements of the variation of the lattice parameter with temperature^{3,4} are in essential agreement with Laquer's macroscopic measurements.

PHASE TRANSFORMATIONS — The normal crystal structure of lithium at room temperature is body-centered cubic (bcc). However, at temperatures close to that of liquid nitrogen (77°K) and below, lithium transforms spontaneously to a hexagonal close-packed (hcp) structure, and with cold work lithium transforms from either the bcc or hcp structures to a face-centered cubic (fcc) structure.⁴⁻¹⁴

Cooling below a critical temperature results in the initiation of a spontaneous martensitic-type transformation from the bcc phase to a faulted hcp phase. The critical temperature was determined to be 71°K by Barret and Trautz⁸ and Hovi et al.,¹⁴ by x-ray methods, and in the range 74°K to 78°K by Hull and Rosenberg⁹ and Bowles¹² by metallographic techniques. The transformation progresses as the temperature is decreased below the critical temperature, but stops when the temperature is held constant. Hull and Rosenberg⁹ found the transformation to be complete at 20°K and estimated that approximately 90 percent of the material had transformed. The reversion to the bcc phase on heating is similar except for a hysteresis

between heating and cooling curves. The reversion to bcc on heating begins at about 90°K.^{8,11}

When lithium is deformed at temperatures below approximately 77°K, a transformation to the fcc phase is induced. Upon heating, this phase reverts to bcc in the temperature range 140°K to 180°K.^{6,8,13} Garber et al.,¹³ in an internal friction experiment, concluded that this strain-induced transformation is also of the martensitic type.

The martensitic transformation from bcc to hcp in lithium is accompanied by a very small volume contraction. Verdini¹⁵ measured this volume change by a capacitor method. He obtained a value of $\Delta V/V = -6 \times 10^{-4}$ (corresponding to a linear contraction of $\Delta l/l = -2 \times 10^{-4}$), although it was stated that quantitative results were difficult to estimate accurately with the experimental apparatus. Basinski and Verdini¹⁶ found the volume contraction of lithium on transformation by a liquid displacement method to be $\Delta V/V = -7 \times 10^{-4}$ ($\Delta l/l = -2.3 \times 10^{-4}$). A value of $\Delta V/V = -3.3 \times 10^{-4}$ was actually measured, but it was estimated that only 50 percent of the lithium had transformed on cooling to 4.2°K.

Barrett and Trautz⁸ detected no expansion accompanying a complete bcc-fcc transformation in lithium at 78°K. They found that the linear expansion increased from zero for pure lithium to about 0.5 percent for a lithium-24 atomic percent magnesium alloy.

MECHANICAL PROPERTIES – The mechanical properties of lithium at low temperatures are influenced by the martensitic transformation. Hull and Rosenberg¹⁷ made tensile measurements on 99.7 percent pure extruded lithium at temperatures of 4.2, 20.4, 80, 195, and 293°K. From these measurements they obtained stress-strain curves and values of the yield stress as a function of temperature. They stated that the yield stress was small and difficult to determine accurately with the apparatus used. A summary of their low temperature data is shown in Table I.

TABLE I. Summary of Tensile Results of Hull and Rosenberg.¹⁷

T (°K)	Tensile Strength (kg/mm ²)	Yield Strength (kg/mm ²)	Elongation (%)
80	1.3	0.28	20-25
20	4.0-4.5	0.63	25-35
4.2	4.5-5.5	0.75	30-35

They stated that the lithium work hardened very rapidly to relatively high stresses at 20°K and 4.2°K

with elongations of approximately 40 percent. At 20°K, and even more pronounced at 4.2°K, a series of very marked discontinuous yield drops were observed. At 4.2°K the specimens fractured in a brittle fashion after an extension of about 30 to 50 percent.

The general nature of the tensile properties of lithium was explained by Hull and Rosenberg in terms of the low temperature phase transformations. They concluded that transformation takes place at 80°K as evidenced by the continuous hardening of the specimens during the tensile tests at that temperature. At 20°K they found the transformation to the hcp phase to be complete as shown by the similarity of the work hardening at 20°K and at 4.2°K. They suggested that the discontinuous yielding is due to "catastrophic" changes from hcp to fcc.

Gindin et al.,¹⁸ made a similar study of the tensile properties of 99.3 percent purity lithium in the temperature range 1.5 to 300°K. Their results are summarized in Table II.

TABLE II. Summary of Tensile Test Results of (Gindin et al.).¹⁸

T (°K)	Tensile Strength (kg/mm ²)	Yield Strength (kg/mm ²)	Elongation (%)
80	1.3	0.5	90
20	4.8	2.1	100
4.2	6.0	2.2	105

They also observed a rapid strain hardening to relatively high stresses at low temperatures. They attributed this behavior to the polymorphous transformation caused by plastic deformation.

Gindin et al.,¹⁹ studied the creep of 99.3 percent pure lithium at 300, 180, and 77°K. Here too, the behavior was found to be influenced by the polymorphous transformation.

LITHIUM ALLOYS – Very little information exists in the literature on cryogenic properties of lithium-rich alloys. Most of what does exist concerns lithium alloyed with magnesium.

Barrett and Trautz⁸ studied the low temperature phase transformations in lithium-magnesium alloys in the composition range 14.5 to 87.6 weight percent magnesium (4.6 to 66.8 atomic percent magnesium). In addition to the effect on the linear expansion on transformation mentioned above, they found that alloying lithium with up to 12 atomic percent magnesium raises all critical temperatures. For example, they determined the temperature of spontaneous

transformation to be 71°K for pure lithium, and 130°K for the 12 atomic percent magnesium alloy. They also found the strain-induced transformation to exist only in alloys containing less than 24.2 atomic percent magnesium, and the spontaneous transformation to exist only in alloys of 16.3 atomic percent magnesium or less. This was determined for temperatures down to about 60°K.

Martin²⁰ concluded from specific heat measurements on a 0.95 atomic percent magnesium-lithium alloy that addition of small amounts of magnesium to lithium does not significantly alter the course of the martensitic transformation apart from slightly raising the transformation temperature. He also states that up to 70 atomic percent magnesium can be added to lithium without changing the bcc structure of lithium.

Dugdale and Guban¹⁰ determined from electrical resistivity measurements on alloys composed of up to 0.95 atomic percent magnesium, that the transformation temperature increases by about 10°K for each atomic percent of magnesium added in this composition range.

ISOTOPIC EFFECTS – Very little information exists in the literature on isotopic effects on the cryogenic properties of lithium. Snyder²¹ measured the bcc → hcp transformation temperature for lithium⁶ and lithium⁷ of 99 percent isotopic enrichments. He found 73°K for lithium⁷ and 69°K for lithium⁶.

CRYOGENIC PROPERTIES OF BERYLLIUM

GENERAL PROPERTIES OF BERYLLIUM – Although beryllium also has a very low density, its mechanical properties are in marked contrast to those of lithium. For example, at room temperature beryllium is a brittle material and becomes even more brittle at low temperatures. Documenting the properties of beryllium is complicated by the fact that beryllium is hexagonal in crystal structure and thus exhibits anisotropic properties. Even polycrystalline material usually exhibits anisotropy due to preferred orientation, the degree of which depends upon the treatment to which the metal is subjected. Other factors affecting the mechanical properties of beryllium are impurity content, grain size, and surface condition. All of these depend upon the form of the starting material and the metallurgical forming processes. All of these factors must be considered in trying to determine what mechanical properties can be achieved in a particular component of beryllium.

THERMAL EXPANSION – The thermal expansion of single crystalline beryllium between room temperature and 80°K was measured by Erfling.²² The results of these measurements were compiled by Corruccini and Gniewek²³ and by Laquer² and are shown in the appendix. The values listed are the mean values $\alpha = 1/3\alpha_{11} + 2/3\alpha_{11}$, where α_{11} and α_{11} are the expansions measured parallel and perpendicular, respectively, to the hexagonal axis. The values listed for temperatures less than 80°K were obtained by extrapolation using the Grüneisen relation.²³

Also listed in the appendix are the mean thermal expansion values for single crystalline beryllium measured by Meyerhoff and Smith.²⁴ The expansion coefficients in the different crystallographic directions differ from the mean values only by about 20 percent.

As can be seen, in contrast to lithium, beryllium has a significantly lower thermal expansion coefficient. In going from 300°K to 0°K, beryllium would contract less than one-third as much as aluminum. Therefore, in any device in which beryllium is rigidly joined to other common materials, differential thermal contraction is a possible problem.

MECHANICAL PROPERTIES – A comprehensive account of the mechanical properties of beryllium at low temperatures, is given by Klein and Pickett²⁵ in their investigation of the beryllium windows that failed during the accident at the Cambridge Electron Accelerator bubble chamber.

They concluded from a literature survey on the mechanical properties of beryllium at low temperatures that polycrystalline material of commercial purity can undergo a small amount of plastic deformation at 77°K, and that only high purity single crystalline material can undergo plastic deformation at 20°K. They speculated, based on these conclusions, that "polycrystalline beryllium of commercial purity is completely brittle at 20°K, i.e., under an applied stress of sufficient magnitude, fracture will occur before any measurable plastic deformation takes place. If this speculation is correct, there is no way that beryllium can accommodate applied stresses by general or local yielding at 20°K".

Tensile tests on specimens machined from the beryllium windows under investigation were made at room temperature and liquid hydrogen temperature (20°K). Specimens were oriented both perpendicular and

parallel to the faces of the windows. The windows were machined from forged, commercial, polycrystalline beryllium known to exhibit preferred orientation. The results of these tests are shown in Table III.

TABLE III. Results of Tensile Tests Experiments by Klein and Pickett.²⁸

	Range of Values	
	Room Temperature	20°K
Ultimate tensile strength (kpsi)		
	50-84	32-95
⊥	32-49	29-48
Yield strength		
0.2% offset (kpsi)		
	50-54	*
⊥	*	*
% Elongation		
	0.8-16.4	
⊥	0.8- 2.8	

* Specimen failed before a strain equivalent to a 0.2 percent offset was attained.

The mechanical properties of commercial hot pressed beryllium (Brush Q.M.V.-grade) were measured by Powell et al.,²⁵ at the NBS in Boulder, Colorado. These results are summarized in Table IV.

TABLE IV. Summary of Tensile Test Experiments by Powell et al.²⁵

	300°K	76°K	20°K
Ultimate tensile strength (1000 psi)			
	43.2	37.2	50.6
⊥	37.1	34.9	46.5
0.2% offset yield strength (1000 psi)			
	27.8	33.0	-
⊥	27.8	34.2	-
% Elongation			
	1.80	0.42	0.21
⊥	0.81	0.31	0.23

As can be seen from the small elongations, beryllium is very brittle at the lower temperatures. Fracture occurred before a yield point could be determined at 20°K.

Jacobsen^{26,27} also made tensile measurements on extruded Brush Q.M.V.-grade beryllium from 78 to 473°K. The specimens were tested in the directions perpendicular (⊥) and parallel (||) to the extrusion direction. These results are shown in Table V.

TABLE V. Summary of Tensile Test Experiments by Jacobsen.^{26,27}

	Range of Values	
	300°K	78°K
Ultimate tensile strength (1000 psi)		
	60-92	45-95
⊥	40-65	50-78
0.2% offset yield strength (1000 psi)		
	30-50	40-60
⊥	20-50	28-45
% Elongation		
	3-13	<1-2
⊥	3-7	<1-4

APPENDIX

TABULATION OF LINEAR DIMENSIONAL CHANGES AS A FUNCTION OF TEMPERATURE

TABLE I. Thermal Expansion Data from Corruccini and Gniewek.²³

T (°K)	Al $\Delta l/l \times 10^5$	Be $\Delta l/l \times 10^5$	Cu $\Delta l/l \times 10^5$	Au $\Delta l/l \times 10^5$
0	370	109	293	296
10	370		293	
20	370	109	293	295
30	369	109	292	291
40	368	109	291	285
50	365	109	288	278
60	360	109	283	269
70	354	108	277	260
80	346	108	269	250
90	336	107	260	239
100	325	106	250	228
120	298	102	227	205
140	267	97	202	180
160	232	89	175	154
180	195	78	146	128
200	196	63.6	116	101
220	115	50.2	85	74
240	73	32.8	54	46.6
260	30	13.4	22	19.2
273	0	0	0	0
280	-15	-7.5	-11	-9.1
293	-45	-21.8	-33	-27.8
300	-61	-29.7	-44	-38.0

TABLE II. Be Thermal Expansion Data of Meyerhoff and Smith.²⁴

T (°K)	$\Delta l/l \times 10^5$
80	87.8
100	87.0
120	83.1
140	81.3
160	75.4
180	67.3
200	56.9
220	44.3
240	29.5
260	12.5
273	0

TABLE III. Thermal Expansion Data from Laquer.²

T (°K)	Li $\Delta L/L \times 10^5$	Be $\Delta L/L \times 10^5$
0	698	107.5
20	697	107.5
40	692	107.5
60	682	107.0
80	658	106.5
100	623	105.0
120	578	101.5
140	522	96.0
160	458	88.5
180	387	78.0
200	311	65.0
220	230	50.0
240	146	32.5
260	59	13.5
273	0	0
280	-31	-7
300	-122	-29

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